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RESEARCH ARTICLE

'The very term mensuration sounds engineer-like': measurement and engineering authority in nineteenth-century river management

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Abstract

Measurement was vital to nineteenth-century engineering. Focusing on the work of the Stevenson engineering firm in Scotland, this paper explores the processes by which engineers made their measurements credible and explains how measurement, as both a product and a practice, informed engineering decisions and supported claims to engineering authority. By examining attempts made to quantify, measure and map dynamic river spaces, the paper analyses the relationship between engineering experience and judgement and the generation of data that engineers considered to be 'tolerably correct'. While measurement created an abstract and simplified version of the river that accommodated prediction, this abstraction had to be connected to and made meaningful in real river space despite acknowledged limitations to measuring practice. In response, engineers drew on experience gained through the measuring process to support claims to authoritative knowledge. This combination of quantification and experience was then used to support interventions in debates over the proper use and management of rivers. This paper argues that measurement in nineteenth-century engineering served a dual function, producing both data and expertise, which were both significant in underpinning engineering authority and facilitating engineers' intervention in decision making for river management.

Measurement was vital to nineteenth-century engineering. This paper examines the practices and politics of measuring through the everyday work of the Stevenson engineering firm in Scotland. Measurement enabled engineers to construct rivers in specific ways, claim a particular kind of authority over river space and intervene in debates relating to the proper use and management of rivers. It was simultaneously a means of generating data and a foundation for claims to expertise based on experience, and was mobilized in both senses in debates over river management.

Drawing on Daston and Galison's work identifying the ideal of 'mechanical objectivity', historians have highlighted measurement, quantification and instruments as key features of nineteenth-century scientific practice.[1] The ways in which scientific instruments have been used to generate credible knowledge have been analysed in a range of geographical and disciplinary contexts.[2] Some instruments facilitated the investigation of things that could not

[1] Lorraine Daston and Peter Galison, *Objectivity*, London: Zone Books, 2007.

[2] See, for example, Bruce J. Hunt, 'Scientists, engineers and Wildman Whitehouse: measurement and credibility in early cable telegraphy', *BJHS* (1996) 29, pp. 155–69; Marie-Noëlle Bourguet, Christian Licoppe and H. Otto

be directly observed, for example in particle physics, microbiology, astrophysics or oceanography.[3] In other cases, instruments were chosen instead of human observation because the data they produced were considered to be more precise, comparable and reliable.

Credible scientific measurements required audiences to be convinced that the particular instrument or machine used could generate results – that it was effective, properly calibrated and functional – and that the observer had operated the instrument and recorded the data effectively.[4] Measurement was therefore a precarious practice requiring the credibility of things and of the people who operated them to be clearly and carefully established. To establish an instrument as credible, it had to be shown to be able to 'move nature to the page'.[5] This was done through practices of instrument making, advertising, selection, calibration and maintenance.[6] Once a type of instrument had been shown to reliably capture data, further work was required to ensure that the particular instrument used for a measurement had been functional at the time. As has been shown by Schaffer, scientists had to navigate the material instability of instruments that could break, be incorrectly calibrated, or run slow.[7]

In addition to establishing the credibility of the instrument used, authoritative measurement also required scientists to demonstrate that it had been operated effectively. Measuring practices, therefore, were key to the validity of the data generated. Researchers and institutions attempted to use methods including self-discipline, training and issuing instructions to standardize and regulate measuring practices and ensure uniformity.[8] Driver, for example, has examined the use of instructions to field explorers by the Royal Geographical Society to regulate measuring practice.[9] Space was significant here. Engineering, in common with disciplines such as meteorology, geography and oceanography, required the combination of measurements taken in diverse and difficult-to-control field locations, sometimes by different observers.[10] In these

Sibum (eds.), *Instruments, Travel and Science: Itineraries of Precision from the Seventeenth to the Twentieth Century*, London: Routledge, 2002; Graeme Gooday, *The Morals of Measurement: Accuracy, Irony and Trust in Late Victorian Electrical Practice*, Cambridge: Cambridge University Press, 2004; Fraser MacDonald and Charles W.J. Withers (eds.), *Geography, Technology and Instruments of Exploration*, London: Routledge, 2015.

3 Sabine Höhler, 'Depth records and ocean volumes: ocean profiling by sounding technology', *History and Technology* (2002) 18(2), pp. 119–54; Helen M. Rozwadowski, *Fathoming the Ocean: The Discovery and Exploration of the Deep Sea*, Cambridge, MA: Harvard University Press, 2005; Kelley E. Wilder, 'Photography and the art of science', *Visual Studies* (2009) 24(2), pp. 163–8; Simon Schaffer, 'Transport phenomena: space and visibility in Victorian physics', *Early Popular Visual Culture* (2012) 10(1), pp. 71–91.

4 David Gooding, Trevor Pinch and Simon Schaffer, 'Introduction: some uses of experiment', in Gooding, Pinch and Schaffer (eds.), *The Uses of Experiment: Studies in the Natural Sciences*, Cambridge: Cambridge University Press, 1989, pp. 1–29.

5 Daston and Galison, op. cit. (1), p. 121.

6 Gooding, Pinch and Schaffer, op. cit. (4); Deborah Warner, 'What is a scientific instrument, when did it become one, and why?', *BJHS* (1990) 23(1), pp. 83–93; Charles W.J. Withers, 'Science, scientific instruments and questions of method in nineteenth-century British geography', *Transactions of the Institute of British Geographers* (2013) 38(1), pp. 167–79.

7 Simon Schaffer, 'Easily cracked: scientific instruments in states of disrepair', *Isis* (2011) 102, pp. 706–17.

8 Michael Reidy, *Tides of History: Ocean Science and Her Majesty's Navy*, Chicago: The University of Chicago Press, 2008; James Poskett, 'Sounding in silence: men, machines and the changing environment of naval discipline, 1796–1815', *BJHS* (2015) 42(2), pp. 213–32; Lachlan Fleetwood, 'Cultures of regulation and calibration', in Mona Domosh, Michael Heffernan and Charles W.J. Withers (eds.), *The SAGE Handbook of Historical Geography*, London: SAGE, 2020, pp. 897–915; Scott Alan Johnston, 'Managing the observatory: discipline, order and disorder at Greenwich, 1835–1933', *BJHS* (2021) 54, pp. 155–75.

9 Felix Driver, 'Scientific exploration and the construction of geographical knowledge: *Hints to Travellers*', *Finisterra* (1996) 65, pp. 21–30.

10 Driver, op. cit. (9); Simon Naylor, 'Weather instruments all at sea: meteorology and the Royal Navy in the nineteenth century', in MacDonald and Withers, op. cit. (2), pp. 77–96; Naylor, 'Thermometer screens and the

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disciplines, measuring in practice required adaptation of standard protocols in the face of circumstances encountered in the field, which could lead to difficulties in combining and validating data once they had been collected.[11]

This paper explores the processes by which engineers made their measurements credible and explains how measurement, as both a product and a practice, informed engineering decisions and supported claims to engineering authority. Measurement has been referred to as 'scientific engineering's defining feature'.[12] In fact, in 1896, author and ex-trainee engineer Robert Louis Stevenson claimed that measurement was so synonymous with an engineer's work that 'the very term mensuration sounds engineer-like'.[13] Porter suggests, however, that the role played by quantification in engineering was context-dependent: trust in numbers was used to support engineering authority only in certain professional contexts, while, in others, personal expertise remained key.[14] For Porter, these contexts were social, cultural and professional, but were understood to differ on a national scale – in his case study, between France and the United States.[15] This paper similarly understands quantification as context-specific, focusing on the ways in which measurement, experience and expert judgement overlapped and mutually reinforced one another in the practice of a particular engineering firm.

Other recent work has further reconsidered the role of quantitative precision in engineering, exploring case studies where engineers confronted uncertainty and employed estimation or approximation.[16] In the early twentieth century, for example, engineers in the United States and Canada responded to the uncertainty generated by the unique conditions of the St Lawrence river and Niagara Falls by developing cross-border approaches to 'estimation as practice'.[17] By foregrounding the estimated nature of their solutions, they were able to carry out ambitious collaborative engineering works using trial and adaptation methods.[18] Estimation was similarly used in the identification of mean sea level as a vertical datum after numerous unsuccessful attempts at measuring.[19] Such examples demonstrate that engineers in practice acknowledged the limitations of quantitative methods to address complex problems relating to dynamic and unstable environments and incorporated this uncertainty into their work.

It is unsurprising that water has formed a significant context for the exploration of approximation in engineering: water bodies have historically presented particular

geographies of uniformity in nineteenth-century meteorology', *Notes and Records of the Royal Society* (2019) 73, pp. 203–21.

11 Henrika Kuklick and Robert E. Kohler, 'Introduction', *Osiris* (1996) 11, pp. 1–14; Lachlan Fleetwood, '"No former travellers having attained such a height on the Earth's surface": instruments, inscriptions, and bodies in the Himalaya, 1800–1830', *History of Science* (2018) 56(1), pp. 3–34; Charles W.J. Withers, 'Geography and "thing knowledge": instrument epistemology, failure, and narratives of 19th-century exploration', *Transactions of the Institution of British Geographers* (2019) 44, pp. 676–91.

12 David Gilmartin, 'Water and waste: nature, productivity and colonialism in the Indus basin', *Economic and Political Weekly* (2003) 38(48), pp. 5057–65, 5058.

13 Robert Louis Stevenson, *Records of a Family of Engineers*, Cambridge: Cambridge University Press, 2011, 1896, p. 82.

14 Theodore Porter, *Trust in Numbers: The Pursuit of Objectivity in Science and Public Life*, Princeton, NJ: Princeton University Press, 1995.

15 Porter, op. cit. (14).

16 Giacomo Parrinello, Etienne S. Benson and Wilko Graf von Hardenberg, 'Estimated truths: water, science and the politics of approximation', *Journal of Historical Geography* (2020) 68, pp. 3–10.

17 Daniel Macfarlane, 'As nearly as may be: estimating ice and water on the Niagara and St. Lawrence rivers', *Journal of Historical Geography* (2019) 65, pp. 73–84, 74.

18 Macfarlane, op. cit. (17).

19 Wilko Graf von Hardenberg, 'Measuring zero at sea: on the delocalization and abstraction of the geodetic framework', *Journal of Historical Geography* (2020) 68, pp. 11–20.

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difficulties in measurement, both materially and politically. Many historians have considered the practical difficulties of measuring oceanic features such as sea level, depth, ocean floor topography and wave height and motion.[20] River systems similarly challenge terrestrially conceived notions of distinctive and clearly identifiable sites that can be owned, managed and engineered in isolation. Water bodies are material and social things stretching through overlapping, interconnected and dynamic territorial spaces. River historians have identified numerous social, political and environmental issues beyond the technical requirements of engineering that have shaped river management.[21] These have included water's connections with nationhood, colonialism, race, gender, religion, perspectives of nature, notions of progress and modernity, actual and perceived risks of flooding, and the role and status afforded to science and engineering. Rivers have been used for navigation, irrigation, hydropower, industry, fishing, sanitation, drinking water, scenic contemplation, recreation and tourism. River engineering works aim to make a river more useful for a specific purpose or community of users, which might lie in opposition to the needs or preferences of other river users. In the nineteenth century, engineers often remade rivers as part of processes of extending state or colonial control, imposing particular understandings of nature, civilization and order and materially demonstrating power over a territory and its people.[22]

This paper examines the epistemological, practical and political contours of river engineering from the perspective of one engineering firm: the Stevenson engineers. By analysing the Stevensons' measuring practice, the paper highlights the complex combination of expertise, experience and quantitative data that the firm deployed to support proposed engineering interventions in river spaces. Measurement mattered as a means of generating quantitative data, but in practice there were acknowledged limitations to this process. Without perfect data, the experience of having measured a river became an important source of developing and demonstrating expertise. The practice of measurement therefore served a dual function, producing data and experience, which were both significant sources of authority in debates over river management.

This paper is in four sections. The first section contextualizes the Stevenson firm and their work on British river systems. It introduces key individuals and establishes the firm's status and professional reputation. It then explains the range of river engineering work

[20] Höhler, op. cit. (3); Rozwadowski, op. cit. (3); Stefan Helmreich, 'Waves: an anthropology of scientific things', *Hau: Journal of Ethnographic Theory* (2014) 4(3), pp. 265–84, 266; Graf von Hardenberg, op. cit. (19).

[21] See, for example, Richard White, *The Organic Machine: The Remaking of the Columbia River*, New York: Hill and Wang, 1995; Dale H. Porter, *The Thames Embankment: Environment, Technology and Society in Victorian London*, Akron: University of Akron Press, 1998; Matthew D. Evenden, *Fish versus Power: An Environmental History of the Fraser River*, Cambridge: Cambridge University Press, 2004; Maria Kaika, 'Dams as symbols of modernization: the urbanization of nature between geographical imagination and materiality', *Annals of the Association of American Geographers* (2006) 96(2), pp. 276–301; Sara B. Pritchard, *Confluence: The Nature of Technology and the Remaking of the Rhône*, Cambridge, MA: Harvard University Press, 2011; Peter Coates, *A Story of Six Rivers: History, Culture and Ecology*, Chicago: The University of Chicago Press, 2013; Mohira Suyarkulova, 'Between national idea and international conflict: the Roghun HHP as an anti-colonial endeavor, body of the nation, and national wealth', *Water History* (2014) 6, pp. 367–83; Marianna Dudley, 'Muddying the waters: recreational conflict and rights of use of British rivers', *Water History* (2017) 9, pp. 259–77; Paula Schönach, 'River histories: a thematic review', *Water History* (2017) 9, pp. 233–57; David Gilmartin, *Blood and Water: The Indus River Basin in Modern History*, Oakland: University of California Press, 2020; Debjani Bhattacharyya, 'A river is not a pendulum: sediments of science in the world of tides', *Isis* (2021) 112(1), pp. 141–49.

[22] Ben Marsden and Crosbie Smith, *Engineering Empires: A Cultural History of Technology in Nineteenth-Century Britain*, Basingstoke: Palgrave Macmillan, 2005; Michael Brian Schiffer, 'The electric lighthouse in the nineteenth century: aid to navigation and political technology', *Technology and Culture* (2005) 46(2), pp. 275–305; Chandra Mukerji, *Impossible Engineering: Technology and Territoriality on the Canal du Midi*, Princeton, NJ: Princeton University Press, 2009; Caspar Andersen, *British Engineers and Africa, 1875–1914*, London: Pickering & Chatto, 2011.

that the Stevensons carried out, highlighting the particular significance of their work on the river Tay on the east coast of Scotland. The second section considers how the Stevensons used measurement as an epistemological tool to construct knowledge about river space and predict or explain changes to rivers. This section draws primarily on the Stevensons' published books, which they intended to be instructive 'if not to the engineer in his practice, at least to the pupil in the study of his profession', alongside reviews published in the engineering press.[23] It examines the conceptual role that the Stevensons envisaged for measurement in engineering, highlighting distinctions drawn in their published work between measurement as connected with practical experience and therefore within the domain of the engineer, and the generation of scientific theories about rivers, which they considered the responsibility of the natural philosopher.

The third section examines river measurement in practice, drawing primarily from technical reports and reference plans. It analyses how skilled measurement, data correction and visualization were deployed to produce an abstract and predictable 'paper version' of the river. Measurement allowed the complex fluidity of the river to be converted into abstract pieces of information which could be plotted, calculated or mapped, and, in theory, rendered predictable and controllable. Moving between abstract and physical river space, however, was difficult and required compromise and pragmatism. The Stevensons evaluated, refined and improved methods for quantifying river features such as velocity and discharge. They also accepted the necessity of what David Stevenson called 'tolerably correct data' and deployed notions of experience and expertise to overcome the uncertainties generated by the limitations of measurement.[24]

In the final section, I explore measurement as a tool in the politics of river management using reports made by the Stevensons in legal disputes. The question whether, in what ways, by whom and to what ends rivers should be managed has caused conflict across many geographical and historical contexts. The final section of the paper situates the Stevensons within the range of actors who were interested in nineteenth-century British river spaces, identifying how they deployed instrumentally derived data and reference plans alongside personal experience and familial reputation to intervene in debates over river engineering and support their vision of the purpose and function of rivers.

Nineteenth-century river engineering and the Stevenson family firm

The Stevenson engineering firm existed from 1786 until 1952, trading under a range of names.[25] Over four generations, eight members of the Stevenson family worked as engineers for the firm: Robert Stevenson; his sons Alan, David and Thomas; grandsons David A., Charles and Louis; and great-grandson D. Alan.[26] Seven served as engineers to the Northern Lighthouse Board (NLB), the organization responsible for Scotland's lighthouses.[27] Outside the NLB, the Stevensons operated as consulting engineers, participating in significant engineering organizations of the time, including the Institution of Civil Engineers, the Royal Scottish Society of Arts and the Royal Society of Edinburgh. They advised a wide range of clients, including private individuals and trusts. Much of this work, particularly that carried out by David Stevenson, the third son of founding

[23] David Stevenson, *The Principles and Practice of Canal and River Engineering*, 2nd edn, Edinburgh: Adam and Charles Black, 1872, p. vii.

[24] David Stevenson, *Remarks on the Improvement of Tidal Rivers*, Edinburgh: Adam and Charles Black, 1845, p. 29.

[25] Craig Mair, *A Star for Seamen: The Stevenson Family of Engineers*, London: John Murray, 1978.

[26] This paper refers to members of the Stevenson family using the first names by which they were commonly known to distinguish between family members.

[27] Bella Bathurst, *The Lighthouse Stevensons*, London: Harper Perennial, 1999.

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patriarch Robert Stevenson, related to attempts to increase the navigability of British rivers.[28]

Born in 1815, David started training as an engineer in 1830. Despite the growing significance of the railway, transport by sea remained crucial to Britain's international trade and colonial ambitions. There was significant interest in increasing the speed of travel to and from the sea, as well as the maximum size of vessel accommodated in rivers. For David, British rivers were 'too unimportant and feeble' to produce sufficient velocity and depth for shipping without artificial aid.[29] Having toured the United States in 1837, he was fascinated by the Mississippi, which, he argued, showed 'by comparison the smallness of our own rivers'.[30] Engineering works were required for Britain to remain internationally competitive with a nation where the natural landscape provided water courses 'more commodious than any which works of art alone, however costly, could possibly supply'.[31] Navigation was far from the only use to which rivers were put at this time – indeed, navigation works could be controversial precisely because they hampered other uses of a river, such as fishing, irrigation, power generation or water supply. The Stevensons, and David in particular, however, considered the primary purpose of river engineering to be the improvement of navigation, dismissing these other uses as less important, particularly when they impeded navigation.[32]

The work that the Stevensons carried out to achieve the aim of increasing the speed and size of British rivers was highly varied. They surveyed and mapped river systems; measured depth, velocity and discharge; straightened courses; dredged and deepened channels; designed and evaluated bridges, jetties and training walls; and provided expert opinion in legal disputes. Based in Edinburgh, they were predominantly active in Scotland, working at times on the Forth, Ness, Dee (Aberdeeenshire), Don, Nith, Tweed, Tay and Clyde, although they also consulted at times on the Erne and Foyle in Ireland and the Dee (Cheshire), Lune, Mersey and Ribble in the north-west of England and north Wales.[33]

Within Scotland, the Tay and the Clyde were particularly significant. More than half of the 254 plans of Scottish rivers held in the Stevenson firm's archive in the National Library of Scotland relate to either the Tay (ninety-two plans) or the Clyde (seventy-nine plans). The Clyde was significant as the main route into Glasgow and housed many of the lighthouses managed by the Stevensons for the NLB. Works on the Clyde included the identification and alteration of channels and the deepening of the river by dredging. The Tay, as well as facilitating shipping to Perth and Dundee, was significant for personal reasons: David spent months of his apprenticeship in the 1830s surveying the Tay, developing a deep personal knowledge of the river as well as gathering quantitative data.[34] Works on the Tay in the 1830s aimed to transform the previously braided river between Perth and Newburgh into a single straighter, deeper and faster-flowing watercourse by redirecting its channel and removing gravel fords and fishing cairns.[35] They also designed

[28] David Stevenson, *Sketch of Civil Engineering in North America: Comprising Remarks on the Harbours, River and Lake Navigation, Lighthouses, Steam-Navigation, Water-Works, Canals, Roads, Railways, Bridges, and Other Works in That Country*, Cambridge: Cambridge University Press, 2014 (first published 1838), p. 4.

[29] D. Stevenson, op. cit. (28), p. 4.

[30] D. Stevenson, op. cit. (23), p. 135.

[31] D. Stevenson, op. cit. (23), p. 1.

[32] Allan Cunningham, 'Canal and river engineering', *Nature* (23 December 1886), 35(895), p. 169.

[33] 'David Stevenson', *Proceedings of the Royal Society of Edinburgh* (1886) 14, p. 147.

[34] David Stevenson, *Diary 1830–1836*, Stevenson Collection, National Library of Scotland, Edinburgh (subsequently NLS), Acc.10706/223.

[35] Robert Stevenson and Son, 'To the lord provost, magistrates, and town council of the city of Perth, the report of Robert Stevenson and son, civil engineers', 22 January 1834, NLS/Acc 10706/523, number 6; 'Mr David Stevenson on tidal rivers', *Chester Chronicle* (9 February 1849) 3937, p. 3.

an expansion to the harbour at Perth. This experience and the data he collected during the Tay survey in the 1830s became a key reference point for David's later engineering and his reputation as 'one of the principal authorities on all points relating to [canal and river engineering]'.[36]

'The principles are not problematical: they are demonstrated': the epistemological authority of measurement

In the nineteenth century, predicting or identifying the impact of dredging to deepen a river channel, the straightening of river courses, removal of subsidiary channels or the construction of harbours, bridges or jetties was complicated by a lack of definitive theoretical laws relating to river motion.[37] In Scotland in the first half of the century, this was exacerbated by the fact that many river courses had not yet been systematically and reliably mapped. David's solution was to rely on 'experience, there being … no universally acknowledged laws, founded on mathematical investigation, or practical experience, which we can call to our aid'.[38] David believed that developing such laws was not the proper domain of the engineer. His work had 'not for its object the advancement of any new *theory* or *principle* (a task which would, more naturally, fall within the province of the philosophical inquirer, than of the practical Engineer)'.[39] His intended result was much more specific: to improve the accuracy and ease with which engineers could predict and alter river space.

The distinction drawn between engineers and philosophers reflects the firm's understanding of the relationship between 'practical' engineering and natural-philosophical and mathematical ideas more broadly. David situated his interest in the laws regulating the motion of rivers within the context of specific benefits for engineering work, particularly desiring 'more definite and acknowledged principles for our guidance in conducting improvements on inland navigation'.[40] His aim was not to develop abstract understanding of how rivers worked, but to create specific guidelines for engineering works. David's brother Thomas was characterized similarly by his son Louis: 'It was about this nucleus of his professional labours that all my father's scientific inquiries and inventions centred; these proceeded from, and acted back upon, his daily business'.[41] Theorizing should be left to 'others who have leisure and inclination to prosecute the inquiry'.[42]

The Stevensons were aware that scientific theory could not be straightforwardly applied to the real-world problems engineers faced and had to be modified by practical engineering experience and personal expertise. Louis argued, 'Even the mechanical engineer comes at last to an end of his figures, and must stand up, a practical man, face to face with the discrepancies of nature and the hiatuses of theory', and rely instead on experience, judgement and engineering expertise to fit broader practical guidelines to specific situations.[43]

Measurement was therefore vitally important in understanding the specific situation within which general guidance might be applied. Writing for the *Encyclopaedia Britannica* in 1858, David outlined the first concern in any river engineering work: 'a

[36] 'The principles and practice of canal and river engineering by David Stevenson', *The Engineer* (26 July 1872) 34, p. 58.

[37] For the quote in the section head see 'Mr David Stevenson on tidal rivers' op. cit. (35), p. 3.

[38] D. Stevenson, op. cit. (24), p. 17.

[39] D. Stevenson, op. cit. (24), p. 5, original emphasis.

[40] D. Stevenson, op. cit. (24), pp. 5–6.

[41] Robert Louis Stevenson, *Memories and Portraits*, London: Chatto & Windus, 1887, p. 135.

[42] D. Stevenson, op. cit. (24), p. 33.

[43] R.L. Stevenson, op. cit. (13), p. 83.

correct knowledge of its physical characteristics'.[44] This was a common starting point for engineers, and the principle was echoed by Thomas in his 1868 book on harbour design.[45] Measurement was the most significant theme throughout David's instructive books written for trainee engineers, which included *A Treatise on the Application of Marine Surveying and Hydrometry to the Practice of Civil Engineering* (1842) and *The Principles and Practice of Canal and River Engineering* (1858, 1872, 1886).[46] *Principles and Practice* in particular was highly successful, going to three editions and prompting David to be invited to deliver a lecture series on the subject at Chatham School of Military Engineering in 1877.[47] It was described in the engineering press as 'an excellent account', 'the standard work on the difficult subject of which it treats', and deserving of a 'permanent place in engineering literature'.[48] In *Principles and Practice*, David argued that the first step in river engineering should be to investigate characteristics such as the depth, material and topography of the riverbed – calculated based on sounding – as well as the velocity of the water – calculated using the float method or a tachometer.[49] This information could then, in theory, be used to identify channels; to calculate the total volume, speed and discharge of water; and to identify appropriate interventions to reshape river flow.

Measurement was also used to demonstrate the success of river works, enhancing status and providing proof of competence. In areas close to existing Stevenson-designed river management schemes, quantitative measures were used to support new works. One such location was the north-west of England. By the 1840s, Robert Stevenson had published on the Dee and Mersey, David had spent significant time in Liverpool in the 1830s and the firm had worked on the Lune and Ribble in Lancashire.[50] In the 1840s, the Stevensons proposed the removal of groynes that had been placed in the river in order to deepen the channel of the river Dee between Chester and the sea to between fifteen and twenty feet and increase the speed at which the tide could move up through the river, in theory carrying larger vessels further and faster than before.[51] In 1849, the *Chester Chronicle* used works on the nearby Lune that had increased the speed of the tidal wave reaching Lancaster by a quantifiable amount – the tide began to flow twenty-five minutes earlier at spring tides and fifty minutes earlier at neap tides – to argue in support of David's plans for the Dee.[52] Understanding the impact of engineering works on rivers by direct observation could be challenging given their large scale and constant motion. Local examples expressed in terms directly relevant to shipping interests – precisely how much faster they could expect ships to travel – were key to explaining David's plans for the Dee to the local population.

The ability to quantify success was particularly important when the Stevensons challenged established systems for improving rivers, such as the use of groynes, which had been designed by established and reputable engineers. The groynes on the Dee had

[44] David Stevenson, 'Inland navigation', in *Encyclopaedia Britannica*, 8th edn, vol. 16, Edinburgh: Adam and Charles Black, 1858, p. 61.

[45] Thomas Stevenson, *The Design and Construction of Harbours: A Treatise on Maritime Engineering*, 2nd edn, Cambridge: Cambridge University Press, 2011 (first published 1874), p. 5.

[46] 'David Stevenson', op. cit. (33), p. 147.

[47] David Stevenson, 'Lectures: canal and river engineering', 1877, NLS/Acc.10706/530, number 39.

[48] Cunningham, op. cit. (32), p. 169; 'David Stevenson, 1815–1886', *Minutes of Proceedings of the Institution of Civil Engineers* (1887) 87, p. 441; 'David Stevenson', *The Engineer* (23 July 1886) 62, p. 76.

[49] D. Stevenson, op. cit. (23), p. 54.

[50] Robert Stevenson, 'Remarks upon the wasting effects of the sea on the shore of Cheshire, between the rivers Mersey and Dee', *Edinburgh New Philosophical Journal* (1828) 4, pp. 386–9; D. Stevenson, op. cit. (34); David Stevenson, 'Observations on the Liverpool and Manchester Railway', *Transactions of the Royal Scottish Society of Arts* (1841) 1, pp. 43–53.

[51] 'Improvement of the Dee', *Chester Chronicle* (28 July 1848) 3909, p. 2.

[52] 'Mr David Stevenson on tidal rivers', op. cit. (35).

been designed by Thomas Telford, the first president of the Institution of Civil Engineers and a renowned canal and road engineer.[53] In advocating for their removal, the *Chester Chronicle* argued, 'this gentleman [David] and his brother have had all the prejudices of the old school to contend against. When they have questioned the utility of groins [*sic*], the authority of Telford has been appealed to'.[54]

Telford was only one of the civil engineers who had been constructed as national heroes in the mid-century through publications such as those by biographer Samuel Smiles.[55] On the Tay, the Stevensons instead had to negotiate the legacies of two similarly influential early engineers: John Smeaton, widely considered the 'father of British engineers', and John Rennie, a Scottish canal and waterway engineer, and fellow of the Royal Society and the Royal Society of Edinburgh.[56] Like Telford, both Smeaton and Rennie were established figures with substantial reputations.[57] In their 1834 report on the Tay, Robert and Alan Stevenson called them 'SMEATON and RENNIE, the most celebrated Engineers of their time'.[58] Both had made suggestions for works on the Tay. Smeaton had proposed a line of quays near Perth and Rennie the construction of new wet docks at South Inch, Perth. The Stevensons acknowledged that these works were advisable, but suggested that it was more important to change the bed and course of the river between Perth and Newburgh, a stretch of river which had to be traversed by vessels travelling east from Perth to the North Sea and which contained many gravel fords that made passage difficult.[59] By simply arguing that works elsewhere in the river were more pressing, the Stevensons did not directly challenge Smeaton and Rennie's suggestions at Perth, and made clear the respect that they had for the older engineers while introducing their suggestions.

When directly opposing established principles and suggestions made by renowned engineers, on the other hand, the Stevensons had to persuade landowners, trustees and the public that these famous authorities were incorrect. Practical experience and measurement were often deployed as a source of authority in such cases. On the Clyde, where David suggested the removal of obstructions designed by Smeaton, he framed his criticism as informed by 'growing experience' and hoped that his comments therefore would not 'appear to be throwing any reflection on the Father of British Engineers'.[60] On the Dee, it was argued that David and Thomas's work on other rivers had 'proved that groins [*sic*] are injurious instead of beneficial'.[61] The Stevensons' successful record was cited as proving, retrospectively, that they had been right to challenge established practice, and became one source of David's growing reputation as 'one of the best authorities of the day'.[62]

The Tay, perhaps due to the extensiveness of the data available, or to the pivotal role it played in David's career as the first river he worked on, was particularly significant in constructing his, and by extension the firm's, reputation. The Stevensons' reports on the Tay consistently emphasized the extensiveness of their data. They claimed not to know of 'any

[53] 'Improvement of the Dee', op. cit. (51), p. 2.

[54] 'Mr David Stevenson on tidal rivers', op. cit. (35).

[55] Samuel Smiles, *Lives of the Engineers*, vol. 2: *Harbours – Lighthouses – Bridges, Smeaton and Rennie*, London: John Murray, 1874; R. Angus Buchanan, 'The Rolt memorial lecture 1987: the lives of the engineers', *Industrial Archaeology Review* (1987) 11(1), pp. 5–15.

[56] Smiles, op. cit. (55); D. Stevenson, op. cit. (24), p. 11.

[57] Smiles, op. cit. (55).

[58] Robert Stevenson and Son, op. cit. (35), p. 1.

[59] Robert Stevenson and Son, op. cit. (35), p. 1.

[60] D. Stevenson, op. cit. (24), p. 11.

[61] 'Mr David Stevenson on tidal rivers', op. cit. (35).

[62] 'River Dee question', *Chester Chronicle* (20 April 1849) 3947, p. 3.

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case in which the improvements effected by particular works are more fully and satisfactorily confirmed by a comparison of observations made, *previously* and *subsequently* to their execution, than in that of the Tay Navigation'.[63] In a report on the Forth, Robert supported his recommendations using 'additional confirmation from our past experience, more especially in the case of the Tay'.[64] Similarly, in defending his plans for the Dee, David discussed 'designs that have been adopted, under the direction of my brother and myself, for the improvement of four navigable rivers', using the Tay as his first and most extensive example, followed by the Ribble, Lune and Forth.[65]

These reports presented experience gained on the Tay as held collectively by the Stevenson family – based on 'our past experience' and designs completed by 'my brother and myself'. This familial authority derived from work on the Tay could even extend to Stevenson engineers who had no personal experience of that survey. In a legal case considering changes to the Tay's channels and banks in 1866, Thomas provided evidence as an expert, explaining, 'I have no personal knowledge of the survey upon which the plan was made, except that the survey took place under the superintendence and direction of my father and brother.'[66] Despite the surveying having taken place before he was an engineer, Thomas presented his familial connection to its makers as a form of personal knowledge of the survey itself, and by implication of the Tay, and used it as the basis for making claims about changes to the river over time.

Intentionally combining the work of different family members to bolster the experience upon which they could draw was characteristic of the Stevenson firm. Engineering projects and even publications started by one family member were often finished or continued by another. Reports, plans and letters were often signed D. & T. Stevenson rather than with an individual name, and many were written in the plural. By associating their experience, measurement taking and successful engineering works with a combined family identity and working to obscure the individual differences between Stevenson engineers, each individual member could draw on a wider range of experience to support claims to expertise – David could cite successful works carried out by himself and his brother as proof of his expertise; Robert and Thomas could deploy measurements taken by David and Alan on the Tay. This use of family identity complicated questions around individual competence, experience and expertise, particularly in combination with measurement which was itself dependent for its credibility on establishing the competence of the measurer and the appropriateness of the methods and instruments used.

'Tolerably correct data': methods, instruments and the problem of time

Despite relying on measurement to demonstrate credibility and quantify their past practical success, the Stevensons were aware that it had limitations. Much of their guidance explained how deficiencies in measuring characteristics such as depth and velocity occurred and how these could be minimized by controlling the methods and people involved.

David described his ideal method of measuring the overall mean discharge of a river – the average amount of water that flowed through a river in a given time – as dividing the entire course into small sections, calculating the area of each section and measuring the

[63] Robert Stevenson and Sons, 'To the Lord Provost, Magistrates and Town Council of the City of Perth, Conservators of the Tay Navigation, the Report of Robert Stevenson and Sons', 7 January 1845, NLS/Acc.10706/528, number 1, p. 9, original emphasis.

[64] Robert Stevenson and Sons, 'To the hon. The provost, magistrates, and council of the Royal Burgh of Stirling, the report of Robert Stevenson, Civil Engineer', 10 December 1838, NLS/Acc.10706/523, number 37, p. 1.

[65] 'Mr David Stevenson on tidal rivers' op. cit. (35).

[66] Thomas Stevenson, 'Defenders Proof', 26 February 1866, NLS/Acc.10706/528, number 39, p. 5.

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velocity of each section individually. Such in-depth work throughout a river, however, was rarely practical. Cost was often prohibitive and necessitated the simplification of data collection. Increased accuracy had to be weighed against the expense and difficulty of increased observations. More observations required more time, labour and equipment, and river surveying was very labour-intensive – on the Tay, it involved Robert, David and Alan Stevenson, a surveyor and at least two assistants.[67] As David reflected, 'every additional station involves additional trouble and expense, and as great difficulty is often experienced in finding persons properly qualified to make the observations'.[68]

Moreover, riverbeds did not have a standard depth, river channels were not static and clearly bounded, and river velocity and depth changed with time and the tide, so measurements could only ever be approximate. The observer when measuring could not know the exact moment of high or low tide, and therefore the data always had to be corrected.[69] More results enabled a closer approximation, but the dynamic physical characteristics of rivers presented a challenge to measurement techniques that could not be solved through additional resources alone. To account for the dynamism of rivers, methodological innovation was required.[70]

Awareness of the limitations of common measuring practices led David to advocate for alternative methods. He suggested, for example, that engineers should replace the common 'float' method of calculating river velocity with a tachometer. The float method involved dropping a float into a river and noting how long it took to travel a marked distance, using this to calculate the water velocity. David described this as the 'most common, but by no means the most satisfactory, mode of proceeding'.[71] He identified many problems with float measuring: it could not be used on wide rivers due to the difficulty in observing a float from the banks; eddies or currents could interfere with the progression of the float; irregularities of the bottom of the river could cause isolated alterations to velocity; obtaining a sufficient number of independent observations was impossible; and, due to the irregularities of width, depth and velocity on most rivers, measuring distances rarely extended beyond a hundred feet.[72]

David's solution was the tachometer – an instrument used to measure the velocity of running water (Figure 1). When a tachometer was submerged, the water flowing past pushed on a revolving gauge. An observer positioned the tachometer in the water, put the registering wheel in gear and waited for one minute before reading off the number of revolutions completed. Knowing the value of one revolution, the observer could calculate the velocity of the water at that point. This was repeated at intervals along the river and the results were combined to generate an approximate mean velocity. The velocity could then be used to calculate the overall the mean discharge.

As an example of this method in practice, David pointed to the work of Adam Anderson, civil engineer and professor of natural philosophy at the university of St Andrews, who had calculated the discharge of the Tay in 1831 using a tachometer.[73] In addition to presenting Anderson's work as more reliable than the float method, David also used it to criticize attempts to replace measuring with the use of formulae to calculate mean discharge. As Gooday argues, the introduction of 'Cambridge' mathematics

[67] D. Stevenson, op. cit. (34), p. 169.
[68] David Stevenson, *A Treatise on the Application of Marine Surveying and Hydrometry to the Practice of Civil Engineering*, Edinburgh: Adam and Charles Black, 1842, p. 38.
[69] D. Stevenson, op. cit. (34), p. 169.
[70] D. Stevenson, op. cit. (68), p. 57.
[71] D. Stevenson, op. cit. (23), p. 99.
[72] D. Stevenson, op. cit. (23), p. 100.
[73] Adam Anderson, 'Tay, River – Sections to determine the quantity of water discharged', 1831, NLS/MS.5863, 21.

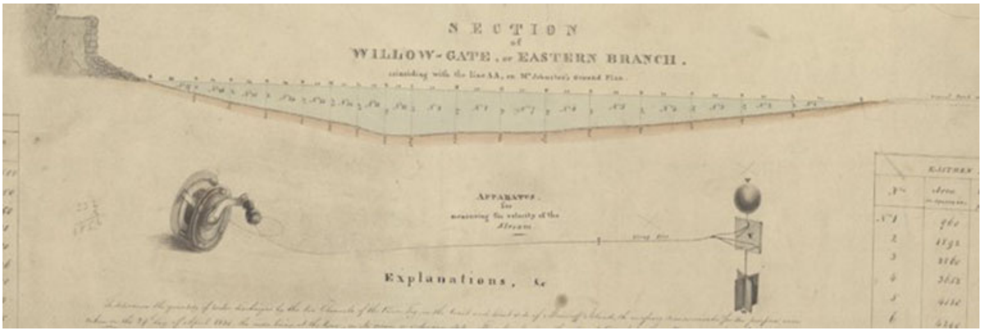

Figure 1. Tachometer diagram, as shown in Adam Anderson (1831), 'Tay, River – Sections to determine the quantity of water discharged', NLS/MS 5863/22. Image courtesy of the National Library of Scotland.

which relied on abstract calculation could be controversial among engineers.[74] In the 1870s, engineers used a range of formulae for calculating the mean discharge of a river, but there was a lack of consensus on which provided the best results.[75] Many believed that, due to the diversity of physical characteristics of rivers, no single formula could account for the behaviour of all river types and sizes.

In *Principles and Practice*, David tested the range of common formulae against one another, initially in 1858 using a mill lead at Canonmills in Edinburgh (Figure 2) and then in 1872 using data for the river Tay (Figure 3). Mill leads were considered a good site for the study of hydraulics because the channel was artificially regular, and the Tay was a clear choice for testing formulae on a real river given the extensive data and experience the Stevensons had there.[76] David's comparisons in *Principles and Practice* showed that 'no formula is correctly applicable to rivers of different sizes, nor holds its own equally as regards correctness throughout'.[77] A reviewer for *Engineering* suggested that David's findings meant that engineers should use the formula that had achieved the closest results and which could be easily applied to most cases. This was Downing's formula, $V = 100(RS)^{\frac{1}{2}}$, where mean velocity was calculated using the hydraulic radius (R) and hydraulic slope (S) of the river as a whole.[78] David, however, refused to suggest any formula, arguing that until a result 'has been compared with the discharge obtained by actual measurement of the velocities at different parts of the cross section, we do not think that the discharge … can be relied on as accurate'.[79]

Because of this prioritization of measurement over calculation, measuring practice remained vital. As has been shown in other fields, the instructions in David's books on engineering measurement advised carefully controlling the practices and people involved.[80] In *Treatise on the Application of Marine Surveying*, he noted that 'it is almost unnecessary to remark, that the observations ought to be carefully and systematically registered'.[81] Systematic approaches, he argued, were vital to facilitate the later combination of individual data points into a composite understanding of the river.

[74] Graeme Gooday, 'Fear, shunning and valuelessness: controversy over the use of "Cambridge" mathematics in late Victorian electro-technology', in David Kaiser (ed.), *Pedagogy and the Practice of Science*, Cambridge, MA: MIT Press, 2005, pp. 111–50.
[75] 'Hydrodynamic formulae', *Engineering* (4 July 1873) 16, pp. 13–14.
[76] D. Stevenson, op. cit. (23).
[77] 'Hydrodynamic formulae', op. cit. (75), p. 13.
[78] 'Hydrodynamic formulae', op. cit. (75), p. 13.
[79] D. Stevenson, op. cit. (23), p. 138.
[80] See Driver, op. cit. (9); Withers, op. cit. (6); Fleetwood, op. cit. (8).
[81] D. Stevenson, op. cit. (68), p. 66.

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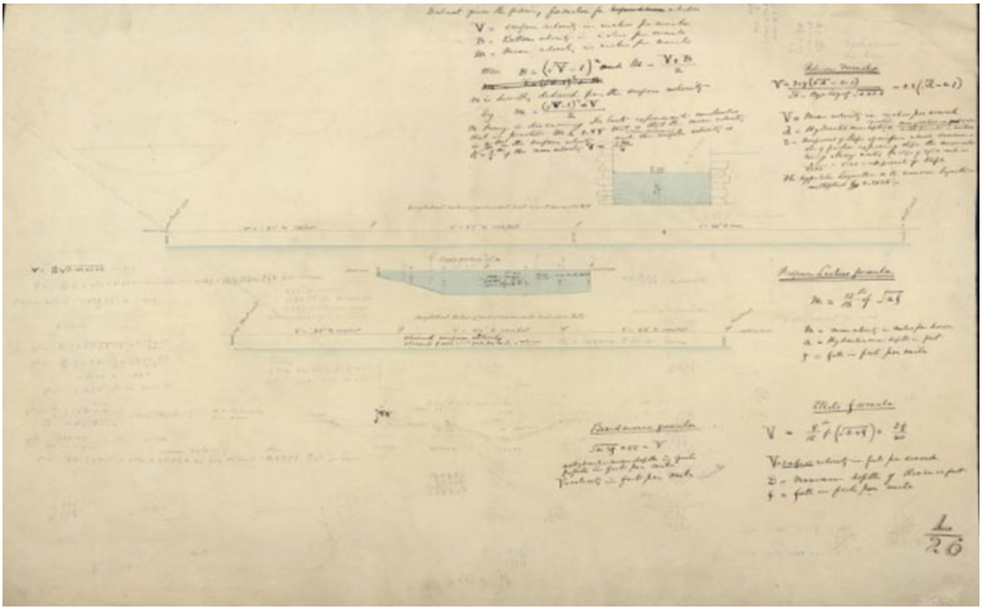

Figure 2. St Bernard's Well – section of mill leads at St Bernard's Well and Canonmills and formulae for the calculation of water velocity in ink and pencil on paper, watermarked 1852. NLS/Acc.10706/286, 547 × 757 mm. Image courtesy of the National Library of Scotland.

	Cubic feet.	
Discharge from measurement as above,	1653	per minute.
1*st*. By Robison's formula.................	2214	do.
2*d*. By Leslie's do.	2474	do.
3*d*. By Ellet's do.	2784	do.
4*th*. By Beardmore's do.	2335	do.
5*th*. By formula assuming the mean deduced from the centre surface velocity as the mean for the whole section ...	1950	do.

Figure 3. Table of water discharge calculation results included in David Stevenson, 'Inland navigation', in *Encyclopaedia Britannica*, 8th edn, Edinburgh: Adam and Charles Black, vol. 16, 1858, p. 60. Image courtesy of the National Library of Scotland.

David advocated that a river should be measured in small sections which could then be reassembled into an overall system representation. Organized and disciplined activity was essential to ensure that measurements made of sections of river could be effectively combined. David made the consequences of a non-systematic approach to surveying depth clear, arguing that if soundings

> are taken at random, without reference to any particular marks or lines of direction, it will, in all probability, be found, on protracting them, that large areas occur without a single sounding to indicate the depth of water, while in other places, in consequence of several lines of soundings crossing each other, owing to the want of proper arrangement, the observations are so numerous that it is impossible to protract the whole of them on the plan.[82]

[82] D. Stevenson, op. cit. (68), p. 63.

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Systematic and controlled practice was important in river work because, like other large-scale geographical features or systems measured by survey sciences, rivers could not practically be apprehended in their entirety. In engineering, the creation of a plan or chart was not only a representation of the process of measuring a river, but was also a means by which an abstract, quantifiable and theoretically predictable river could be brought into being.

Through this process of subdivision and reassembly, the engineer had to work to maintain the authority of the measurements that connected the abstract visualization of a river with the real thing and therefore enabled the plan to be used in design. As Helmreich argues of oceanic waves, although they 'have a manifest materiality to them, they are also only apprehensible through abstractions'.[83] The tension between the material, the abstract and the means employed to move between them has been explored in work on the history of oceanography and underground spaces, but is equally important in river engineering.[84] River engineering works were designed and explained using the abstract, paper version of the river but carried out on the tangible, material thing.

Despite attempts to create a stable and uniform version of the river, the dynamism and fluidity of rivers, coupled with an acceptance of the impossibility of perfectly accurate measurement, required an additional quality that Louis called 'the trained eye and the *feelings* of the engineer'.[85] This 'trained eye', like the forms of tacit and embodied knowledge that have been identified as significant for engineering in other contexts, was trained by experience over a long period of time, either personally or, in the case of the Stevensons, collectively.[86] Rivers existed in constant motion. Tides, weather and seasons altered flows, while erosion, silting and human intervention created change over longer time spans. Engineers studying rivers had to account for constant change. As Louis wrote of his father, 'he visits a river, its summer water babbling on shallows; and he must not only read, in a thousand indications, the measure of winter freshets, but be able to predict the violence of occasional great floods'.[87]

On the Clyde, the idea that rivers changed naturally over time complicated attempts to pinpoint the impact of specific engineering decisions. As engineers to the Clyde Lighthouse Trust, the Stevensons were responsible for dredging at Garvel Point and around the harbour at Greenock in 1873.[88] When it was alleged three years later by the Greenock Harbour Trust that this dredging had caused localized shallowing or shoaling on the opposite bank, the Stevensons argued that 'periodic change is a well-known feature of most navigable rivers, and the origins of such changes is [*sic*], in most cases, not easily traceable to any one special cause'.[89] Possible causes of shoaling, they suggested, included natural phenomena such as tides and wind or rainfall patterns as well as engineering interventions and human use. Using the Dee as an example, the Stevensons argued that change was common in river landscapes, and that 'natural causes, unaided by

83 Helmreich, op. cit. (20), p. 266.

84 Höhler, op. cit. (3); Rozwadowski, op. cit. (3); Eric C. Nystrom, *Seeing Underground: Maps, Models and Mining Engineering in America*, Reno: University of Nevada Press, 2014.

85 R.L. Stevenson, op. cit. (13), p. 85, original emphasis.

86 Mukerji, op. cit. (22); Paul Nightingale, 'Tacit knowledge and engineering design', in Anthonie Meijers (ed.), *Handbook of the Philosophy of Science*, vol. 9: *Philosophy of Technology and Engineering Sciences*, Burlington, Oxford and Amsterdam: Elsevier, 2009, pp. 351–74; Macfarlane, op. cit. (17).

87 R.L. Stevenson, op. cit. (13), p. 84.

88 'Proposed improvement of the Clyde Navigation', *Engineering* (1 August 1873) 16, p. 79.

89 D. & T. Stevenson, 'Report to the Clyde Lighthouse Trustees relative to the dredging at Garvel Point, by D. & T. Stevenson, civil engineers, Edinburgh', 29 September 1876, NLS/Acc.10706/530, number 34, p. 2.

artificial works, have been found, by prolonged and careful observation, materially to affect the soft beds of rivers such as the Clyde'.[90]

To understand and explain such change, the Stevensons developed creative visualization procedures. One method was the superimposing of channels identified in surveys of different dates onto a single plan using colour or line style. David used this method in the *Encyclopaedia Britannica* to illustrate his argument that the course of the river Lune was inherently unstable (Figure 4). Such images do not attempt to reflect any 'real' river but rather represent a visual narrative of change over time.

Other mapping methods combined different ways of depicting rivers to account for time. In an 1848 plan of the Tay (Figure 5), the Stevensons combined cross sections of the riverbed made in 1833 and 1848 with a top-down view of the river. The plan was multidimensional, simultaneously using vertical and horizontal perspectives. This was an unusual way of mapping a river which combined perspectives to present dynamic change through a static image.[91]

Even when executed perfectly, then, a precise measurement could only reflect a river's state at one moment in time, while engineers had to consider the river across all seasons and weather events. As David explained, 'the level of the sea is more or less affected by every breeze of wind, which necessarily must pen up [*sic*] and elevate some portions of its surface, and cause corresponding depression at other places, so that an unvarying low-water level will not be found to exist'.[92] This dynamism and fluidity presented complex problems for engineering practice and were often in conflict with legal systems that imagined physical space as clearly delineated and largely unchanging, as well as scientific discourses that prized precision. As Bhattacharyya has shown in Bengal, engineers had to navigate this tension between dynamic rivers and contemporary understandings of static territorial space which, in the Stevensons' case, caused them to innovate, expanding practices of measurement and visualization to accommodate temporal change.[93]

Due to the ongoing problem of change, observations completed over a long period, or archived from earlier periods, held substantial value for tracking the impacts of works such as bridge or pier construction. For the Stevensons, this often meant drawing on observations collected by earlier members of the family and stored in the form of reference plans and indexed report books in the family's business archive. In 1845, the Stevensons supported their evaluation of a proposed railway bridge to be built over the river Tay at Mugdrum island near Perth by referencing data collected over the previous ten years.[94] In 1876, they drew on 'a comparison of observations extended over eight years' on the Dee between Chester and Connah's Quay to argue that the river was deepest in February and shallowest in September and October.[95] In a case brought in 1866 by Thomas Dundas, Earl of Zetland, against the Glover Incorporation of Perth which hinged on whether jetties Dundas had constructed on the Tay in the 1840s had caused the movement of the river channel to the north and the shrinking of a bank known as Eppie's Taes, Thomas Stevenson exhibited a plan made in 1834 by Robert, Alan and David. The version he presented was the 'office copy'. Kept in the engineers' offices, an 'office copy' of a plan was considered the most authoritative version and was the most closely aligned with field measurement. Thomas stated that 'the office copy was made out from field books' and that 'the principal plan is a copy from the office copy'.[96] Such reference plans were

[90] D. & T. Stevenson, op. cit. (89), p. 2.
[91] David Stevenson, 'Tay, River – Section with Sand Island', 28 November 1848, NLS/MS.5863, 55.
[92] D. Stevenson, op. cit. (23), p. 58.
[93] Bhattacharyya, op. cit. (21), p. 142.
[94] Robert Stevenson and Sons, op. cit. (63), p. 9.
[95] D. and T. Stevenson, op. cit. (89), p. 2.
[96] T. Stevenson, op. cit. (66), p. 4.

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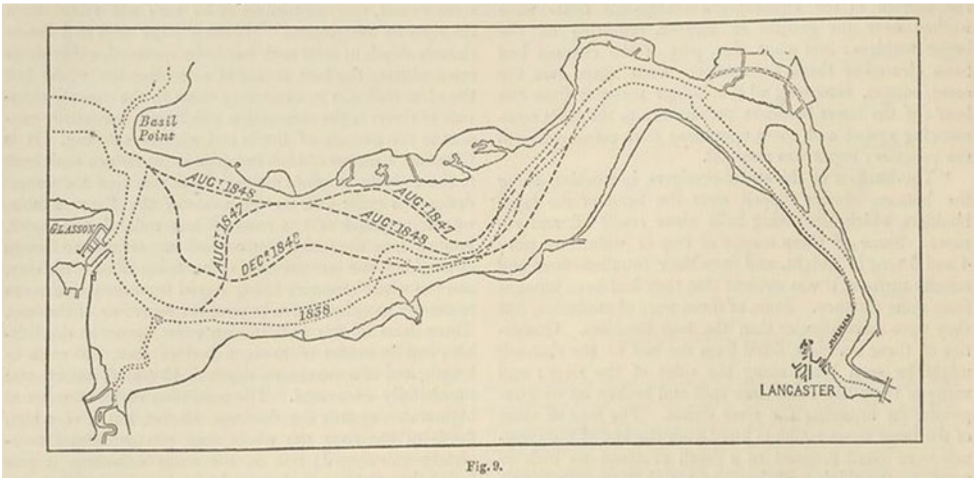

Figure 4. The river Lune from Lancaster to Glasson showing the changing course of the channel over time, included in Stevenson, 'Inland navigation', op. cit., p. 72. Image courtesy of the National Library of Scotland.

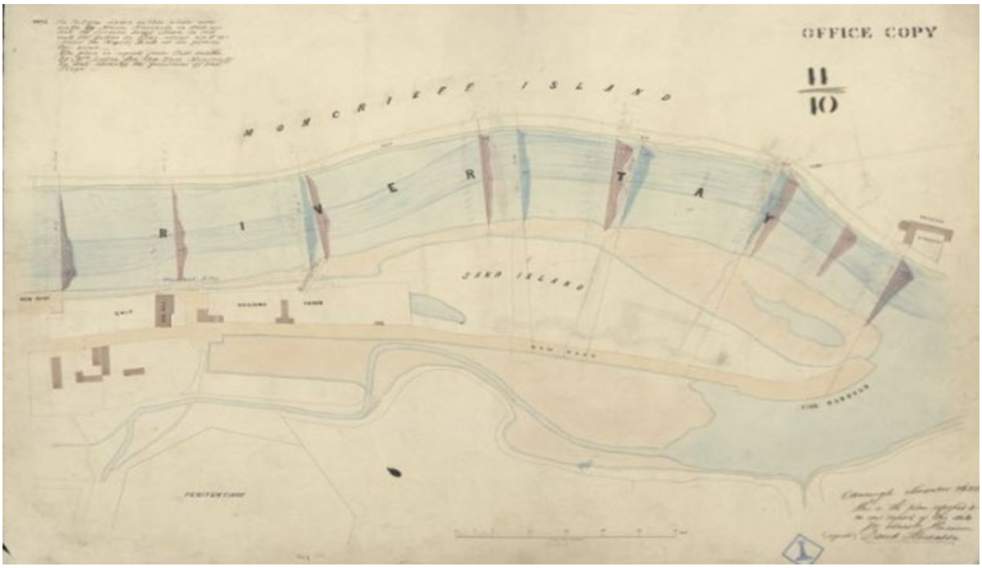

Figure 5. David Stevenson, 'Tay River – Section with Sand Island' (28 November 1848), NLS/MS 5863/55, 465 × 670 mm. Image courtesy of the National Library of Scotland.

very valuable to the Stevensons as a source of authoritative data that could be clearly linked with specific field measurement practices carried out by previous family members who were recognized authorities in river measurement. Thomas explained, 'I would not part with any office copy of a plan', and provided a tracing to the inquiry.[97]

These visual tools and the historical measurements they contained could foreground the fluidity of river systems and emphasize the necessity of engineering expertise. Due

[97] T. Stevenson, op. cit. (66), p. 4.

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to conditions including storms, tides, floods or ice, changes to river channels were 'impossible for any Engineer to predict' with certainty.[98] Instead, David acknowledged the difficulties, again emphasizing the role of engineering experience and judgement by making provisional claims based on 'what I consider to be tolerably correct data'.[99] David gave no criteria for how he judged whether data were 'tolerably correct', simply expecting readers to trust his expert judgement that the data discussed were good enough to support prediction without explaining it in greater detail.

'Beyond the *legal boundaries*': jurisdiction, expertise and power

Although rivers were divided between proprietors who could lease land, water and fishing rights and alter river banks, the Stevensons often worked on behalf of trusts formed to manage river navigation. As such, they were often in disagreement with others interested in the management and use of rivers and access to them.[100] The interconnectedness of river systems challenges terrestrial notions of legal jurisdiction and authority. Where legal understandings rely on drawing static, single lines on a map, the physical reality of flows, changes and fluidity in rivers resists such definition. This challenge presented by the materiality of rivers has been used productively to reconfigure the scale of historical inquiry to the transnational and international.[101] Rivers are never simply local; works in one place affect the whole system. River engineering works carried out on behalf of one group, and the measurements upon which they were based, therefore, were often disputed by others with interests in the river. Questions of measurement and method were embedded within the politics of river management, which were themselves deeply implicated in, and key to replicating, the hierarchies and power structures that shaped society.[102]

River engineering was famously controversial in Britain. By the 1870s it was 'notorious that in many cases attempts to reclaim or protect property have led to serious and costly legal proceedings between landowners and the local conservators of navigation'.[103] David's proposed solution was new boundaries. He suggested that a universal line be drawn by the government, based on similar divisions between sea and river fishing, to define where landowners could and could not act. This solution, David argued, would remove 'a source of much difference of opinion and expensive litigation' as the unintended consequences of land reclamation for navigation, and vice versa, were debated in court.[104]

In the absence of such a centralized solution, however, the Stevensons were often called upon to evaluate the impact of works in legal proceedings. In 1870, for example, Thomas was asked to judge the impact on navigation, net fishing, angling and landing passengers of a wall constructed along the bank of the Tay by the Hon. John Rollo.[105] He found that, although the navigation was unimpeded, the new wall had caused significant inconvenience for fishing, angling and the landing of passengers, particularly women. In

[98] Robert Stevenson and Sons, op. cit. (63), p. 7.
[99] D. Stevenson, op. cit. (24), p. 29.
[100] Dudley, op. cit. (21).
[101] Evenden, op. cit. (21); Coates, op. cit. (21); Schönach, op. cit. (21); Matthew Evenden, 'Beyond the organic machine? New approaches to river historiography', *Environmental History* (2018) 23, pp. 698–720; Luminita Gatejel, 'Building a better passage to the sea: engineering and river management at the mouth of the Danube, 1829–61', *Technology and Culture* (2018) 59(4), pp. 925–53.
[102] Mukerji, op. cit. (22); Marsden and Smith, op. cit. (22); Andersen, op. cit. (22).
[103] D. Stevenson, op. cit. (23), p. 324.
[104] D. Stevenson, op. cit. (23), p. 325.
[105] Thomas Stevenson, 'Report by Thomas Stevenson, C.E., in suspension and interdict John Stewart and others against the Hon. John Rollo', 2 November 1870, NLS/Acc.10706/530, number 46, p. 3.

this case, Thomas had to prove the accuracy of the data he used after his claims were disputed based on sections presented by another engineer, Mr Ritchie, CE, of Perth. Thomas claimed that Ritchie's sections 'were drawn to an exaggerated scale' and argued that, because Ritchie 'had not preserved his field notes', his work could not be accepted and the sections should be retaken.[106] This criticism was not of Ritchie's measuring practice, but of his translation of measurements into an abstract version of the river. Because Ritchie could not validate his version of the river by demonstrating correspondence between his plan and his field notes – a source of authority directly generated through measuring practice – Thomas could discredit Ritchie's work and persuade the court to retake the sections.

The Stevensons consistently drew attention to the difficulty of translating between the material river and the abstract conceptions of it used in law and politics. In 1877, they reported to the Clyde Lighthouse Trust, 'we were obliged to extend our views beyond the *legal boundaries* imposed by Parliament, and to regard the improvement of the River as *one Engineering question*'.[107]Despite ongoing disputes between the various interests who controlled the Clyde, the Stevensons continued to advocate treating the river as one continuous system, attempting to persuade the trustees to treat legal jurisdiction as secondary to physical characteristics.

This preference for working with physical rather than political river boundaries was common among engineers, although no clear consensus existed for how and where such boundaries should be drawn. Admiralty surveyor Edward Calver in 1853, for example, conceptualized rivers as divided into spaces of two types, the tidal and freshwater 'compartments', while David Stevenson, in *Principles and Practice*, instead identified three – the river proper, the tidal compartment and the sea proper.[108] Such categories were defined by physical characteristics, particularly in how they were affected by tides. In David's model, the river proper was not tidally influenced at all, the sea proper was affected like the sea, and the influence of the tide in the tidal compartment existed but was modified by the characteristics of the river. He matched specific types of river engineering to each section: dam, bridge and weir construction in the river proper; straightening, widening and deepening courses and removing subsidiary channels in the tidal compartment, and removing bars and shoals in the sea proper.[109] This division existed independently of political or legal jurisdictions, and boundaries between compartments were identified using measurement and observation of tidal effects.

The Stevensons were not, however, able to effectively convince others to categorize rivers systematically based on their physical features. Even if they had been, different groups continued to understand the ideal state of rivers and therefore the purpose of river works differently. Gilmartin has argued that engineers in India positioned themselves as improving rivers for the public benefit by imagining a certain kind of public composed of those engaged in the 'rational, productive exploitation of nature'.[110] The Stevensons in Scotland adopted a similar utilitarian understanding of rivers and of the acceptable functions they might serve.

For David, river engineering was 'the art of using, for the purposes of inland communication, rivers flowing in their natural courses, and of applying means to render them

[106] T. Stevenson, op. cit. (105), p. 3.

[107] D. & T. Stevenson, 'Report to the Clyde Lighthouse Trustees on the improvements of the navigation of the River Clyde within the limits of their jurisdiction', 13 February 1877, NLS/Acc.10706/530, number 35, p. 5, original emphasis.

[108] Edward Kilwick Calver, *The Conservation and Improvement of Tidal Rivers: Considered Principally with Reference to Their Tidal and Fluvial Powers*, London: John Weale, 1853; D. Stevenson, op. cit. (23), p. 55.

[109] D. Stevenson, op. cit. (23), p. 66.

[110] Gilmartin, op. cit. (21), p. 9.

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subservient to the purposes of navigation'.[111] Echoing the language of Thomas Tredgold's charter of the Institution of Civil Engineers, which defined engineering as 'the art of directing the great sources of Power in Nature for the use and convenience of man', David's explanation of river engineering focused fundamentally on navigation, in conflict with agriculturalists and industrialists who prioritized land reclamation or the supply of water and power for industrial processes, and elites who used rivers for sport and leisure.[112] Addressing the Royal Scottish Society of Arts in 1850, David said of the Mersey, 'What amount of latent power lies there! And how invaluable was that energy to the commerce of this country!'[113] Instead of understanding this energy as having potential for industrial production, however, David saw it as valuable for transporting goods. The river's energy, however, was being wasted because it was not engineered for navigation. David did not apply this concept of wasted energy to all rivers. Steep, fast-flowing rivers such as the Ness and the Erne, which presented a significant potential source of energy for industry, were not what David considered to be 'improvable rivers'.[114] Unlike the Mersey, the energy of these rivers could not be harnessed for the specific commercial end of moving goods, and therefore they could be neglected without being wasteful.

David positioned his approach to river management as a moral imperative. In 1858, he used the language of permission and neglect to describe the imperative to intervene:

> A river left in this state of nature cannot possibly attain the maximum depth due to the natural scour of the tidal currents … [if work is done] the constant action of the currents of flood and ebb tide flowing in the same channel, will secure a much greater permanent depth than they could possibly do if permitted to wander at random through the estuary.[115]

Random wandering was presented as the result of poor river management, rather than as a choice made to prioritize features of the river other than navigation. A river was 'left in this state' and 'permitted to wander' by humans who, David assumed, always had the authority and responsibility to manage river spaces for the purposes of commercial transport. For David, a river not being altered to increase the speed of navigation was a sign of irresponsible management, anathema to ideas of efficiency and water as resource that characterized engineering at the time.[116] This perspective was not, however, a view shared by others with interests in river management. In practice, the Stevensons had to negotiate complex political landscapes around river management.

It was widely recognized that, in river works, 'although every tenant and proprietor of land must be aware of the urgent necessity that exists … it is hopeless to expect that they will voluntarily make any united movement'.[117] While calls for 'a reunion of all interests' in support of a systemic river management plan were often made, they rarely succeeded in bringing about meaningful compromise and river projects were often postponed for

111 D. Stevenson, op. cit. (23), p. 54.

112 Thomas Tredgold, 'Charter of the Institution of Civil Engineers (1828)' *Charter, Supplemental Charters, By-Laws and Regulations*, London: Institution of Civil Engineers, 1867, p. 9.

113 David Stevenson, 'Abstract of an exposition of the art of navigation as applied to inland transit, and of the works by means of which communication with the ocean is improved and maintained', 1850, NLS/Acc.10706/528, number 11, p. 9.

114 D. Stevenson, op. cit. (23), p. 257.

115 D. Stevenson, op. cit. (44), p. 72.

116 Gilmartin, op. cit. (12); Jennifer Karns Alexander, *The Mantra of Efficiency: From Waterwheel to Social Control*, Baltimore: Johns Hopkins University Press, 2008.

117 'The prevention of floods', *The Engineer* (2 May 1873) 35, p. 270.

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years due to lack of consensus.[118] In the early years of the Stevensons' work on the Tay, proprietors were concerned that 'operations would disturb the passage of the salmon, and annihilate the very valuable fishings of the Tay'.[119] While the *Chester Chronicle* in 1849 was happy to dismiss these concerns as 'prejudice' against an 'eminent engineer' in order to support David's plans for improving the Dee, in the 1830s David, Alan and Robert had to address the risk to salmon fishing on the Tay directly.[120]

Their strategy in doing so was twofold. First, they drew heavily on the idea of public benefit, arguing that rivers should, like the rivers David had observed in the United States, form 'great public highways'.[121] The public, as the Stevensons imagined them, would naturally prioritize navigation over fishing. They note, tellingly, in their 1834 report that 'it has been said that the navigation of the Tay is an object of greater public importance than the salmon fishings'.[122] They stop short of explicitly endorsing this opinion, claiming that it 'is a point upon which the Reporters do not consider themselves competent to offer any opinion'; however, they suggest that 'fishing-cairns, or collections of stone and gravel' placed in the river to impede salmon, should be removed to facilitate better navigation, despite the clear problems this could cause for fishing.[123]

Alongside using the language of public benefit, the Stevensons also suggested that the conservators agree to pay compensation for any damage to the fisheries. This solution was common in road and harbour construction, but in a river was risky. Rivers reacted to engineering works unpredictably, so the Stevensons acknowledged that 'the extent of damage cannot *a priori* be ascertained'.[124] The conservators would be required to agree to pay compensation to the owners of the fisheries without certainty about how much this could cost. To convince the authorities in Perth to agree, the Stevensons presented examples of engineering works that had been carried out without damaging fishing on the Clyde, Dee, Tyne, Humber and Thames.[125] By drawing on engineering experience in these places, the Stevensons convinced the conservators to pay an unspecified level of compensation for damage to the fisheries, appeasing local landowners.

In prosecuting their works, the Stevensons had to operate within the constrictions of politics and the law. Despite their attempts to convince local authorities to treat the river as one engineering question, in practice they had to navigate multiple jurisdictions and proprietors whose understandings of the nature and purpose of river space differed. Assertions about the real or predicted impact of works on river space were often deployed in these contexts, but required validation through effective connection with measuring practice and engineering experience. These political negotiations required skilful manoeuvring that drew on credibility based on measurement, on engineering experience and on the family's reputation.

Conclusion

This paper has examined the multifaceted role played by measurement in supporting engineering authority over rivers. It traced the ways in which the quantitative and visual data produced by measurement were used to connect river spaces, legal disputes and engineering practices. Numerical understanding of depth, speed, volume and rate of flow played an increasingly important role in decisions about what to construct where,

[118] 'River Dee question', op. cit. (62), p. 3.
[119] 'Mr David Stevenson on tidal rivers', op. cit. (35).
[120] 'Mr David Stevenson on tidal rivers', op. cit. (35); Robert Stevenson and Son, op. cit. (35).
[121] D. Stevenson, op. cit. (28), p. 75.
[122] Robert Stevenson and Son, op. cit. (35), p. 2.
[123] Robert Stevenson and Son, op. cit. (35), p. 2; D. Stevenson, op. cit. (24), p. 22.
[124] Robert Stevenson and Son, op. cit. (35), p. 2.
[125] Robert Stevenson and Son, op. cit. (35), p. 3.

and in calculating the impact of engineering works in progress or on completion. Through measurement and the making of plans, the Stevensons were able to translate a river from a material reality into an abstract and controllable paper form, compatible with engineering processes that would render it subservient to human purposes, and legible in legal and political contexts where the dynamic materiality of water could not be easily translated.

Beyond the quantitative results it generated, however, it is clear that measurement as practice – the experience of having measured – acted as a powerful source of engineering authority. Due to acknowledged flaws in the correspondence between the abstracted version of a river and the real thing, the tacit knowledge of river space developed through in-depth and laborious practices of measurement in the field came to play a significant role in supporting engineering authority. This experience qualified engineers to make judgements of data, to challenge their legitimacy or to validate them as 'tolerably correct'.

For the Stevensons, the engineering experience upon which claims to authoritative knowledge was founded could be familial rather than individual. The experience of other family members was invoked both linguistically and materially through office copies that were directly connected to field books and retained in the archive of the family firm. As the family's reputation grew and reference material accumulated, the amount of time that each individual Stevenson had to spend personally observing in order to be recognized as able to make authoritative judgements was reduced, and the scope of the claims that could be made about changes to rivers over time expanded, although personal experience of measuring in the field was never completely replaced.

Engineers' ability to support their projects using authority derived from measurement had significant and lasting implications. River works required engineers to engage with landowners, business, local and national government and the public at large, many of whom had their own understandings of what rivers were and should be. Within these debates, engineers were able to harness the authority provided by measurement as product and practice to garner support for their proposed intervention and, in many cases, implement substantial and long-standing changes to the physical characteristics of Britain's rivers.

By conceptualizing measurement as producing both data and experience, this paper has challenged understandings of engineering that contrast quantification with tacit knowledge. Instead, this paper has shown that personal experience and quantitative measurement were interconnected and mutually reinforcing, often being used in combination to support claims to personal or familial engineering authority. In this way, it has extended understanding of the practice of measurement and the nature of engineering authority in nineteenth-century Britain.

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