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Measuring and Manipulating the Rhine River Branches: Interactions of Theory and Embodied Understanding in Eighteenth Century River Hydraulics

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Summary: Eighteenth century river hydraulics used both theory and measurement to address problems of flood safety, navigation and defense related to the rivers. In the late eighteenth century the Dutch overseer of the rivers, Christiaan Brunings, integrated hydraulic theory and meteorological practices, which enabled him to design a unique instrument for measuring river flow. The question is whether the unprecedented detail of measurements fits the putative empirical stance in the eighteenth century. The interactions between theory, instrument, measurement, and other knowledge practices are here assessed using experiences in similar measurement practices. I argue that Brunings had theoretical and embodied understanding of hydrodynamics, as he knew how to design an instrument for flow measurement of sufficient accuracy for his purpose in the sociopolitical context of river management.

Keywords: measurement instrument, embodied understanding, practice of knowledge creation, water management, river hydraulics

1. Introduction

In the last two weeks of April 1792, the division of river flow over the branches of the Rhine River in the Netherlands was measured in unprecedented detail. A double boat was used to deploy an instrument into the water at hundreds of positions to measure the velocity of the flow, and to calculate the division of river discharge over the main branches of the Rhine delta. The principles of the measurement instrument suggest that the builder, Christiaan Brunings (1736–

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1805), had know-how of fluid mechanics and turbulence that were not covered by the theories available at that time.[1] The instrument was developed in the context of the changing division of river discharge over the Rhine branches, which caused serious problems in the Dutch lowlands and led to the creation of a national institution of water infrastructure in the Netherlands that continues to exist today: Rijkswaterstaat.[2] Brunings is an interesting figure with a double role as active member of learned societies and a central position in many water management, coastal and river engineering projects and in the setup of Rijkswaterstaat. In the seventeenth century the northern Rhine branch (the Nederrijn) gradually silted up while the southern branch (the Waal) enlarged. The discharge reduction in the Nederrijn also affected the IJssel River, which branches off south of Arnhem (Figure 1).[3] All this caused navigation problems during low river flow, and many inundations and land loss during discharge peaks, which led to political conflicts about flood risk and navigability between cities along the Rhine branches. It also led to defense problems for the Republic, as demonstrated by the unhindered invasion by the French in 1672 across a wadable Nederrijn. In a series of conventions, the provinces of Gelderland, Overijssel, Utrecht and Holland, and the state of Prussia agreed on various differences, principles and measures, including a preferred and fixed division of discharge over the Rhine's branches. To bypass the nearly blocked Nederrijn at Lobith, a canal was dug around 1707. Subsequent floods eroded the riverbanks around the new mouth and formed sand bars in the river, which partially blocked the entry of the canal. In 1784, the mouth was modified by design, and under supervision of, Brunings in an attempt to reach the preferred division of discharge.[4]

The actual division of discharge was only roughly known. The practical problem of quantifying river flow led to combination and production of knowledge. Brunings, informally educated in physics, first established that the available theories of river hydraulics were deficient for the calculation of the discharge division and then developed and used the instrument to check the discharge division. Past readings of Brunings' prize-winning essay on the flow velocity of water[5] emphasized that Brunings showed a predilection towards empirically oriented authors of river hydraulics,[6] that he drastically refused the mathematical theory of river hydraulics of the Italian engineer Guglielmini, and that he was "a first-class observer and analyzer of the observed data" but

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[1] See Hesselink et al. 2006 for a description of the instrument and reanalysis of the data using twentieth-century theory.

[2] Van de Ven 1976 describes river management and the developments in the seventeenth and eighteenth century centering on the Pannerdensch Kanaal that led to the Rijkswaterstaat institution, and see Toussaint 2006 for further development of Rijkswaterstaat in the nineteenth and twentieth century.

[3] Kleinhans et al. 2011 describe the development of the Rhine River branches on the geologic and historic timescale until 1707.

[4] Van de Ven 1976. The design purpose was imposed by the 1745 convention, which stated that one-third of the flow discharge should enter the Nederrijn and two-thirds the Waal.

[5] Brunings 1789a.

[6] Maffioli 1989.

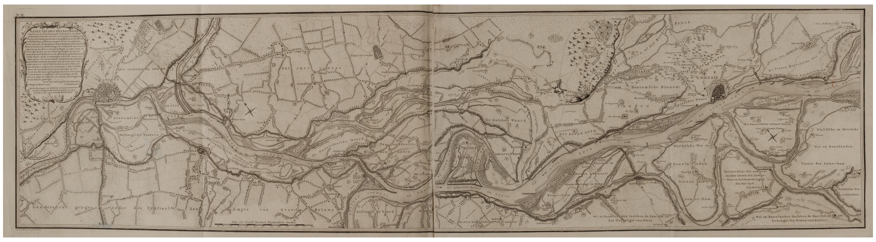

Figure 1. Map by Engelman (29 March 1790) of the Rhine River branches from Emmerich to Arnhem. Source: Gelders Archief Arnhem; https://permalink.geldersarchief.nl/4DFE872893FE4302847FD4A6EAF40D65.

was "reluctant about theoretically underpinning or generalizing his results."[7] These readings fit the common notion of the eighteenth century as a time of data and quantification "mania" without a theoretical framework to guide interpretation, such as shown for early meteorology where vast amounts of underused data were collected.[8] At first sight, Brunings case fits this common notion perfectly, with his experience in meteorological observation and the collection of quantitative data in the form of tables. I will argue that these readings of Brunings being disinclined to apply theory, are at odds with the fact that he first applied theories and then built and applied an advanced instrument that suggests links to theories.

If Brunings did more than cite hydraulic theories—showing by thorough review and application that he evidently understood them—then this would argue against a predominantly empirical stance in the eighteenth century practices of river hydraulics. What knowledge and understanding of theory instigated Brunings to put the theories to the side? What understanding of river flow gained by the designer is embodied in the instrument? Were the instrument and its application informed by theories for river hydraulics, were they used to test these theories or was the whole project directed at quantification for its own sake?

The notion of understanding needs to be unpacked for careful assessment of Brunings' empirical and theoretical predilections from his writing and his instrument design. To assess the scientific understanding of the theories and as embodied in the instrument, the account of Henk de Regt is useful.[9] According to de Regt, scientific understanding a phenomenon requires a theory that is intelligible, meaning that its consequences are recognizable (for a scientist) without performing exact calculations. Intelligibility, in turn, is pragmatic in that it depends on the skills and the background knowledge of the involved scientists and the context in which they operate. As such, the technological expertise and the ability to manipulate (mathematical) models and phenomena are not merely a means for knowledge production: they are epistemic skills and

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[7] Toussaint 2006.

[8] Zuidervaart 2005, on 410.

[9] de Regt 2017.

components of embodied knowledge that enable scientists to use theoretical knowledge for the explanation of phenomena. Sabina Leonelli[10] distinguishes three kinds of scientific understanding of a phenomenon: *theoretical understanding* allows the application of theory to the phenomenon, and, by implication, seeing where application would fail; *embodied understanding* allows exploration, measurement, and manipulation of the phenomenon; and *integrated understanding* derives from balanced exercise and coordination of theoretical and embodied knowledge. The latter is considered epistemically superior and the question addressed here is whether and how Brunings gained integrated understanding.[11]

Moreover, embodied understanding plays a double role: in the historic actor and in the historian. In the analysis of the historical case of Brunings' instrument, which no longer exists, access to the embodied understanding is problematic. The size of the instrument and the danger of measurement on the present Rhine River due to the intense navigation make performative research and embodied interaction with a rebuilt instrument and the turbulent river flow impractical and dangerous.[12] The historic actor, Brunings, left signs in writing and in the design of the instrument that I need to interpret based on experience with other, similar kinds of measurements. Also, it needs to be articulated accessibly for a readership without access to such embodied understanding. Here, the necessary sensitivity to the understanding embodied in the instrument can come from my own scientific expertise in river science and experience with measurement instruments in similar applications as Brunings' case. In other words, I must use my earth-scientific understanding. Brunings' description of the measurement practice and his experiences during testing are sufficiently palpable to me because I gained understanding in sufficiently similar practices by partaking in measurements on the Rhine River and by conducting laboratory experiments. However, avoiding anachronism requires avoiding theory-ladenness in interpreting aspects of the instrument design in view of present-day theory on turbulence. Some theory-guidance is unavoidable in selecting aspects;[13] here the elements of Brunings' essay and instrument design that are relevant in assessing Brunings' embodied understanding of turbulent river flow. Moreover, the instrument had a purpose and it is therefore plausible that the various parts of instrument had purposes. The historic instrument design as such embodies a working knowledge placed there by the builder, to which access may be gained with my experience.[14] This working knowledge is sufficient to perform regularly and reliably irrespective of theoretical knowledge.

This articulation of the twofold instance of scientific understanding can also be recognized in historiography of instruments. For example, re-enactment

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[10] Leonelli 2009.

[11] Leonelli built her account of understanding on an earlier version of de Regt's account.

[12] Such as advocated by Hendriksen 2020.

[13] Schickore 2016, on 23.

[14] This agrees with the working knowledge of instruments, or "thing knowledge," of Baird 2003, but the author does not endorse Baird's neo-Popperian account of objectivity.

of projections of solar microscopes enriched the study of books and images by enabling analysis of the historic visual culture[15] and teamwork with artisans in their knowledge production.[16] Working with replicas and re-enactment of the practices yield embodied understanding for the historian, which provides epistemic access to the historic experimental setting and the experiences of the actors in it, that can then be articulated as historiographic knowledge.[17] Voskuhl[18] expands the historiographic gains of reperformance of experiments: they serve historical research and complement texts by providing knowledge of the experimental practice at three levels: technical (how the instrument was designed), procedural (how the instrument was dealt with in its environment), and epistemic (how manipulation of the instrument resulted in facts). Using my understanding, the assessment of Brunings' understanding will be used to explore the historical interactions between theoretical understanding and practices and the putative empirical stance of eighteenth-century river hydraulics.[19]

In part 1 I will argue how Brunings treatment of theory in relation to available data at that time shows that Brunings was not disinclined to apply theory as Cesare Maffioli and Bert Toussaint argued. Rather, he demonstrated it to be inadequate for his purposes, showing the need to collect a large amount of data. In part 2 I describe what practices of knowledge creation Brunings combined, and how this is situated in the sociopolitical situation around the river problems. His informal education and practices of knowledge creation allowed Brunings to develop various empirical skills as expected in his position as practitioner, but also to gain the necessary theoretical knowledge to publish as a member of learned societies. In part 3 the understanding of theory, river flow and instruments that Brunings gained is viewed through the lens of scientific understanding. Whether he understood and integrated both theoretical and empirical approaches, rather than copied them from other authors, will be assessed from the 1789 essay and the embodied understanding recorded in his measurement instrument, employing the author's theoretical and embodied understanding of river hydraulics and river measurements to interpret the detailed drawings and descriptions of the instrument. This will show that Brunings developed integrated understanding by coordinating theoretical and empirical aspects, which argues against a purely empirical stance. In part 4, I argue that Brunings' motivation for accuracy and the socio-political context of his project make it plausible that his aim was to produce knowledge that was as uncontestable as possible, which explains the significant effort put into the

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[15] Heering 2008.

[16] Fransen 2019.

[17] Developmental psychology also recognizes the important and perhaps prior role of embodiment and situated motor skills for linguistic skills. See Oudgenoeg-Paz et al. 2016 for review.

[18] Voskuhl 1997.

[19] As Voskuhl (1997, on 340) argues, the main challenge in a reperformance approach is "not to confuse historical knowledge with the insights a performance yields, and to shift the historical object-of-research away from the document or the performance itself towards an interpretation of textual and non-textual sources that has its foundation in the analysis of a historical context where documents and practices come into being."

exhaustive essay, the extraordinary instrument and the unparalleled measurements.

1. Theory Meets Empirical River Hydraulics in Brunings' 1789 Essay

The prize essay by Brunings, awarded a gold medal of the Koninklijke Hollandsche Maatschappij der Wetenschappen (Royal Holland Society of Sciences and Humanities) in 1786 and published in the 1789 proceedings, was an answer to the prize question how to determine the average flow velocity of a river.[20] The essay deals with three connected questions: whether a theory exists, confirmed by measurement, for the calculation of the average flow velocity, or whether the flow can only be determined by direct measurement, and, if the latter is the case, what sufficiently tested instrument is available to measure the flow velocity.[21] The problem, as Brunings explains on the first eight pages, is that no simple relation exists between the width and depth of the river channel and the flow discharge through it. Wider and deeper rivers have larger flow discharge than smaller rivers, but how flow velocity also depends on other factors was unclear and debated. Brunings refers to seventeenth century Italian scientists such as Castelli and Guglielmini, who developed geometrical theories for river hydraulics. Benedetto Castelli (c. 1577–1643) was the successor of Galileo as mathematician at the University of Pisa. Domenico Guglielmini (1655–1710) was a water administrator for Bologna and, after writing his well-known work, *Della natura dei fiumi*, he became a professor at the University of Bologna. Their motivation was similar to that of Brunings: a conflict between the cities Bologna and Ferrara about the best solutions for the river flooding and navigation problems of the branches of the Po River, which were caused by the silting up of a river branch that previously allowed shipping to Venice.

Where was Brunings situated between theoreticians on fluid mechanics and the practitioners involved in river management? Brunings confronted two approaches: geometrical theories between river flow, channel depth and slope, and measurement of the flow velocity. The relation of flow discharge with channel depth motivated an important innovation in the mid-eighteenth century in the creation of river maps by surveyors: the drawing of depth contours.[22] As channel depth was necessary but insufficient information, velocity measurements by flotation devices were sometimes reported. This method of flotation, Brunings argued, was inadequate, because Castelli and others had observed in small laboratory setups that the flow velocity varied in

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[20] The prize competition essay was a common form of communication in the Hollandsche Maatschappij in the eighteenth and nineteenth century.

[21] Brunings 1789a.

[22] The rapid development of detailed hydrographic map making in the second quarter of the eighteenth century by surveyors such as Nicolaas Cruquius (1678–1754) is described by van den Brink 1998. Note, however, that Italian "scientists of water," as pointed out by Lugaresi 2021, called themselves "perito" which is Italian for both expert and surveyor.

the cross-section and in the depth of the flow. There were geometrical theories describing the flow velocity profile, but Lecchi, Michelotti, and others argued that it should be measured.[23] Antonio Lecchi (1702–1776) was a lecturer in mathematics and hydraulics in Milan. To obtain the flow discharge, flow velocity needed to be averaged over the entire cross-section and multiplied with the cross-sectional area of the river channel. Regardless of the empirical stance of authors cited by Brunings, he puts theory *before* measurement in the introduction:

> In the first place one has to ascertain what theoretical rules have been devised to determine the velocity at various depths and also the average velocity in every cross-section, after which one can in the second place which of these theories has been confirmed by tests […] and if it appears that the velocities can only be determined by direct tests, then in the third place the question is what instrument is most applicable.[24]

The first part of the essay expands in 31 pages on the theories for river hydraulics. The second part of the essay reviews in 108 pages the published measurements and tests that Italian authors conducted to support their theories. He begins by stating that most theories reviewed in part one are either built on the analogy of water flowing out of a barrel (Toricelli) or water flowing out over a slope (Galileo). Brunings dwells in detail on the velocity profile over the depth, supported by tables with measurements and calculations. The various kinds of instruments and measurement methods are likewise described in some detail, stating that he conducted experiments himself with various instruments. The main problem is that various theories by Guglielmini and others predicted either a linear increase of flow velocity from the riverbed upwards, or a decrease following a parabolic profile, with the fastest flow at the riverbed.[25] This gives very different results, and both theories are contradicted by measurements in flumes (small artificial channels) reported by Michelotti as demonstrated in text and tables by Brunings. Francesco Domenico Michelotti (1710–1787) was professor at the university of Turin and hydraulic engineer of Sardinia, where he conducted experiments and compared and designed flow instruments. Brunings concludes that none of the theories are supported by the data for accurate and reliable determination of discharge in a flume, let alone a real river.[26] As such, he used existing measurements to reject the theories for quantification of the divided river discharge. Brunings needed that accuracy

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[23] See Di Fidio and Gandolfi 2011 for Lecchi's empirical hydraulics, and Maffioli 1989 for his arguments for Brunings' empirical stance

[24] Brunings 1789a, on 9–10. Translated by the author from the Dutch text: "Men dient, naamlyk, in de *eerste* plaats nategaan, welke Theoretische Regels tot hier toe uitgedacht zyn, om de snelheid van stroomend water op allerleïe diepten, en dus ook de middelbaare snelheid in iedere doorsnede te bepaalen: ten einde vervolgens in de *tweede* plaats te onderzoeken, welke van deeze Theoriën door proeven bevestigd is. En by aldien geene van dezelven aan de ondervinding beantwoorden mogt, zo dat de snelheden alleen door middel van daadlyke proeven zouden moeten gevonden worden; dan is in de *derde* plaats de vraag, welk in zodanig geval het werktuig zy, het geen aan de vereischten by de Vraag opgegeeven, meest voldoet?"

[25] See Lugaresi 2021 for a detailed account of the theory development in Italy in its context of the Po river problem.

[26] Brunings 1789a, on 93–96 for comparison of measured flow and the parabolic profile.

and reliability, because, as he made crystal clear in the introduction of the essay, flood safety of the rivers is his main concern and the quantity of water determines the possible improvement by engineering measures.[27] Moreover, Brunings ended the second section with reasons why such a theory is "highly unlikely" to exist. He wrote about the complicated spatial variation of flow velocity in relation to the irregularities of the riverbed and banks that contribute to the "deceleration" of the flow. This indicates that Brunings thought the irregularities to cause flow resistance, which was debated at the time by authors he referred to.[28]

The third part of Brunings' essay is devoted to the design principles, testing and improvements, and application of Brunings instrument in the Rhine River, with more detail about existing instruments and a great level of detail on his innovative instrument (discussed in part 3).[29] Auxiliary theory needed for the instrument, such as that of drag force on submerged bodies, is mentioned, as well as the geometrical theory underlying mechanical instruments such as vanes and waterwheels, and the averaging procedure of parabolic velocity profiles.[30] The appendices, submitted later, are continuations of the third part. The first appendix reports on various improvements on his instrument based on measurements in several of the Rhine branches in 1787.[31] The second appendix, and some footnotes added after first submission of the essay, reports on further improvements, insights in best measurement practices, experiences by others than Brunings with the instruments, and a direct comparison in 1789 between measurements by flotation devices and his instrument.[32]

2. A Stellar Conjunction of Practices of Knowledge Creation

A brief biography is needed to explore how Christiaan Brunings was educated in physics and hydraulics, and what other practices of knowledge creation he gained access to.[33] Brunings was born in Neckerau (near Mannheim, Germany)

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[27] Ibid., on 5–6.

[28] Di Fidio and Gandolfi 2011 discuss the development of measurement instruments, mainly in Italy, that demonstrated at the time the invalidity of the hypothesis of proportionality between local velocity and the square root of depth. Eckert 2021 discusses the extensive studies of flow friction by Du Buat and D'Alembert, both of which are cited by Brunings.

[29] Brunings 1777 account of Poleni's wind speed instrument is followed by a long table of measurements conducted by Brunings in 1772, with daily observations and monthly averages, but not a word spent on interpretation.

[30] Clearly the instrument is not so much theory-laden as theory-informed or theory-directed (*sensu* Schickore 2016). There was not sufficient theory to design the instrument for its purpose, but aspects of it were informed by theory, such as fluid drag on objects and the role of momentum in the dynamic force balance.

[31] Brunings 1789a, on 188–210.

[32] Ibid., on 213–233.

[33] Conrad, a close friend of Brunings, published a biography (in Dutch) in 1827 that is mentioned as "biased" in the brief biography of Brunings (in Dutch) by Blok and Molhuysen 1911. The only known portrait of Brunings is in the collection of the Rijksmuseum: https://www.rijksmuseum.nl/nl/collectie/RP-P-OB-62.710

on 8 November 1736. His family moved to Amsterdam in 1741 when his father, a minister, was offered a position there in the Reformed church. However, Christiaan moved to Hennersdorff, Germany, in 1751 to attend the gymnasium, and enrolled in the University of Heidelberg in 1753 to study law, philosophy, and physics. When his father died in 1754, Christiaan had to return to Holland to take care of his mother and five siblings. He then held several positions and jobs.

Through a brother-in-law he met Jan Noppen (1706–1764). This accidental meeting had several significant consequences. Noppen was supervisor in the Rijnland water authority in Spaarndam (west of Amsterdam) and member of the country's oldest learned society: the Hollandsche Maatschappij der Wetenschappen located in Haarlem. Brunings befriended Noppen, who taught him astronomy, music and physics, in particular fluid dynamics and the fluid drag theory of D'Alembert. Which other works of physics they studied is unknown, but Brunings, in his essay, mentions Newton and 's Gravesande directly in relation to fluid drag on balls.[34] It is likely that he accessed these general works in his informal education, or fairly early in his Rijnland career.

Following Noppen's death in 1764, Christiaan obtained the Rijnland position in 1765. He married Noppen's daughter in June 1766, but she died after the birth of their daughter in the same year. Brunings then buried himself in work, according to his friend, colleague, successor, and biographer Frederik Willem Conrad.[35] He became closely involved with the foremost authorities of Dutch water management and, having made an impression with a report on the land reclamation Haarlemmermeer, became Inspector-General in 1769. He corresponded with the Hollandsche Maatschappij and other learned societies and became a member. Brunings designed and supervised many projects related to water infrastructure, coastal defense, and river management. Many other functions were added until his death. He played a central role in the creation of Rijkswaterstaat, a national institution for water management, of which he was the first Inspector-General. Brunings died suddenly on 16 May 1805. In summary, the fortuitous meeting with Noppen, and Noppens informal role as tutor, put Christiaan accidentally on a path to a stellar career in water management, which seemed not initially to have had his interest in his prematurely terminated formal education.

What practices of knowledge creation were combined with the theories of river hydraulics that allowed the development of the instrument and the measurements? The brief biography indicates that Brunings operated in three practices of knowledge that were relevant for the development of his instrument in the context of the problems of the Rhine River branches. These practices, accessible to him thanks to his informal education in physics, were learning on the job at Rijnland; second, meteorological measurements and instrument development; and third, the interactions in learned societies. While these practices are loosely connected through practitioners active in combina-

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[34] Brunings 1789a, on 129.

[35] Conrad 1827.

tions of these activities,[36] they are distinct in the activities, skills and interests. These practices became tightly connected in various ways as expanded below.

Brunings, unlike many of his colleagues in river engineering, was not trained in surveying, but gained experience with measurement through his use of House Swanenburgh (later Zwanenburg) that came with the function at Rijnland. Here, he had to conduct daily meteorological measurements, especially of temperature, wind and precipitation, and maintain and develop the instruments. Noppen initiated these systematic daily observations in 1735 supported by Petrus van Musschenbroek (1692–1761), professor in mathematics and philosophy at the university of Leiden, and Nicolaus Cruquius (1678–1754), surveyor of the rivers, both advocates of data collection. Brunings filled long tables with his daily meteorological measurements. Brunings also wrote several essays about meteorological measurement instruments in the proceedings of the Hollandsche Maatschappij, for example a new rain meter of Brunings' design was built by John Cuthbertson (1743–1821),[37] who would also play a role in modifications of the flow velocity instrument.[38] Already in 1777, a decade before he wrote the 1789 essay, Brunings published about the wind speed instrument adopted from Giovanni Poleni (1683–1761), professor at the university of Padua, whose work he built on in the 1789 essay on flow velocity.[39] What with the practical skills needed to maintain and use meteorological instruments, especially those with moving parts, it is quite plausible that this practice allowed Brunings to gain experience with measurement and instrument design, wherein the principles of some instruments for measuring the flow of wind were also used to measure flow of water.

The gain of knowledge and know-how of measurement was enabled by, or strengthened, his knowledge of international river hydraulics literature and access to Italian authors. Brunings will not have had difficulties with German, Latin, French, and Italian, languages that he also read and wrote in for pleasure.[40] In turn, his participation in the learned society offered Brunings access to the practice of knowledge creation of studying literature, discussions, and (sometimes written) comments on Brunings' essays. For example, in the same 1777 volume that Brunings published his rain meter in, Paolo Frisi (1728–1784), professor at the university of Pisa, published an essay on the discharge division in the Italian rivers, referring to many Italian authors that Brunings also referred to in the 1789 essay.

In his positions as supervisor and inspector-general, Brunings undoubtedly gained knowledge and know-how of management and design and supervision

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[36] E.g., Van de Ven 1976, on 272.

[37] Brunings 1789b.

[38] This situation is analogous to that in the collaboration in microscopic experiments between Antoni van Leeuwenhoek and artists, who closely worked together with draughtsmen to depict the observations in drawings that show evidence of idealization and of different hands of draughtsmen and engravers (Fransen 2019). Brunings also had artisan knowledge of instrument building himself but collaborated with instrument makers such as John Cuthbertson for their construction.

[39] Brunings 1777.

[40] Conrad 1827, on 68.

of engineering measures for flood safety of the rivers, coasts, and water infrastructure. This position had gained momentum with the frequent inundations in the eighteenth century, the navigability problems, and the damaged defense function of the rivers. Notably, a convention in 1771 on the problematically unbalanced division of river discharge over the Rhine branches set in motion a series of works, including modifications of the upstream mouths of the Pannerdensch Kanaal and the IJssel River.[41] With Brunings involvement in this convention, as inspector general, and his nascent knowledge of flow measurement, the convention possibly also initiated his focus on the discharge division and flow velocity measurement to determine what the division had become.

Arguably, the entanglement of theoretical work, empirical work and the practice in direct response to societal needs renders the presumption of Brunings' predilection towards the empirical moot. To be sure, Brunings himself made a point of calling certain authors mathematicians (*wiskundigen*), as opposed to physicists (*natuurkundigen*), which could be read as a deliberate division of labor between theoreticians and empiricists, but this was a common theme in the second half of the eighteenth century that Brunings was influenced by and need not be taken as evidence of Brunings' purported empirical predilection.[42] Maffioli, in comparing the Italian and Dutch river scientists, argues that there are not so much differences between the countries as there are professional differences.[43] More theoretical work was done in the universities, especially in Italy where it became an autonomous university subject in Bologna at the end of the seventeenth century, and more practical work was devoted to the control of the rivers in institutions. Both practices were equally touched by the enlightened ideal of utility, which natural philosophy could only become in its practical application.[44] This ideal is clearly shared by Brunings, but the fact is that he, in his role and employment as practitioner, put considerable effort in theory, in which he was informally educated, only to find it inadequate for his purpose.

This case suggests that the supposedly predominant empirical stance of that time needs to be called into question. This supposition might be the result of positivistic influences on twentieth century historians. The case of Brunings suggests that the entanglement of theory, empiricism, technology, and politics was a fulcrum rather than an exception in the knowledge creation practices of the eighteenth century.

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[41] Van de Ven 1976, chapters 7 and 8, reports on the decade of negotiations between the provinces of Holland, Gelderland, Utrecht, and Overijssel preceding the convention.

[42] See Heilbron 1993, on 28 for similar trends (and similar examples of boundary work)

[43] Maffioli 1989.

[44] Argument developed by Maffioli 1989. Davids 2006 confirms this by contrasting it to the theory-oriented private academies in China. Lugaresi 2021 shows how river hydraulics was considered "virtuous" because it was considered of societal importance, and shows that theoretical and practical approaches were developed side by side in Italian universities in the eighteenth century.

3. Embodied Understanding of Theory, of River Flow, and of Measurement

Arguments for interactions between theory, instrument, and measurement hinge on the understanding, as opposed to mere citation, of theory and measurement by instruments. Brunings' development of theoretical understanding is evident in the first part of the essay, where he reviews mathematical theories for river hydraulics and states that most theories are either built on the analogy of water flowing out of a barrel or of mass flowing out over a slope. Here he contrasts the theories and experiments of Castelli and Guglielmini but also explains how subsequent theories of many Italian, Dutch, and French theoreticians are variations with similar underlying principles and assumptions. Brunings argues early in the second part how the principles lead to problematic predictions. In particular, prediction of velocity from the Toricellian principle of outflow from a barrel ignores the deceleration of flow by the irregularities of the riverbed and bank. The alternative, a fluid accelerating down the slope in analogy with Galileo's experiments on acceleration, is equally wrong as the higher and higher flow velocity would have led to more scour and deepening of the riverbed, which would lead to reduction of the slope. Here, Brunings recognizes consequences (for his problem) of the propositional knowledge that the theories are formulated in, without performing the exact calculations (although he later also presents some calculations).[45] This implies that he had theoretical understanding of these theories and what they could predict, without implying that the theories were correct for the phenomenon that Brunings was interested in. In fact, he had understanding of how the underlying principles made it impossible for the theories to predict flow velocity adequately in rivers. He could in part have copied from others who debated causes of friction and validity of hydraulic theories, but Brunings' extensive review, calculations, and reasoning about consequences of the theories for the specific context of his problem demonstrates that he obtained this understanding himself.

Brunings also gained embodied understanding of river hydraulics and its measurement in the material practices surrounding the instrument development. Brunings wrote in great detail about existing instruments to measure flow velocity at various depths, such as the tracking of submerged balls that are kept at certain depths by flotation devices (Da Vinci), the Pitot tube, the water vane (Michelotti), and measurement of the drag force on a submerged pendulum ball inferred from quadrant reading (Guglielmini), or from a water balance (Lorgna), where the drag on a submerged ball, suspended from a chain or cable, is balanced by a counterweight on a steelyard balance above the water.[46] The flotation technique directly gives velocity as travel distance over a certain time, but lack of control over the depth at which the velocity is measured led Brunings to reject this as suitable for his purpose. All other techniques give indirect measures for velocity, requiring theory and sometimes

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[45] Brunings 1789a, on 45–48.

[46] Also see Di Fidio and Gandolfi 2011 for a review of flow velocity measurement in Italy.

calibration to link the measured quantity to velocity. The Pitot tube used the overpressure of flowing water, but was difficult to handle at larger water depths, as Brunings explains in detail on two pages. Furthermore, the fluctuations of pressure that Brunings frequently remarks on, translate to very large velocity fluctuations, rendering this instrument overly sensitive. The quadrant has poor control on the submergence depth, which Brunings needed to measure velocity in great spatial detail, due to the inaccuracy of the angle measurement and the weight and curving of the rope holding the ball. On the other hand, the water steelyard allows some control on depth. Brunings rebuilt and tested it in sluices, where he probably gained both confidence in the instrument and his embodied understanding of flow and its fluctuations.[47] He then argued that the existing water steelyard design was impractical for use in deep rivers due to its large weight, the long balance arm and its sensitivity to motion of the boat, the operator or flow velocity fluctuations. Yet it was the starting point for the development of the new flow velocity instrument for deep rivers, which he called "tachometer," and is sometimes also called "water unster" (in Dutch), or water steelyard.

Brunings' tachometer consisted of four parts (Figure 2): a double boat connected by a gantry protected by a shelter against rain and wind for working and making notes, a tethered pole that was lowered from the gantry into the water and pushed into the riverbed, a steelyard connected to the top of the pole, and a movable plate that was positioned at the required depth through a gear rack. The square plate, which had sides of six Rhenish inches (0.156 meter), was positioned perpendicular to the flow by a horizontal square bar between two sets of four small lubricated rollers. The bar and plate could freely move in the flow direction but were fixed in perpendicular orientation. A thin chain, going through a pulley, connected the bar and the short arm of the steelyard, such that the gravitational force of the weights on the long arm of the steelyard balanced the drag force of the flow on the plate. The position of the weight on the long arm was converted into flow velocity. Brunings understood the mechanisms of drag and force balance and mentioned Newton's experiments of drag on a submerged sphere, and gave the plate its dimensions to allow a manageable weight on the steelyard of 2.4 Troic pounds (slightly over one kilogram) that also minimized effects of oscillations of the flow.[48] Hesselink, Kleinhans, and Boreel reanalyzed Brunings' calibration data of flotation measurements and near-surface measurements with the tachometer.[49] They found that flow velocity was related with high accuracy to the square root of the weight, and the drag coefficient of the plate was well within values reported independently in contemporary engineering literature, showing that the instrument performed well. Also in other technical aspects Brunings demonstrated his tacit knowledge. For example, the chain between steelyard and plate was sheltered in a groove on the lee side of the pole, such that the

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[47] Brunings 1789a, on 146–154.

[48] Brunings 1789a mentions Newton on 129 but did not provide a reference, suggesting that he thought part 2 of the *Principia* sufficiently well-known to his readership.

[49] Hesselink et al. 2006.

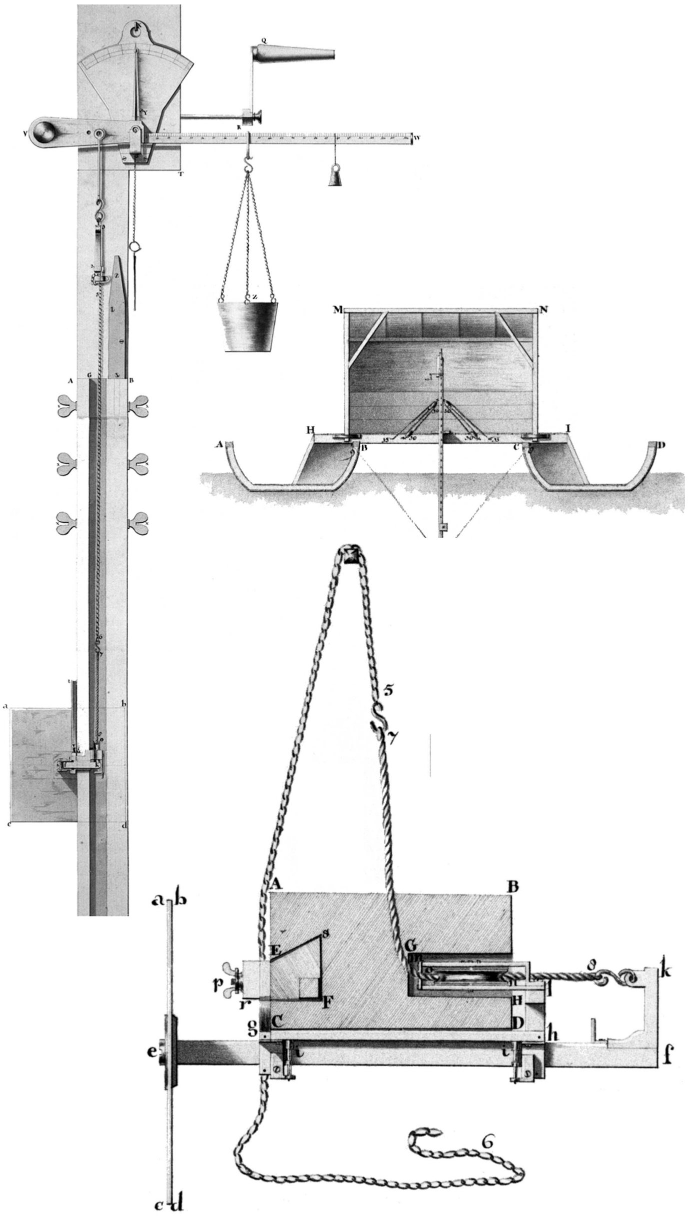

Figure 2. Drawings by Conrad of the “tachometer” to measure river flow velocity at any height above the riverbed. Left: the pole with the steelyard balance and the vertical plate oriented towards the flow. Top right: the boat with the gantry, shelter, and tethered pole. Bottom right: the vertical plate (abcd) and its suspension mechanism with the horizontal pole (ef) in its rollers, and the chain connecting the plate to the short arm of the steelyard. The scale is indicated by the size of the plate (0.156 m). Source: Frederik Willem Conrad, “Aftekening van den stroom-meter tot het neemen der proeven wegens de snelheid van den stroom” [in Dutch], 1798, The Hague, NL, General State Archive, Supplement of the Map Collection of Hingman, Inventory Number 137.

flow would not drag it. Furthermore, a small, second weight on the steelyard compensated for the weight of the chain depending on its length in relation to the depth of measurement.

What understanding of river flow is embodied in the instrument? Evidence can be found in the design that the instrument was adapted to harsh conditions to obtain accurate numbers. To give the reader a feeling for what Brunings and coworkers were up against on the river, the author here describes first-hand experiences with instruments lowered into the Waal River just downstream of Pannerden, on a Rijkswaterstaat boat named "Conrad." During high discharge, the water is entirely opaque from the dissolved and suspended matter in the flow, meaning that the operators are chasing the invisible as they are blind to what happens below the surface. Keeping the boat in position is hard. The drag force on the boat is tremendous, and the pole on Brunings instrument would not have been strong enough to keep his boat in position. Nowhere made he clear how he did it, but to avoid breaking the pole, the boat would have to be securely fixed at sub-meter accuracy. This requires, in the authors experience, at least three anchors with tightly pulled ropes. In the modern case, the steel boat is kept in place by a vertical steel cylinder pushed into the bed by an engine, a brute force unavailable to Brunings. We lowered a stainless steel frame from a steel cable. The 1.5 m long frame with acoustic sensors for flow velocity and suspended sand concentration was lowered in about eight meter water depth by a motorized crane. Despite the weight of about 150 kg, the cable, taut enough to cut off nearly frozen fingers, is curved by flow drag, showing that even a thin steel cable's length significantly affects instrument position. The electronic pressure sensor records at least one meter variation in elevation above the bed, and the flow velocity variations displace the instrument by several meters per minute. Flow turbulence is generated by the mega-ripples on the riverbed and the irregularities of the submerged riverbanks, aspects that Brunings correctly linked to flow friction.[50] The turbulence is observable as fluctuations in flow velocity and pressure, proportional to the velocity itself, and as meter-wide boils on the water surface. Here, Brunings' lean construction was an advantage if indeed the boat could be kept at position accurately. But even then the drag force and the leverage on the pole increases with submerged length and would have become unmanageable for water depths larger than several meters, as one can experience with any pole or paddle on a boat on the river.[51]

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[50] While avoiding anachronistic interpretation of Brunings' work, it is worth remarking that it has been known only from the early twentieth century that this turbulence leads to a logarithmic velocity profile above the channel bed, or boundary, to the water surface, and boundary layer theory for the velocity profile and its integration to discharge exists since the 1950s (Figure 3).

[51] To give the reader a feeling for the drag force on the pole of Brunings' instrument in comparison to a common experience: a cyclist of 1 m^2 frontal surface area travelling 15 km/hour (about 4 m/s), experiences a drag force by the air of approximately 11 Newton. The pole and plate in 7 m water depth also have approximately a 1 m^2 frontal area (Figure 2), and the river flow velocity is about one third of that of the cyclist, but the density of water is about 800 times larger than that of air, yielding a drag force of over 900 N, which is much more than a single operator can handle.

Brunings clearly gained embodied understanding of river flow by measurement with the instruments.[52] In several places in his essay, fluctuations in flow velocity are described in such detail[53] that Brunings undoubtedly had felt these in terms of weight on the balance with his own hands during measurements with Lorgna's water steelyard and with his tachometer. The tachometer embodies his know-how and understanding: the lubricated rollers allowed the plate to move freely with the turbulent fluctuations in the streamwise direction, while the plate's dimensions allowed the weight of the whole instrument and the drag forces by the range of flow velocity encountered in rivers to be manageable by a few operators. The epistemic value of the understanding gained during tests in canals and measurements on the river branches is that it helped improve the instrument, the quality of the measurements, and his assessment of that quality.[54]

Did Brunings develop what Leonelli would call *integrated understanding*? In the 1789 essay, Brunings developed and demonstrated his ability to reason about consequences of the theories for river hydraulics for flow velocity. He was evidently skilled in design and operation of measurement instruments, through which he gained new knowledge as well as embodied understanding of river flow. The instrument shows readable marks (to someone with sufficiently similar expertise) that carry a working knowledge of fluctuating river flow regardless of the fact that propositional knowledge of turbulent boundary layers was unavailable when Brunings built it (Figure 3). Brunings did not use the data as evidence to falsify existing river hydraulics theories, because he had already spelled out how these did not correctly quantify the variation of flow velocity over depth and across the width. But some theoretical understanding underpinned the instrument, which was meant to cover this variation caused by flow deceleration at the river bed and banks. Moreover, Brunings developed and demonstrated the ability to reason about consequences of mechanics of gravity and drag force on objects, force balances, water pressure, and other auxiliary theories needed for the design and application of the instruments. Such evidence for integrated understanding involving the complex of theories, instrument, and target phenomenon is found throughout the essay.

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[52] Another record of embodied understanding is the skilled design, improvements and handling of instruments suitable for deep and dirty river flow. Brunings 1789a mentions friction in the measurement instrument on, e.g., 149, 157, 164, 166, and lubrication on 168. Brunings made a setup to measure the friction force directly on 169 and considerably improved this in the appendices on 196–201 and 218. He discusses various contributions of weights of parts of the instrument, such as the chain connecting the plate to the short arm of the steelyard on, e.g., 164.

[53] Brunings 1789a mentions flow velocity fluctuations, or variations, or oscillations, on, e.g., 121, 127, 141, 161, and an improvement of the instrument to make it less sensitive to these fluctuations in the second appendix, on 214. Reducing this sensitivity makes it less ambiguous to read off a time-averaged value on the balance that removes the turbulent fluctuations from the observational data.

[54] Brunings' 1777 account of his tests of Poleni's wind speed instrument used in Zwanenburg is similarly thorough with theoretical and technical aspects relevant to instrument functioning and accuracy discussed in great detail

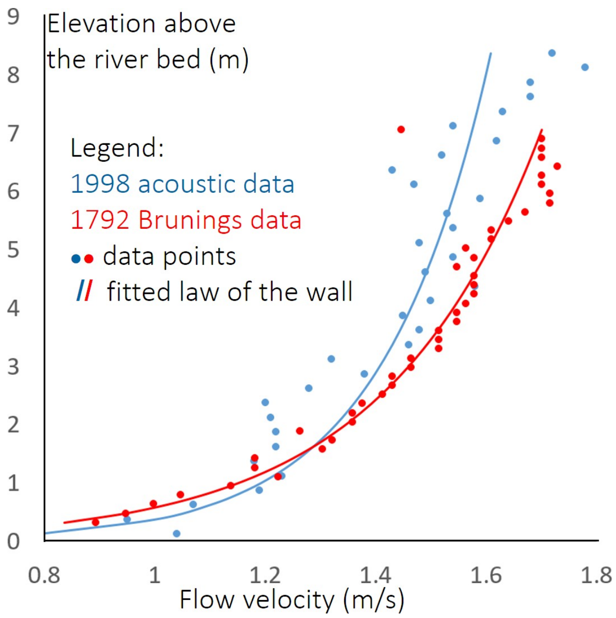

Figure 3. Example of flow velocity data in the Rhine. Brunings data was collected in a deep outer bend on 1792. See Hesselink et al. 2006. The acoustic doppler profile data was collected on 11 November 1998 in slightly higher discharge by Rijkswaterstaat. The lines are least squares fits of the law of the wall (nineteenth-century boundary layer theory), showing a logarithmic velocity profile. The plot is a-historic, as Brunings only provided tables.

Scientific understanding resides in a scientist but can be propagated. Propagation of knowledge can involve propositional knowledge (here, river hydraulics), expertise or know-how (here, the measurement procedure and tabulation), material objects (here, the tachometer with its "thing knowledge") and an environment in which these are situated (here, the immediate co-workers of Brunings as well as the institutions in which he operated).[55] The essay was published in the proceedings of a learned society and has been cited in many later Rijkswaterstaat reports and national and some international papers, suggesting that the knowledge was distributed widely.[56] The embodied understanding, potentially situated in the environments of instrument design

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[55] Also see Gooding 1990 and Nersessian et al. 2003 for accounts of the practice of knowledge creation with instruments that emphasize the cognitive aspects distributed between artifacts, their engineering constraints, and the people who construct artifacts and the mental models of the phenomena.

[56] The proportional division of discharge over the Rhine branches is taught in secondary and higher education as a fact (usually without mentioning Brunings), but already in the early nineteenth century, Rijkswaterstaat will have known that the division of discharge was unlikely to remain constant, as it had changed considerably since the Pannerdensch Kanaal was dug and necessitated he modification by Brunings in 1784, but it is unclear whether the instrument ever was operated again. Nowadays, Brunings measurements are frequently repeated with modern acoustic instruments but at the same cross-sections.

and of engineering practice, is harder to trace. Brunings' instrument was used for systematic measurements of flow velocity and determination of the flow discharge division over the six Rhine branches in 1789, 1790, and 1792 by himself and, independently also by three surveyors: Johannes Sabrier, Jan Engelman, and Frederik William Conrad.[57] They undoubtedly gained embodied understanding by operating the instrument, but it is unclear whether they gained theoretical understanding of river flow. Conrad also produced a detailed drawing of the instrument and spent five pages on it in his biography of Brunings, showing that he knew the history of development of the instrument.[58] The reader may have gained some embodied understanding of river flow measurement through the description of present-day measurements that I used to assess Brunings' instrument.

4. Uncontestable Knowledge?

Why did Brunings deem necessary this level of detail of the measurements and the labor-intensive effort of many years of development and measurement? Was this a case of quantification mania after all? In his position in Rijnland, Brunings certainly knew that the changeable division of discharge over the Rhine branches and its consequences was a political issue with high local and national stakes. None of the, often politically independent, cities along the Rhine River wanted inundations, and they all had a commercial interest in navigability of different branches. This is similar to the situation around the Po delta, where one branch had silted up to render the discharge division highly asymmetrical as well. The debate which river branch to open up was seemingly held in two arenas: that of the involved states and cities, in particular Bologna, Ferrara, Venice, and the Pope in Rome, and that of the scientists, who, perhaps unwittingly, took sides by advocating one or the other solution.[59] In the Dutch Republic, cities and provinces also took different views on how to deal with the discharge division because of their interests. They shared a common national military interest, but the costs of measures taken in the river, and the selective emphasis on certain causes and effects underlying the problems, were a matter

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[57] Brunings 1789a, on 219; Christiaan Brunings, Jan Engelman, and Frederik Willem Conrad, "Verbaal van de proeven omtrend de snelheden der Boven-Rivieren," 1790, The Hague, NL, General State Archive, Archive of Directorates for Public Works and Water Management, Inventory Number 54; Christiaan Brunings, Jan Engelman, and Frederik Willem Conrad, "Proeven wegens de snelheden der Boven Rivieren," 1792, ibid.

[58] Conrad 1827, on 48–52. As Nersessian et al. 2003, on 861–862 argues, knowing the history of development of an instrument is also an important part of the knowledge propagation and creation.

[59] Maffioli 1989, on 245. The financial dependence of the scientists played a role, also in the professional growth of the field, as universities in several cities instated chairs in hydraulics as the conflict in the Po delta evolved. For instance, Guglielmini, of the university of Bologna, strongly argued for the Bolognese view. Lugaresi 2021, on 141 quotes other hydraulic papers written with political interests.

of negotiation.[60] The question is whether the practitioners in the Netherlands, particularly Brunings, took a side and voiced their interested opinions so clearly as the professors did in Italy.

His 1789 essay for the Hollandsche Maatschappij der Wetenschappen speaks volumes of what Brunings does not write about but certainly knew of. In fact, Brunings neither mentions the preferred division of discharge nor the conventions where this was decided, and as such entirely leaves out the explanation why the measured division is the final statement in his 1789 essay. Neither does he mention the 1784 change in configuration of the mouth of the Pannerdensch Kanaal that he supervised, even though the measured discharge division was proof of the effectiveness of his own design. He does not even use the metaphoric body language of "sick rivers" found in earlier and later works on the Rhine branches where authors avoid political statements with such metaphores.[61] However, the whole essay is evidence for a tremendous time investment in a critique of the theory and practice of river hydraulics, the development of the instrument, and the collection of a remarkably extensive, detailed, and accurate dataset. Furthermore, the essay is published in the proceedings of a prestigious knowledge society, and it is unlikely to have escaped Brunings' attention that such a publication channel helped to legitimize the knowledge much more than a report within the Rijnland water authority would have accomplished. Moreover, he remains entirely a-political in the essay, phrasing his motivation entirely in technical terms: to avoid an uneven distribution of disasters along the Rhine branches, which he argues is avoided when the flow discharge is divided such as to match the capacity of each and every channel. In the 1777 convention Brunings experienced how hard it was to reach such consensus with such different political interests. Inaccurate measurements with simple floatation devices would not have convinced any party and Brunings was clearly at pains to make his quantification of the discharge division as direct and uncontestable as possible to help avoid renewed political conflicts between cities with interests in a different distribution.

At first sight, Brunings refrained from interpretation. He tabulated the data in a similar systematic manner as in his daily meteorological observations and he calculated an average flow discharge per river cross-section. All the procedures and protocol-like descriptions turned the numbers into a stable generalization of the division of discharge over the branches of the Rhine River. The instrument was designed by its dimensions and weight on the balance to minimize the effects of turbulent flow fluctuation for the particular conditions of the Rhine River and actively selected the readings on the instrument to ignore the remaining fluctuations. This partly fits Daston and Galison's eighteenth-century tendency of truth-to-nature, wherein the observer depicts

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[60] See Van de Ven 1976, on 64–65 for detailed accounts of such interest-driven negotiations in knowledge construction

[61] Brunings mentions "shortcoming" (*gebrek*) only once for an aspect of the rivers on 5 and more often for the reviewed instruments.

nature without accidental traits and irrelevant details.[62] Brunings sees the "oscillations" as a peculiar property of the flow and projects this as a flaw in all hydrometric instruments that cannot be avoided but needs to be minimized in the design of an instrument, and indeed the oscillations played a major role in the design of his instrument.[63] This suggests that Brunings had some idealization of river flow in mind despite the lack of an adequate theory. However, he included the spatial variation in the cross-section that he ascribed to accidental irregularities in the riverbed, and designed his instrument to map this, because he understood how the spatial variations affected the discharge.

5. Conclusion: A Measure of River Science in the Late Eighteenth Century

In this paper I argue that Brunings' text and instrument show how he used his combined theoretical and embodied understanding to gain integrated understanding of an open and relevant problem in river hydraulics. He carefully applied and tested available theories, showing his scientific understanding of the theories, demonstrated their inadequacy for the determination of the division of discharge between river branches with existing knowledge and data, and provided pertinent arguments why a better theory can in fact not possibly be constructed. Furthermore, he extensively described, tested, and criticized all available instruments for flow velocity and innovated the measurement of flow in ways that show entanglement with theory as well as embodied understanding of river flow, and show that he did not merely cite others. His aim with the data was not to refute theories of river hydraulics that he had already shown inadequate and neither was this a case of eighteenth-century quantification mania. This case offer a nuanced view on the entanglement of theoretical and empirical aspects in knowledge creation in the eighteenth century when viewed through the lens of scientific understanding in the historic actor and in the historian.[64]

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[62] Daston and Galison 2007, on 59.

[63] Brunings 1789a, on 120–121.

[64] A rich case study with similarities in optimization of an instrument, its relations to theory and the entanglement of technology and science is found in the works of John Smeaton (1724–1792) as described by Morris 2021.

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