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Estimated truths: water, science, and the politics of approximation

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ABSTRACT

This article introduces the special issue on 'Estimated Truths' which investigates the role of estimation in knowledge-making about water and, through it, contributes to thinking place as environment in the historical geography and history of knowledge. It argues that while historical geographers and historians of science have paid much attention to precision and quantification, approximation and estimation have also played an important role in knowledge-making and deserve more attention. It discusses the roles played by uncertainty and estimation in the water sciences and makes the case for more sustained engagement with the influence of the environment – understood as a dynamic set of human and non-human actors and forces – on knowledge-making. Finally, the article presents the five papers and discusses their individual and collective contributions to the themes of the special issue and to further investigation into the making and operation of estimated truths.

The five papers in this special issue investigate the role of estimation in knowledge-making about water and, through that, contribute to thinking place as environment in the historical geography and history of knowledge. The papers stem from a workshop on 'Estimated Truths: Water, Science, and the Politics of Approximation' convened by the editors at the Max Planck Institute for the History of Science in Berlin in 2017. This introduction will present the aims of this set of papers and situate them in relation to broader conversations happening at the intersection of historical geography, the history of science and technology, and environmental history.

Estimation is a versatile technique for finding order in nature (and, often, for asserting control over it) that does not require that the claims being made are necessarily true in all their details. At the same time, estimation can be used rhetorically both to defend the validity of a claim and to limit or undermine its applicability. Depending on the social, political, and environmental circumstances, labelling a claim an 'estimate' or an 'approximation' can be a means of either consolidating or contesting power. The production, validation, and use of estimated truths is a political process, a matter of power relationships and confrontations that affects (and is affected by) issues of management, distribution, and access.

The water sciences are not the only ones in which estimation plays a central role. They provide, however, a rich and distinctive perspective on its history. Water is essential to life, economically valuable, politically contested, and the object of many forms of knowledge-making, both expert and non-expert. At the same time, water changes form, circulates, slips through, leaks out, behaves unpredictably, and challenges observers to adapt their methods to its constantly changing shape and form. Moreover, the geographical and physical variability of water highlights the importance of local and material conditions in knowledge-making. This variability conditions the precision that can be achieved in measurement, and even the possibility of any measurement at all. In its ubiquity and variability, water thus provides an excellent entry point into the multiplicity of estimation practices and their politics.

In what follows, we discuss the subject of approximation and estimation in the history and historical geography of science, the way these processes manifest themselves in the water sciences, and how scholarship on this theme can contribute to thinking place as environment in knowledge-making. A final section compares and contrasts the five papers of the special issue, highlighting their individual and collective contributions to understanding estimated truths in the history and historical geography of water knowledge and beyond.

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The place of approximation in science

The history and geography of science have long been concerned with precision, both the means to achieve it and its broader social and cultural rationales and implications. In the 1990s, scholars sought to move beyond the simple assertion of the importance of precision in science to showing how and why it had become important in specific cases. Writing in 1995, for example, Norton Wise argued that the overwhelming focus of existing scholarship was on the technical means through which the natural and social sciences had achieved quantitative precision.[1] To Wise, it was necessary to ask why precision itself was valued, even more than how it was achieved. This, in turn, entailed taking into account the 'values of precision' for administrative and political control, as well as for military organization and industrial production. In the same year, Theodore Porter associated quantification in the social sciences to the politics of uncertain expertise. Bureaucracies under attack and unsure of their position, he argued, had historically relied on 'trust in numbers' as a means of holding their ground. Quantification was thus valued as a rhetorical source of precision and certainty and upheld as the ultimate validation of truth claims.[2]

An important strand of the scholarship on precision by historians of science and historical geographers has focused on the role of instruments and instrumentation. As Fraser MacDonald and Charles Withers recall in a recent edited collection, the instruments of science and the idea of exactitude were already at the centre of Eva Taylor's pioneering 1930 work on early-modern geography.[3] The question of instrumentation and precision, they argue, gained new salience from the eighteenth century onward, when it was linked to the epistemic authority granted to science 'as methodised procedures' through 'instruments and the data they produce'. MacDonald and Withers encourage a focus on 'what an instrument does rather than what an instrument is' as a way to engage with 'the intimate associations between embodied procedure, authority, accuracy and disciplinary practice'.[4] As Withers argues elsewhere, instruments have held a central place in the development of 'methodological principles for geography', where 'portable precision instruments' and the 'authority of the precision device' have been essential components in the making of truth claims.[5] Similar points have been made by historians of science such as Deborah Coen and Michael Reidy, whose studies of seismology and oceanography, respectively, have shown how instruments such as seismographs and automated tide gauges shaped debates over precision and accuracy and encouraged scientists to focus their attention on certain phenomena rather than others.[6]

However lauded and influential they may be, instruments have their limits. While they are key to claims of precision and accuracy, they are also fallible, their operators unreliable, and the measures they provide only imperfect and partial translations of complex processes. As MacDonald and Withers discuss in regard to exploration, there is an "epistemic gap" between truth claims about exploratory certainty and evidence which, as the result of technical and human failure, reveals shortfalls in recording, numbering, and, even, in knowing quite where one was at all'.[7] Withers argues elsewhere that 'we have paid too little attention to the nature and the fallibility of geography's instruments and to the resultant truth claims'.[8] More broadly, as Lorraine Daston and Peter Galison write, 'even the most fervent advocate of "objective methods" in the sciences – be those methods statistical, mechanical, numerical, or otherwise – would hesitate to claim that they guarantee the truth of a finding'.[9] In a different setting, John Roche has addressed the struggle of physicists to incorporate empirical measurements and algebraic equations into the same 'laws of physics'. Because of the difficulty of doing so, he argues, it became accepted that certain empirically measurable relationships did not have a clear 'foundation in physical principles' and ought not to be 'dignified' as laws. Rather, they could only be understood as handy approximations, serving a specific and limited aim in modeling certain kinds of data. In sum, truth claims are in many cases founded on a structural indeterminacy that is in turn linked to the fallibility of instruments and operators or to the limits of objective methods. In these conditions, best guesses or approximations are the only possible form of knowledge.[10]

However, even when uncertain and approximate, the products of knowledge-making can be presented as scientific truths and perform as such. The case of climate science shows the extent to which estimation and approximation can operate at the very heart of modern science and its truth claims. Climate sensitivity – that is, the temperature changes in response to variations in solar radiation such as those caused by rising CO_2 concentrations in the atmosphere – is a fundamental component of climate science. It is, at the same time, the product of estimates based on varying degrees of uncertainty, stemming from the complexity of interacting forces, limitations of existing data, computing speed, and other factors.[11] From the early estimates of Svante Arrhenius and Guy Stewart Callendar to today's computer-based models, the values of climate sensitivity vary within more or less ample margins of error which incorporate uncertainty and approximation. Those uncertainties are also part of the public face of climate science. The language of uncertainty and estimation permeates the reports of the Intergovernmental Panel on Climate Change, which seek to assess current and future climate change as well as the risks climate change poses for human habitats and society.[12]

Reflecting on the place of uncertainty and estimation in climate science and other environmental assessments, a group of scholars including climate scientist Michael Oppenheimer and historian of science Naomi Oreskes have argued that understanding uncertainty is at once 'a standard part of scientific practice' and a basic component of 'the decision-making process as well as the

[1] M.N. Wise, Introduction, in: M.N. Wise (Ed), *The Values of Precision*, Princeton, 1995, 3–13.

[2] T.M. Porter, *Trust in Numbers: The Pursuit of Objectivity in Science and Public Life*, Princeton, 1995. On precision in the social sciences see also A. Desrosiers, *Gouverner par les nombres: l'argument statistique II*, Paris, 2008.

[3] E.G.R. Taylor, *Tudor Geography, 1485–1583*, London, 1930.

[4] F. MacDonald and C.W.J. Withers, Introduction: geography, technology and instruments of exploration, in: F. MacDonald and C.W.J. Withers (Eds), *Geography, Technology and Instruments of Exploration*, Farnham, 2015, 3 and 6.

[5] C.W.J. Withers, Science, scientific instruments and questions of method in nineteenth-century British geography, *Transactions of the Institute of British Geographers* 38 (2013) 176.

[6] D.R. Coen, *The Earthquake Observers: Disaster Science from Lisbon to Richter*, Chicago, 2012; M.S. Reidy, *Tides of History: Ocean Science and Her Majesty's Navy*, Chicago, 2008.

[7] MacDonald and Withers, Introduction, 10.

[8] Withers, Science, scientific instruments and questions of method, 176.

[9] L. Daston and P. Galison, *Objectivity*, New York, 2007, 51 quote the philosopher Bernard Williams's definition of 'objective knowledge' as 'a systematized theoretical account of how the world really is'.

[10] J.J. Roche, *The Mathematics of Measurement: A Critical History*, London, 1998, 188 and 231.

[11] See P.N. Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*, Cambridge, MA, 2013.

[12] IPCC, *Global Warming of 1.5 °C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, Incheon, 2018, 77.

expression of the knowledge on which it is (at least in part) based'.[13] Thus uncertainty is not a flaw to be overcome, but rather a deeply embedded and unavoidable aspect of climate science. As historian of science Christoph Rosol has noted, areas of climate science such as paleoclimatology developed 'dealing with and on the basis of uncertainties as a matter of principle' as they crossed the disciplinary boundaries between so-called exact sciences like physics, which are given responsibility for analysis, and historical sciences, such as geology, which are tasked with collecting the relevant data.[14] Uncertainty in climate science and other environmental sciences, in sum, is intrinsic to knowledge-making and does not preclude but rather substantiates its truth claims.

Adopting a broader perspective that goes beyond the distinctive challenges of climate science, STS scholar Sheila Jasanoff has demonstrated the limitations of the modern idea that certainty may be attainable at all. Framing the latter idea as a product of a contemporary preference for binary thinking that limits choices in decision making to clear, knowable options, Jasanoff reminds us of the fact that 'for a long time we accepted lack of certainty as humankind's natural lot'.[15] Along with Jasanoff, a number of scholars, including sociologist Ulrich Beck and international relations scholar Richard Ashley, have argued that the idea that science can model the world in a way that overcomes its intrinsic indeterminacies is not only politically determined, but enforces a culture of domination, control, and alienation. Conversely, as Jasanoff writes, 'uncertainty about the environment … increasingly appears as a very special form of politics'.[16] If precision has value, we might say, so does that knowledge which remains approximate and estimated and nonetheless claims to be true. This special issue brings into focus the making and operation of these estimated truths.

Knowing water

The papers of this special issue bring into focus the place of uncertainty, estimation, and approximation through the viewpoint of water and the water sciences, where these forms of estimated truth have played and continue to play major roles in knowledge-making. Essential to life, water seeps into virtually every aspect of human society. It is necessary for the production of food: too little or too much water can make agriculture impossible, and both scarcity and excess have motivated efforts to control the flow of water through irrigation canals and dams. It is also important for transportation, whether through natural rivers, lakes, and oceans or through artificial channels, and efforts have been made both to understand the movements of water that affect transportation and to control them through the building of locks, canals, and dams and the dredging of channels and harbors. Water can also be an agent of disaster, as in floods and tsunamis, or of more gradual and cumulative damage, as in erosion and siltation. It can change phase, evaporating or freezing in ways that affect human lives and livelihoods. Water is essential for many industrial processes, serving as a solvent, a coolant, and a source of power, among other applications. It contains resources that humans can exploit, such as salt, fish, and algae. It also has symbolic, ritual, and recreational uses. The consumption of water is not only necessary to human life but also a medium for the transmission of toxins and agents of infection, which has led to efforts to measure and to maintain or produce the purity of drinking water. The list could go on.[17]

Not surprisingly, such an essential and ubiquitous substance has been the subject of a wide variety of forms of human knowledge-making. Using water effectively often depends on knowing it well: Will there be enough rain to raise a particular crop? Is the river navigable, and if so, at what times? Will the dike hold? Is the water safe to drink? Such questions are often posed in the course of practical activity, and the answers to them arise from the interactions between human actors and the technical, social, and environmental conditions under which they encounter a particular form of water. These conditions change over time, leading to a multiplicity of ways of knowing water across time, space, and social context, ranging from the everyday understandings developed in the course of practical activity – some of it 'expert', but much of it not – to the highly abstracted and formalized. Among this multiplicity of water knowledges are many forms of non-quantitative estimation that both precede and coexist alongside quantitative scientific methods.[18] Some of these ways of knowing are affective, sensory, embodied, and highly personal.[19] Through them, water comes to be known as turbid or clear, odorous or inoffensive, violent or calm, abundant or scarce. Like quantitative claims, such qualitative estimates can serve as the basis of practical action and long-range planning.[20]

Despite this multiplicity of ways of knowing, a certain natural scientific understanding of water has been increasingly influential since the late eighteenth century. Although it has no single origin, and became dominant at different times in different places over the course of the nineteenth century, the experimental work of Antoine Lavoisier in Paris in the 1780s, which showed that water was a compound of two chemical elements, hydrogen and oxygen, can

[13] M. Oppenheimer, N. Oreskes, D. Jamieson, K. Brysse, J. O'Reilly, M. Shindell and M. Wazeck, *Discerning Experts: The Practices of Scientific Assessment for Environmental Policy*, Chicago, 2019, 118.

[14] C. Rosol, Hauling data: anthropocene analogues, paleoceanography and missing paradigm shifts, *Historical Social Research* 40 (2015) 39.

[15] S. Jasanoff, Technologies of humility, *Nature* 450 (2007) 33.

[16] S. Jasanoff, The songlines of risk, *Environmental Values* 8 (1999) 144.

[17] Water history literature fills stacks. For examples of the environmental history of rivers, see M. Cioc, *The Rhine: An Eco-Biography, 1815–2000*, Seattle, 2002; S.B. Pritchard, *Confluence*, Cambridge, MA, 2011; R. White, *The Organic Machine: The Remaking of the Columbia River*, New York, 1995; P. Coates, *A Story of Six Rivers: History, Culture, and Ecology*, Chicago, 2013; D. Worster, *Rivers of Empire: Water, Aridity, and the Growth of the American West*, New York, 1985; M.D. Evenden, *Fish versus Power: An Environmental History of the Fraser River*, Cambridge, 2004; P.V. Scarpino, *Great River: An Environmental History of the Upper Mississippi, 1890–1950*, Columbia, 1985; C. Mauch and T. Zeller (Eds), *Rivers in History: Perspectives on Waterways in Europe and North America*, Pittsburgh, 2008; D.A. Pietz, *The Yellow River: The Problem of Water in Modern China*, Cambridge, MA, 2015; J. Taylor, *Making Salmon: An Environmental History of the Northwest Fisheries Crisis*, Seattle, 1999. On marine environmental history and oceans, see G. Kroll, *America's Ocean Wilderness: A Cultural History of Twentieth-Century Exploration*, Lawrence, 2008; N. Oreskes, Scaling up our vision, *Isis* 105 (2014) 379–391; K. Schwerdtner Máñez and B. Poulsen (Eds), *Perspectives on Oceans Past: A Handbook of Marine Environmental History*, Dordrecht, 2016; J.R. Gillis and F. Thorma, *Fluid Frontiers: New Currents in Marine Environmental History*, Winwick, 2015. A recent, sweeping account of the history of how science has tackled water in its different phases over the last couple of centuries is provided in S. Dry, *Waters of the World: The Story of the Scientists Who Unraveled the Mysteries of Our Oceans, Atmosphere, and Ice Sheets and Made the Planet Whole*, Chicago, 2019.

[18] C. Mukerji, *Impossible Engineering: Technology and Territoriality in the Canal du Midi*, Princeton, 2009 provides an interesting example of the role of non-quantitative, 'local' and 'tacit' hydrological knowledge in the construction of the Canal du Midi.

[19] On sensorial and bodily knowledge, see J. Parr, *Sensing Changes: Technologies, Environments, and the Everyday, 1953–2003*, Vancouver, 2009. On senses and water, as well as on philosophical meanings of water, see also I. Illich, *H_2O and the Waters of Forgetfulness: Reflections on the Historicity of Stuff*, San Francisco, 1985.

[20] B. Latour, How to talk about the body? The normative dimension of science studies, *Body & Society* 10 (2004) 205–229. On the role of the senses, particularly sight and smell, in early twentieth-century wastewater treatment in the United States, see D. Schneider, *Hybrid Nature: Sewage Treatment and the Contradictions of the Industrial Ecosystem*, Cambridge, MA, 2011, 83–124.

serve as a convenient starting point for understanding the emergence of modern water.[21] In addition to having fundamental implications for the understanding of matter, this research was closely related to practical considerations that arose in part from Lavoisier's involvement in assessing the quality of Paris's water supply.[22] Over the course of the nineteenth century, public health experts and municipal sanitation engineers embraced the idea of water as a chemically defined substance that was always and everywhere the same, varying only in the extent to which it was contaminated by other substances or affected by external forces.[23] At the same time, hydrographers were mapping river basins, oceanographers were fathoming the depths, and meteorologists were developing increasingly precise models of precipitation. Scientists working in these diverse disciplines all assumed that water itself was singular, not multiple; that there was only one water, not multiple waters.[24] Twentieth-century advances in the water sciences strengthened this idea, while continuing to link basic claims about the essential properties of water to practical concerns of water management. Robert E. Horton's influential model of the hydrologic cycle, for example, which emerged from his long career as a hydraulic engineer, offered a framework within which all of the forms in which water found on the Earth's surface – in rivers, lakes, oceans, rain, ice, the bodies of living beings, and so forth – could be understood as stages in the flow of a single, chemically defined substance.[25]

Still, none of these ways of studying water – neither the discovery of water's chemical composition, nor the mapping of the seas, nor the idea of the hydrological cycle – put an end to water's multiplicity. 'Modern' water may have been understood as a well-defined chemical substance (H_2O) circulating through a unitary global system, but it continued to be encountered, manipulated, consumed, and represented in ways that reflected its diverse origins, contexts, and qualities. Even within the natural sciences, where estimation of water's properties, quantities, and movements became increasingly quantitative from the eighteenth century onward, the methods and aims of quantification varied widely. Certain kinds of measurements were directed toward understanding river flows, others toward understanding ocean currents; some scientists sought measurements of water's quality, while others sought measurements of its velocity or quantity. Scientists who saw a river as a habitat for fish made certain kinds of measurements (such as chemical or biological composition); scientists who saw it as a source of hydropower made others (such as flow discharge). Each of these ways of estimating was made possible by the use of certain instruments, in certain environments, by scientists with certain kinds of bodies and certain kinds of relationships to the society around them – including other members of that society with their own distinctive ways of producing knowledge about water. How and why bodies of water have come to be understood and encountered differently is itself a historical process that deserves further inquiry. It may therefore remain useful to speak not of water in the singular, but of waters in the plural; not of knowledge of water, but of knowledges of waters.[26] The papers in this special issue all engage with this plurality, revealing how deeply knowledges of waters are shaped by their local environments.

Place and environment in knowledge-making

Because water's multiplicity emerges in large part from the highly specific ways in which it is encountered in particular places, scholarship on knowledge-making about water (or waters) must attend carefully to place and environment. In that regard, this special issue's focus on uncertainty, estimation, and approximation in the water sciences takes part in a larger project of situating science in place. For the last three or four decades, an ongoing debate among historical geographers and historians of science over the significance of the spatial dimension of knowledge-making has gradually resulted in a growing convergence in views.

For historical geographers, interest in the geographical study of science began with investigations in the 1980s into the history of geography itself as a science but soon broadened into a consideration of the geographical aspects of science in general. In an influential 1995 article, David Livingstone took stock of the 'increasingly prominent position' of space and place in the social sciences – as demonstrated through authors from Michel Foucault and Edward Said to Anthony Giddens and Donna Haraway – and argued programmatically for a 'geography of science'.[27] In his view, a geographical approach to science could take multiple avenues. One was the investigation of the 'regionalization of scientific style', that is, both the spatially uneven reception of science and the way location and national or regional styles of investigation affect the cognitive content of scientific claims. Another avenue involved close scrutiny of the influence of political geographies on the diffusion and reception of scientific claims. Yet another involved examining scientific sites such as the laboratory and the scientific society to uncover the spatial logics proper to these sites and how they influenced the making and circulation of scientific claims. In *Putting Science in Its Place*, written almost ten years later, Livingstone broadened the typology introduced in his article to include the study of sites of knowledge production, the larger spatial influences on knowledge-making, and the way circulation of scientific claims is favored or hampered.[28]

As discussed by Richard Powell in his 2007 survey of the historical geography of science, the field evolved in close dialogue with space-aware histories of science and science studies (and, he argued, it should continue to do so).[29] In the 1990s, just as Livingstone and other geographers of science were developing their own programme of research, historians of science were arguing in a similar vein for the importance of space and place in the understanding of science, and of knowledge-making in general. In an

[21] For a sketch of the many factors that contributed to the transition from 'waters' to 'water' in the nineteenth century, see C. Hamlin, 'Waters' or 'Water'? – master narratives in water history and their implications for contemporary water policy, *Water Policy* 2 (2000) 321. On Lavoisier, see A. Donovan, *Antoine Lavoisier: Science, Administration and Revolution*, Cambridge, 1993; H. Chang, *Is Water H_2O? Evidence, Realism and Pluralism*, Dordrecht, 2012; R. Siegfried, *From Elements to Atoms: A History of Chemical Composition*, Philadelphia, 2002. For the philosophical literature on water, reference, and realism, see P. Needham, The discovery that water is H_2O, *International Studies in the Philosophy of Science* 16 (2002) 205–226.

[22] Donovan, *Antoine Lavoisier,* 42–43.

[23] F. Graber, *Paris a besoin d'eau: projet, dispute et délibération technique dans la France napoléonienne*, Paris, 2009, provides an interesting example of early nineteenth-century knowledge-making about water supply (including both quality and quantity) in the Canal de l'Orcq in Paris. C. Hamlin, *A Science of Impurity: Water Analysis in Nineteenth-Century Britain*, Bristol, 1990, discusses nineteenth-century controversies on water quality in the UK.

[24] Hamlin, 'Waters' to 'Water'?, 315.

[25] On Horton, see J. Linton, Is the hydrologic cycle sustainable? A historical–geographical critique of a modern concept, *Annals of the American Association of Geographers* 98 (2008) 630–649.

[26] On pluralism in the sciences, with water as an example, see Chang, *Is Water H_2O?* On ontological multiplicity, see J. Law and M.E. Lien, Slippery: field notes in empirical ontology, *Social Studies of Science* 43 (2012) 363–378.

[27] D.N. Livingstone, The spaces of knowledge: contributions towards a historical geography of science, *Environment and Planning D* 13 (1995) 5 and 14.

[28] D.N. Livingstone, *Putting Science in Its Place: Geographies of Scientific Knowledge*, Chicago, 2003, 3.

[29] R. Powell, Geographies of science: histories, localities, practices, futures, *Progress in Human Geography* 31 (2007) 309–329.

important edited collection published in 1998, *Making Space for Science*, Crosbie Smith and Jon Agar summarized their aim as a contribution to the spatial location of science, through a twin focus on the construction of territory through knowledge and on the role of sites of knowledge-making in granting authority to scientific claims.[30] Other scholars soon drew attention to the importance of following knowledge as it moved from site to site. Steven Shapin, for example, emphasized the importance of moving beyond the 'local, situated, and embedded nature of science' to understand how 'transactions occur between places'. Using the example of Robert Boyle, he suggested, moreover, that taking into account the location and site of knowledge-making might provide important insights into the meaning of knowledge itself. Historians have interpreted Boyle's moral and philosophical tracts as targeting radical and sectarian groups that emerged during the civil wars. However, by taking into account the London neighborhood where Boyle was living when writing, Shapin suggests that Boyle's target might have actually been the libertine elite antics he witnessed close to his own home.[31]

The convergence and reciprocal influence between historians and geographers has been explicitly acknowledged by both communities. Science, these scholars conclude, is locally rooted and yet capable of travelling.[32] It may produce the appearance of universality, but its reach in fact extends only as far as the network of instruments, practices, and social arrangements that has been built to support it.[33] Thus place plays a critical role in knowledge-making, and scholarship 'putting science in its place' and tracing the networks, circuits, infrastructures, and translations that allow it to move from one place to another has proliferated.[34] Place, as Livingstone effectively summarized, 'matters in the way scientific claims come to be regarded as true, in how theories are established and justified, in the means by which science exercises the power that it does in the world'.[35]

But what exactly does 'place' mean? In many cases, scholars have understood place as the physical site where knowledge is produced or discussed. Literature in the history and historical geography of science has investigated a number of examples: the botanical garden, the museum, the ship, the field station, and, above all, the laboratory, which has been the object of an impressive array of studies.[36] The configuration and features of these sites, scholars have shown, as well as their location and accessibility, influence the very content of scientific knowledge-making. 'Place' can also allude to the social, cultural, or political characteristics of a location, which can also shape in significant ways the making of scientific truth claims.

Within this body of literature, however, 'place' is rarely considered in terms of its environmental features. The reasons may have to do with the history of geography as a field, particularly the excesses of environmental determinism in the early twentieth century. Since then, historical geographers have been wary of attributing too much importance to environmental factors. In his 1995 article advocating for a geography of science, for example, Livingstone took great care to distance himself from approaches such as that of Harold Dorn, whose *The Geography of Science* (1991) argued that physical geography explained the uneven spatial distribution of science.[37] Livingstone forcefully rejected what he saw as an 'ecological constructivism that prioritises material environment over other factors' in favour of a 'more diverse range of spatial arenas'.[38] Although skepticism toward environmental explanations remains, it has softened somewhat in recent years. In 2011, Livingstone and Withers returned to the question of the environmental determinants of science. While they reiterated the criticism of Dorn's 'ecological reductionism' and 'a priori assumptions about the determining impact of the physical environment', they expressed an openness to more nuanced ways of incorporating environmental factors. Their criticism of environmental determinism, explained Withers and Livingstone, 'should not be taken to mean that physical landscapes have no influence on the shape of scientific knowledge'.[39]

Some historians who draw on both the history of science and environmental history – what we might call environmental historians of science – as well as environmental historical geographers have started to shed light on this influence by taking into account a more explicitly environmental understanding of place.[40] Environmental history offers a view of 'place' that differs significantly from that offered by most historical geographers and historians of science. Whereas the latter tend to study place as a site (or a series of interconnected sites), environmental historians have adopted place as a dynamic set of human and non-human actors. This approach can be usefully applied to the history and historical geography of science, and to STS more broadly. In their introduction to a special issue of *Osiris*, Gregg Mitman, Michelle Murphy, and Christopher Sellers argue that the dynamism of the material environment needs to be taken into account when discussing the histories of knowledge-making. 'Ecological approaches to history', they write, assume that 'nonhuman substances or organisms have concrete effects on history', and by so doing they 'open the doors of inquiry into a widening variety of roles nonhuman actors have played in the human past'.[41] More recently, historian of technology Sara Pritchard has argued that taking into account the agency of ecosystems is what distinguishes environmental history. According to Pritchard, the incorporation of the influence of physical environments and the contingencies that nonhuman actors and processes can produce is the most important contribution that environmental

[30] C. Smith and J. Agar, Introduction: making space for science, in: C. Smith and J. Agar (Eds), *Making Space for Science: Territorial Themes in the Shaping of Knowledge*, Basingstoke, 1998, 1–23.

[31] S. Shapin, Placing the view from nowhere: historical and sociological problems in the location of science, *Transactions of the Institute of British Geographers* 23 (1998) 6–7 and 9.

[32] J.A. Secord, Knowledge in transit, *Isis* 95 (2004) 654–672.

[33] On the idea of the global as a combination of local instances, see B. Latour, *We Have Never Been Modern*, Cambridge, MA, 1993, 117–119.

[34] D. Finnegan, The spatial turn: geographical approaches in the history of science, *Journal of the History of Biology* 41 (2008) 369–388. See also work on circulation of science, K. Raj, *Relocating Modern Science: Circulation and the Construction of Knowledge in South Asia and Europe, 1650–1900*, London, 2007.

[35] Livingstone, *Putting Science in Its Place*, 14.

[36] For examples, see E.C. Spary, *Utopia's Garden: French Natural History from Old Regime to Revolution*, Chicago, 2000; R. Drayton, *Nature's Government: Science, Imperial Britain and the 'Improvement' of the World*, New Haven, 2000; S.L. Star and J.R. Griesemer, Institutional ecology, 'translations' and boundary objects: amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907–39, *Social Studies of Science* 19 (1989) 387–420; R. Sorrenson, The ship as a scientific instrument in the eighteenth century, *Osiris* 11 (1996) 221–236; R. de Bont, *Stations in the Field: A History of Place-Based Animal Research, 1870–1930*, Chicago, 2015; S. Shapin, The house of experiment in seventeenth-century England, *Isis* 79 (1988) 373–404; G. Gooday, The premisses of premises: spatial issues in the historical construction of laboratory credibility, in: Smith and Agar (Eds), *Making Space for Science*, 216–245.

[37] H. Dorn, *The Geography of Science*, Baltimore, 1991.

[38] Livingstone, The spaces of knowledge, 15.

[39] D.N. Livingstone and C.W.J. Withers, *Geographies of Nineteenth-Century Science*, Chicago, 2011, 4.

[40] See, for instance, A. Keeling, Charting marine pollution science: oceanography on Canada's Pacific coast, 1938–1970, *Journal of Historical Geography* 33 (2007) 403–428. See also S. Bocking, Landscapes of science, in: T. Adcock (Ed), *Landscapes of Science*, Toronto, 2019, 1–8.

[41] G. Mitman, M. Murphy and C. Sellers, Introduction: a cloud over history, *Osiris* 19 (2004) 10–11.

historians can make to STS.[42]

Some of the most sophisticated work in the environmental history of science has been done by historians of the field sciences, who are almost by necessity required to consider both the role of physical geography and the nonhuman environment in knowledge-making and the shifting methods and theories used by their historical subjects. Histories of the field/lab border, for example, have broadened the perspective of where and how science is performed, reframing and renarrating the struggles of practitioners to assert the legitimacy of their approaches to knowledge-making. In doing so they have helped expand the variety of sites in which different kinds of science are performed and refined the overall understanding of what the sciences are and how they produce knowledge.[43] At the same time, these studies have problematized categories of 'place' and 'environment' themselves in ways that show how they have evolved and been contested over time.

Drawing on this scholarship at the intersection of environmental history, the history of science, and historical geography, this special issue emphasizes the multiple ways in which the environmental dimension of place shapes estimation practices and truth claims about water.

Understanding estimated truths

The five papers in this collection shed light on these issues in original ways, collectively emphasizing the influence of place (understood both as site and as environment), the importance of approximation and other forms of estimated truth, and the role of politics in knowledge-making and of knowledge-making in politics. While adopting radically different perspectives, all of them present water as a contested object, whose scientific understanding and interpretation is subject to a variety of social influences and which in turn has social and political effects. Deciding what is true about water, these studies show, emerges from place-based research and has concrete and immediate repercussions on human and more-than-human communities. In this way, knowledge about water is inevitably local in its origins and effects. At the same time, the environmental constraints that shape the production of knowledge of water have pushed decision makers, scientists, and practitioners to look for ways to overcome these necessarily local dimensions of knowledge to reach for 'placeless' and global forms of knowledge. The papers also unpack the political determinants of the value attributed to approximation and uncertainty. Different actors may, they show, push for different levels of precision and accuracy in ways that serve their own interests. Complicating some of the foundational scholarship on quantification in the history of science and historical geography, these papers show that it is not always or necessarily the case that numbers are trusted and precision is valued.

Matthew Evenden and Christy Spackman focus on water pollution, and hence on the chemical composition and organoleptic or sensory properties of water. Spackman discusses attempts by municipal water services during the twentieth century to standardize the assessment of water's odour and taste. Her paper analyzes how municipal workers in Chicago sought to develop a 'placeless' method to estimate water quality. It sheds light on the continued role of the human senses in assessing water quality well into the twentieth century, despite the increasing abstraction of water knowledge and the increasingly authoritative role of chemistry and bacteriology in assessing water purity.

Place as a dynamic set of environmental conditions rather than simply as a site or location is critical to Spackman's account. Chicago's constantly changing water supply, she shows, complicated efforts to standardize assessment of taste and smell. Spackman demonstrates that place mattered to these efforts in ways that are complex, intriguing, and changed over time. On the one hand, operators sought to obtain the best possible approximation of the unique organoleptic qualities of a water body. This estimation was purposefully and inextricably bound to place through 'individual operator's bodies and the bodies of water they were working with'.[44] On the other hand, water workers discussed, revised and ultimately changed their assessment methods in order to produce estimates of water quality that could be separated from both the subjectivity of the observer and the uniqueness of the observed. Spackman, moreover, reminds us of the politics behind sensing water – that is, the fact that water workers were seeking to mitigate some of the worst consequences of industrial pollution of water bodies in the name of economic growth.

The politics of place-based knowledge-making are at the centre of Matthiew Evenden's paper on water purity in 1940s Vancouver. Evenden discusses the controversy between federal and local authorities over the safety of Vancouver's water supply and the need (or lack thereof) to chlorinate it. Here place plays a different role. In the period discussed by Evenden, substantial uncertainty remained about the purity of Vancouver's water supply. The knowledge of local authorities was admittedly insufficient and tests performed by the federal authorities offered nothing more than an estimate of potential bacteriological charge. As the paper argues, however, the debate did not revolve so much around how truth was produced or how accurate particular truth claims were, but rather around what counted as truth and above all who could tell it. In the public arena, where the controversy mostly played out, the issue was mainly about experts and which forms of expertise should be trusted. Because place was essential to establishing trust, place-based experience became a guarantee of water purity even in the face of competing forms of knowledge suggesting the opposite. Opposition to chlorination was therefore rooted in 'local claims and perceptions of pure water and a deep distrust of scientific measurement, expertise and federal state authority', and it depended on the control of the entire catchment of the city's municipal supply.[45] Until the unique circumstances of World War II changed the conditions and stakes of the debate, this place-based knowledge held fast against the placeless standards that federal authorities sought to impose.

Differing from Spackman and Evenden's focus on water quality, Daniel Macfarlane and Etienne Benson bring our attention to the physical properties of water and river systems, and specifically to the morphological agency of water flows in larger river systems, be it through the attention to river ice in Macfarlane's account or the attempts at predicting river channel dynamics in Benson's recounting of Luna Leopold's intellectual trajectory in the 1960s.

42 S.B. Pritchard, Joining environmental history with science and technology studies, in: D. Jørgensen, F.A. Jørgensen and S.B. Pritchard (Eds), *New Natures: Joining Environmental History with Science and Technology Studies*, Pittsburgh, 2013, 4.

43 J. Vetter (Ed), *Knowing Global Environments: New Historical Perspectives on the Field Sciences*, New Brunswick, 2010; J. Vetter, Labs in the field? Rocky Mountain biological stations in the early twentieth century, *Journal of the History of Biology* 45 (2012) 587–611; R.E. Kohler, *Landscapes and Labscapes: Exploring the Lab-Field Border in Biology*, Chicago, 2002; A. Adler, The ship as laboratory: making space for field science at sea, *Journal of the History of Biology* 47 (2014) 333–362; de Bont, *Stations in the Field*.

44 C. Spackman, Just noticeable: erasing place in municipal water treatment in the U.S. during the interwar period, *Journal of Historical Geography* 67 (2020) 7.

45 M. Evenden, Debating water purity and expertise: the chlorination controversy in Vancouver during the Second World War, *Journal of Historical Geography* 65 (2019) 95.

Macfarlane discusses the knowledge-making that was associated with, and indispensable to, two of the most important large-scale water infrastructure projects of the twentieth century: the St Lawrence Seaway and Power Project and the replumbing of the Niagara Falls. In his paper, place is not just something experts seek to escape from in order to obtain placeless knowledge, but also something they incorporate into their knowledge-making to produce what he calls 'place specific expertise'.[46] Macfarlane also provides a key example of knowledge-making being shaped by its dynamic environment. In his case study, engineers were confronted with environmental conditions typical to the water system they were trying to replumb, notably the presence of so-called 'frazil' ice, for which there were no identical cases elsewhere that could be used as models. They therefore had to adapt the knowledge on which they based their engineering efforts to these environmental conditions through a continuous engagement with place. The role of environmental conditions in knowledge-making is also evident in engineers' construction of models through an iterative process that moved back and forth between the river and the laboratory. The importance of place is reinforced by the fact that, as Macfarlane demonstrates, engineers from both the United States and Canada arrived at the same approach despite their differing engineering cultures and political contexts. Further complicating the story is the fact that these locally built models did not remain confined to the place for which they were devised but rather played an important role in shaping hydraulic modelling worldwide.[47]

In a similar way, Benson's paper moves away from urban water pollution and into knowledge-making about the geomorphic dynamics of large-scale water systems. It traces the trajectory of US geomorphology between the 1950s and 1970s through the pivotal figure of Luna Leopold, influential geomorphologist and head of the Water Resource Division of the U.S. Geological Survey. In it, Benson provides a fascinating case of the changing role of estimation and how it is linked to place and environment.

Under Leopold's leadership, US geomorphologists at the Water Resource Division sought in the 1950s to develop a method to identify the 'timeless, placeless natural laws' which supposedly regulated the forms and behaviors of all rivers. This attempt, as Benson shows, was motivated by the desire to consolidate geomorphology's position in the policy arena: being able to produce an exact knowledge of river systems, Leopold and his colleagues believed, would bolster the Water Resource Division's authority. This method, however, which was based on the assumption of underlying mathematical regularities, did not deliver the expected result. Once tested in different geographical settings, the alleged universal model failed to predict river behaviour due to the influence of place and environmental conditions and the fundamental uniqueness of each site's geomorphological processes. While some geomorphologists argued (in parallel with the 'as nearly as may be' engineering approach described by Macfarlane) that the failures of mathematical models could be compensated for by the scientist's field experience and trained judgment, Leopold embraced a more radical conception of the inherent indeterminacy of geomorphological processes and the irreducible uncertainty of scientific claims about them.[48] Place mattered so much to Leopold, in other words, as to invalidate any claim to prediction, instead suggesting the need to relinquish any hope of total control. Estimation, in short, became the only possible way of knowing complex, emplaced river systems. In the context of the rising environmental movement, Leopold's claim that science was incapable of deterministically modeling river systems helped to justify skepticism and opposition to water engineering projects whose legitimacy derived from their predictive abilities. Benson's paper thus offers insights into the politics of estimation: if scientists can sometimes mobilize precision to claim authority, his case shows that they can also achieve a different kind of authority by embracing uncertainty.

Wilko Graf von Hardenberg's paper, finally, focuses on the water of the world's oceans in his analysis of nineteenth-century attempts to measure the level of the sea.[49] The paper discusses the different approaches that German geodesists developed to obtain a reliable estimate of the mean sea level, from coordination of coastal measurements up to the embrace of a speculative approach based on the estimation of gravitational forces.

As in other papers in this collection, place in Hardenberg's paper is an obstacle to precision and something scientists seek to escape from, but it is also something that continuously conditions knowledge-making about the water of the planet. Thus, nineteenth-century measurements of sea level from coastal stations proved unsuitable largely due to the physical variations of the coastline and the seas themselves as well as to technical obstacles. These failures led some geodesists to move away from the coast and its variability toward high sea islands, yet doing so failed to produce more accurate or reliable results. The attempt to escape from the variability of place also motivated the use of measurements of the gravitational field to estimate mean sea level, in the hope of eliminating the insurmountable variability of physical geography. However, as Hardenberg demonstrates, even these geophysical methods could not escape from the environmental dynamism and physical variability of water: once measurement moved from land to sea, storms and waves hindered the operation of precision instruments. This case illustrates the significance of estimation and approximation in knowledge-making as well as the role of place as a set of environmental conditions. In all of the attempts to measure sea level that Hardenberg discusses in his paper, scientists assumed they would need to approximate in order to obtain reliable knowledge. At the same time, this approach proved only partly successful. Environmental conditions and processes hindered the reliability of estimates, leading geodesists to progressively discard each promising new method, from coastal and island measurements to gravimetry.

Each of the cases presented in this special issue provides original and valuable insights that simultaneously build on the rich literature of the history and historical geography of precision and quantification and point beyond it in provocative ways. Together, they show the value of focusing on estimation and approximation in knowledge-making, the specific significance of this topic in the water sciences and engineering (including their political dimensions), and the utility of this approach for broadening the incorporation of place as environment into historical geographies and histories of knowledge-making. They also show, we hope, the tremendous potential of a more sustained conversation between historical geographers, historians of science and technology, and environmental historians in the investigation of knowledge-making.

[46] D. Macfarlane, As nearly as may be: estimating ice and water on the Niagara and St. Lawrence Rivers, *Journal of Historical Geography* 65 (2019) 74.

[47] Macfarlane, As nearly as may be, 80–81.

[48] E.S. Benson, Random river: Luna Leopold and the promise of chance in fluvial geomorphology, *Journal of Historical Geography* 67 (2020) 14–23.

[49] W. Graf von Hardenberg, Measuring zero at sea: on the delocalization and abstraction of the geodetic framework, *Journal of Historical Geography* 68 (2020) 11-20.

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