Modern Asian Studies **41,** 5 (2007) pp. 967–994.
doi:10.1017/S0026749X06002721 First published online 23 March 2007

The Personal Equation: Political Economy and Social Technology on India's Canals, 1850–1930

MICHAEL LEWIS

Christ's College, Cambridge

Abstract

This article engages with a long critical tradition, particularly amongst historians of India but also more generally within environmental and economic history, which describes the modern West's hubristic scientific domination of Asian environments. Confidence in the universal applicability of scientific knowledge, such critiques argue, justified one-size-fits-all technical schemes being exported across vastly different climates and societies, and landscape and communities reshaped to fit the rational visions of planners and engineers. The article examines the actual procedures of Indian canal engineering, whose protagonists ostensibly portrayed precisely this scientific hubris. It finds that even the most 'scientific' canal construction and management, borrowing ideas and procedures from steam engines and astronomy, involved precisely the sorts of local knowledge and social reliability evident in opposing forms of flexible, administrative irrigation management. While these two types of water management attempted literally to engineer two different political economies into India's agrarian landscape, in practice their management styles differed little. Both enlisted social and racial prejudice, rather than scientific knowledge, to defend the administrative superiority and actions of British officials. Instruments for economic governance and administrative control, it argues, thus derived as much from the colonial limits of 'universal' European science as from its global applicability.

As Deputy Commissioner Gladstone remarked:—"....To deal with inundation canals a man must be always on the spot, must be thoroughly acquainted with the practical geography of his circle, and must learn that rules of hydro-dynamics cannot always be applied to the Indus. He must, to a certain extent, forget that he is an engineer, and he must acquire an instinct."

— Alfred Deakin, *Irrigated India* (1893)[1]

[1] A. Deakin, *Irrigated India: An Australian View of India and Ceylon their Irrigation and Agriculture* (Calcutta 1893), p. 312. C.E. Gladstone was Deputy Commissioner at Dera Ghazi Khan, Punjab, in the late 1870s and 1880s.

I 'Trained Powers of Observation': Hydraulic and Social Administration

The late nineteenth century witnessed the proliferation of experts within new specialist departments of the Raj, responsible for India's canals, roads, bodies, forests, and surveys. In 1903 the Indian Irrigation Commission produced a revealing portrait of the qualities required of one such expert: the Indian Public Works Department canal engineer. The '*ideal* irrigation officer . . . something more than either engineer or revenue officer',

> should be required to keep as strict an account of the disposition of every cubic foot of water entering their canals as they keep of the cash which they draw from the Government treasury . . . . systematically gauging and recording the supplies entering or utilized in the different sections of the canal system.[2]

He would also, however, need administrative discretion, being 'progressive and sympathetic', 'closely . . . connected with the work of assessment and remissions, and . . . the settlement of all questions connected with the internal distribution of water within the villages on which a reference is necessary to external authority.'[3]

Historians have largely understood this phase of 'constructive imperialism' as a high-point in European science's colonisation of Indian society and economy.[4] The Indian Irrigation Commission, one of an outbreak of late-nineteenth century enquiries and commissions, imperial and domestic, perfectly exemplifies this late-Victorian faith in the capacity and guidance of professional expertise in government and economy.[5] Established in 1900 after four decades of building large-scale Indian irrigation works which had persistently failed either to be financially remunerative or to prevent famine, the Commission nonetheless gave the task of solving this problem of ostensibly

[2] *Report of the Indian Irrigation Commission 1901–3, Part I. General* (Reports of Commissioners, 1904, LXVI, Command Paper 1851) [hereafter Cd. 1851], pp. 120–1.

[3] Cd. 1851, p. 121.

[4] S.B. Saul, 'The Economic Significance of "Constructive Imperialism"', *Journal of Economic History* 17 (1957), pp. 173–92. For experts and empire, see R. Drayton, *Nature's Government: Science, Imperial Britain, and the 'Improvement' of the World* (New Haven, 2000), esp. pp. 170–200; W.H.G. Armytage, *A Social History of Engineering* (Cambridge Mass, 1961), pp. 162–167; R.A. Stafford, *Scientist of Empire: Sir Roderick Murchison, Scientific Exploration and Victorian Imperialism* (Cambridge 1989).

[5] R. MacLeod (ed.), *Government and Expertise: Specialists, Administrators and Professionals, 1860–1919* (Cambridge 1988); G.R. Searle, *The Quest for National Efficiency: Study in British Politics and Political Thought, 1899–1914* (Oxford, 1971).

https://doi.org/10.1017/S0026749X06002721 Published online by Cambridge University Press

misplaced technical confidence to a committee of prominent Indian engineers, charged with finding ways to reverse their colleagues' record of water-logging, salinisation, malaria, famine and debt.[6] Equally characteristically, the Commission's report defended grandiose hydraulic schemes, and their faith in technical expertise. It called for an expanded Public Works Department (PWD) corps to construct new 'vast irrigation schemes of Bengal, the United Provinces, and the Punjab'. It further insisted that 'Engineers, besides constructing and maintaining the canals, [should] manage the distribution of the supply to individual cultivators and assess the revenue due'; tasks which, as they admitted, many administrators considered 'not properly an engineer's work at all, and . . . better carried out by revenue officers and their subordinates'.[7]

The social and political shockwaves generated by the intrusion of the new expert services into the colonial management of nature and society are exemplified in this conflict between the competences of PWD Irrigation engineers and the generalist Indian Civil Service (ICS), whose duties came to overlap in many regions. David Gilmartin has portrayed this as a clash of administrative ideologies. The civilian administrator's ideal of flexible administrative discretion grated, he argues, against the rigid control of land and water idealised by the new PWD engineers, confident about the foundations of engineering in universal scientific knowledge about nature, and thus rejecting the need to deal with local and contingent knowledge of the social and environmental contexts of their canals: '[v]iewed in mathematical terms, the hydraulics of irrigation channels and the mechanics of dam construction were the same whether applied in California or the Indus Basin. From this perspective, 'local knowledge' counted for little'.[8]

Gilmartin does not claim that the ICS generalists were in fact more closely in touch with the needs and practices of Indian agrarian society. Nonetheless, the complaints of *ryotwari* cultivators and *zamindar* landowners did draw a rhetorical contrast between a scientific management that regarded agrarian problems as purely engineering ones, and sensitivity to agrarian, social and environmental conditions.

[6] On the Commission, see E. Whitcombe, 'Irrigation' in D. Kumar and M. Desai (eds), *The Cambridge Economic History of India Vol. II: c. 1757–c. 1970* (Cambridge, 1983), pp. 717–22.

[7] 'Establishments', Cd. 1851, pp. 119, 120–1.

[8] D. Gilmartin, 'Scientific Empire and Imperial Science: Colonialism and Irrigation Technology in the Indus Basin', *Journal of Asian Studies* 53, 4 (1994), pp. 1127–49, quote at p. 1136.

This contrast resonates with a long critical tradition, most recently explored by James Scott, which describes the modern West's hubristic scientific domination of Asian environments.[9] Confidence in the universal applicability of scientific knowledge, such critiques argue, justified one-size-fits-all technical schemes being exported across vastly different climates and societies, and landscape and communities reshaped to fit the rational visions of planners and engineers.[10]

Yet here the Commission used the qualities of careful observation and assiduous empiricism precisely to defend the expertise of 'highly qualified engineers, with trained powers of observation' *against* the civilian administrator, and combined them with the strict control of water supply that Gilmartin has argued was characteristic of inflexible 'scientific management'.[11] Engineer administrators would be

> constantly inspecting every part of the system . . . being thus in daily touch with the canal staff and the cultivators . . . always on the alert to propose improvements in the distribution of water and in all matters of management . . . not only by localizing waste from Government channels or village water-supply, but also by constant adaptation of the distribution to the requirements of the moment or of the locality.[12]

This article argues that the Commission's peculiar depiction of engineering expertise reflects the fact that colonial and environmental historians have misconstrued the conflict, either real or imagined, between adaptive administrative discretion and rigid theoretical science. This is partly attributable to the fact that while the ideology and institutions of colonial science have been extensively investigated, relatively little detailed attention has been paid to its actual procedures and practices.[13] These reveal that the idealised

[9] J. Scott, *Seeing like a State* (New Haven, 1998). For a selection of the hydraulic sections of a much larger historiography, see R. Tignor, 'British Agricultural and Hydraulic Policy in Egypt 1882–1892', *Agricultural History* 37 (1963), pp. 63–74, esp. p. 72; N. Sengupta, 'Irrigation: Traditional versus Modern', *Economic and Political Weekly* 20, 47 (Nov. 1985), pp. 1919–38.

[10] For similar contemporary critiques of 'engineering bias', see M. Cernea, 'Poverty Risks from Population Displacement in Water Resources Development' (Harvard Institute for International Development, Development Discussion Paper No. 355, August 1990); S. Singh, *Taming the Waters: the Political Economy of Large Dams in India* (New Delhi, 1997); F. Pearce, *The Dammed: Rivers, Dams and the Coming World Water Crisis* (London, 1992).

[11] Cd. 1851, p. 120; Gilmartin, 'Scientific Empire', pp. 1130–2.

[12] Cd. 1851, p. 122.

[13] A notable exception is K. Raj, 'When human travellers become instruments: The Indo-British exploration of Central Asia in the nineteenth century', in M.-N. Bourguet,

https://doi.org/10.1017/S0026749X06002721 Published online by Cambridge University Press

mathematical models and predictive theories of canal engineering in this period actually invoked a series of technical practices and problems which imbued hydraulic science with precisely the sorts of social discretion, agrarian negotiation and local knowledge which Gilmartin has argued lay outside the engineer's narrow concrete vision. While these did reinforce the superiority of the expertise of PWD engineers, they did so not through experts' theoretical knowledge or technical skill, but by appealing to the same social (and racial) charisma with which the ICS officials claimed to administrate.

I have not attempted a comprehensive survey of the operation of India's canals, an enormous historical task still to be completed at the archival coalface of revenue reports and departmental correspondence. Instead I examine the PWD's engineering practices through its manuals, technical reports and textbooks. Often produced before comparable British engineering textbooks were available, these were thus deliberately oriented towards Indian requirements, making it possible to read them as self-portraits of the department's disciplinary ideals.[14] Of course, such theoretical sources might be expected to privilege precisely the communicable, theoretical knowledge whose dominance this article questions. In fact they detail, surprisingly explicitly, the socially-contingent skills and competences inscribed in the routines of the department's work: perhaps an indication of the malleable balance between theory and practice in nineteenth-century European engineering science; but also of the challenges to that science presented by Indian practice.[15]

Through these design practices and managerial routines I trace two 'styles' of irrigation engineering, whose procedures and regimes of resource management did indeed invoke different sources of knowledge and sorts of expertise.[16] Yet ultimately, through the

C. Licoppe, O. Sibum (eds), *Instruments, Travel and Science: Itineraries of Precision from the Seventeenth to the Twentieth Century* (London, 2002), pp. 156–88, and other essays in this collection.

[14] For the lack of prior English textbooks, especially for 'Hydraulic Engineering', see G.T. Chesney, 'Additions to the teaching staff', Public Works Minute No. 244 (2 January 1875), London, British Library, Oriental and India Office Collection [hereafter OIOC], IOR/L/PWD/8/7, ff. 490–494v, 491v.

[15] For 'communicable' and 'incommunicable' expertise, see C. Lawrence, 'Incommunicable Knowledge: Science, Technology and the Clinical Art in Britain 1850–1914', *Journal of Contemporary History* 20 (1985), pp. 503–20.

[16] For technological 'styles', see T.P. Hughes, 'The Evolution of Large Technological Systems', in W.E. Bijker, T.P. Hughes, T.J. Pinch (eds), *The Social Construction of*

social and physical complexities of India's canals, and the theoretical limitations of European science itself, both styles of engineering came to require the empirical capacities of observation and accounting with which the Indian Irrigation Commission united agrarian administration and hydraulic science. These divergent engineering styles did not, therefore, represent a Manichean clash between engineers' rigidly pre-determined mathematical models of resource use, and the complex social and environmental negotiations required by agrarian reality. They did, though, envisage physically different canals, and correspondingly proposed systematically different methods of water management. The conflict which David Gilmartin describes between engineers and civilian administrators was in fact one which existed within the PWD's own ideals of engineering: a conflict not between scientific and social visions of irrigation, but between different engineering economies, both of water and of knowledge. Just as theoretical problems of hydraulic science in Indian canal engineering were in practice indistinguishable from the vagaries of social and economic administration, so their technical solutions engineered different agrarian political economies into the fabric of India's canals.

II. Local Knowledge and Social Reliability

At first glance, early colonial canal builders appeared confident in the universal applicability of European hydraulics. Several toured Italian irrigation works that appeared to confirm that universally applicable engineering methods were produced by the logic of natural investigation. Sir Proby Cautley, designer of the great Ganges Canal project built between 1841 and 1854, expressed

> surprise, mixed with a good deal of satisfaction, at the numerous instances in which we, who were entirely separated from all communication with the Italian engineers, had, by the mere process of simple reason, arrived so frequently at precisely the same results.... expedients being devised by simple inductive reasoning, without the parties having any connection or communication with one another.[17]

Technological Systems: New Directions in the Sociology and History of Technology (Cambridge Mass., 1987), at pp. 68–70.

[17] P.T. Cautley, *Report on the Ganges Canal Works: from their Commencement Until the Opening of the Canal in 1854* (3 vols, London, 1860), Vol. I, p. 103; cf. J. Brown,

https://doi.org/10.1017/S0026749X06002721 Published online by Cambridge University Press

Irrigation manuals and textbooks produced for the theoretically-trained Public Works engineers of the later nineteenth century, such as the successive editions of the *Roorkee Treatise*, repeated this rhetorical insistence on the geographical pedigree of irrigation engineering, and established its status as a discipline whose principles were 'susceptible of universal application'.[18] Yet in contrast, the practical routines specified by these manuals demonstrate substantial reliance upon detailed local knowledge, and adaptation to local circumstances. Firstly, the physical particularities of the location of works required local informants. As late as 1901 Clibborn's manual, confident proponent of 'the science of the distribution of water', insisted that canal surveys rested on '[l]ocal enquiries':

> [T]he Surveyor should . . . commence by fixing a large peg at B in the position best suited for the tail of the proposed channel: then taking with him the most intelligent residents he can get hold of, and consulting his map, he should walk along the line enquiring from these men as he advances, regarding the directions in which the rain water flows, and marking at convenient intervals with ranging rods the line which he fixes on as the true watershed.[19]

Likewise the ability to ascertain knowledge of river discharges, needed to establish the necessary tolerances of canal capacity and distribution, was subject not to the limits of physical science, but the vagaries of local memory:

> The destruction caused by great floods lives in the memories of the inhabitants, while . . . an abnormally low discharge would probably not be considered of much moment . . . . [But] at cattle watering places close to

'Sir Proby Cautley (1802–1871), a Pioneer of Indian Irrigation', *History of Technology* 3 (1978), pp. 35–89. For accounts of other investigative tours of Italian canals by Ganges Canal engineers, see R. Baird Smith, *Italian Irrigation. Being a Report on the Agricultural Canals of Piedmont and Lombardy, addressed to the Honourable Court of Directors of the East India Company* (2 vols, London, 1855); C.C. Scott Moncrieff, *Irrigation in Southern Europe* (London, 1868).

[18] Lieut.-Col. J.G. Medley, *Thomason Civil Engineering College Manuals (New Series), No. X: Irrigation Works* (Roorkee, 1873), p. 82; For the Italian origins of the 'science of the distribution of water', see J. Clibborn, *Roorkee Treatise on Civil Engineering Vol. X: Irrigation in India* (3rd ed. Roorkee, 1901), p. 4; for the use of *Roorkee Treatise* at the Royal Indian Engineering College at Cooper's Hill, Surrey, where superior staff were trained, see Evidence of R.W. Egerton, *Report relating to the expediency of maintaining the Royal Indian Engineering College, and other matters. Minutes of Evidence taken before the Committee, with an analysis and index of the Evidence* (Reports of Commissioners, 1904, LXIV, Cd. 2056), Q625.

[19] Clibborn, *Irrigation Work*, pp. 4, 60.

https://doi.org/10.1017/S0026749X06002721 Published online by Cambridge University Press

villages on the banks, more or less accurate notes can often be made of the traditions regarding very low supplies, particularly when inconvenience has thereby been caused to the inhabitants.[20]

Liaison with local inhabitants became even more necessary in *managing* water distribution. This was due to a second source of contingent local knowledge, both social and natural: the uncertainty of agricultural water use. Technical difficulties in regulating the outflow of irrigation channels led to the widespread practice of distributing water according to the area irrigated off each distribution channel or sluice outlet.[21] This necessitated detailed regimes of land measurement and supervision of cultivators' irrigation practices, partly subsuming older Mughal systems of agrarian management.[22] Irrigated areas were periodically measured by *ameen*s (revenue officials), and variable agrarian needs assessed by *zilladar*s (supervisors), undertaking 'a local investigation of the soils, the contours and the circumstances of the particular case under enquiry'.[23]

Uncertain natural supply, moreover, exacerbated variable human demand. Ensuring relatively equitable supply along the entire length of distribution channels even on constant-flow perennial canals thus required a rotating schedule of *tatils* (channel closures), enforced by *chokidars* (watchmen). Indeed, the supervision this required was so detailed and frequent that by 1901 engineers were being trained

[20] *Ibid*., p. 92. Simon Schaffer has suggestively explored the incorporation of such local 'sign-reading' into other fin-de-siècle sciences (solar astronomy and anthropology): S. Schaffer, 'Laboratories Ashore', unpub. TS. I am grateful to Professor Schaffer for showing me this paper.

[21] 'Irrigation as a Protection against Famine', *Indian Famine Commission Report, Pt. III, Appendices* (Reports of Commissioners, 1881, LXXI), pp. 501–661 at 523–34; For debates about area distribution, see *Indian Famine Commission Report, Pt. III*, pp. 521–32; Cd. 1851, pp. 111–18; *Royal Commission on Agriculture in India Vol. II.i: Evidence taken in the Bombay Presidency* (Calcutta, 1927), pp. 226–33, 263–6; *Royal Commission on Agriculture in India Vol. VII: Evidence Taken in the United Provinces* (Calcutta 1927), pp. 156–7, 168; I. Stone, *Canal Irrigation in British India: Perspectives on Technological Change in a Peasant Economy (Cambridge, 1984)*, pp. 180–8. An exception to the practice of area distribution was the period of experimentation with fixed irrigation contracts and volumetric water measurement on the Eastern Jumna and Sone Canals respectively.

[22] This incorporation and transformation of Mughal and other revenue systems of course requires regional qualification. For a brief summary, see Bayly, *Empire and Information*, pp. 151–3.

[23] Clibborn, *Irrigation work*, p. 305; *Punjab Irrigation Manual Vol. I* (Calcutta, 1890), pp. 199–210. While the personnel designations given here relate to the Punjab and the North-Western Provinces, for comparable mensurative regimes beyond northern India, in Madras and Bombay, see Cd. 1851, pp. 120–1.

to co-ordinate the surveillance of both humans and hydraulics on their canal networks through telegraph stations at each depth gauge and outlet.[24] A web of telegraph lines overlaying the canal network thus reflected the informational weight of highly localised and contingent knowledge required by canal management: a far cry from the *a priori* mathematical determination of canal operation which Gilmartin argues elicited landowners' appeals to the land rights of ancestors who 'did not render service to the British Government after mathematical calculations.'[25] By contrast, as late as the 1930s the Chief Engineer of the new Lloyd Canals insisted that '[i]t is simple to arrange rotations on an arithmetical basis but it is rarely fair.'[26]

Importantly, both ascertaining natural supply and overseeing human demand implicated the social reliability of the canal establishment, always deemed questionable in isolated stations. Constant complaints were made about the dishonest measurements of *ameens* and *chokidars*. The sub-divisional engineer thus had to 'be personally acquainted . . . with the character and capabilities of all his subordinates', and should 'take every opportunity of verifying the accuracy of any irrigation measurements that may be going on in his vicinity'.[27] Such distrust even extended to departmental regulations forbidding *ameens* to use erasers: 'in case of mistakes a line to be drawn through the incorrect entry and initialled. The *khasra* [record book] is on no account to be first written in pencil and then inked over.'[28] But complaints of 'chicanery' were not simply administrative, but also engineering problems, shading into a basic distrust of the record-keeping and observation of PWD subordinates.[29]

[24] Clibborn, *Irrigation Work*, pp. 177–8. For more on the informational uncertainty paradoxically associated with Indian telegraph systems, see D.K. Lahiri Choudhury, 'Sinews of Panic and the Nerves of Empire: the Imagined State's Entanglement with Information Panic, India c. 1880–1912', *Modern Asian Studies* 38, 4 (2004), pp. 965–1002.

[25] Nawab Nisar Ali Khan Qazilbash, petition to Deputy Commissioner, Lahore, 1931, quoted in Gilmartin, 'Scientific Empire', p. 1142. For similar instances of such informational negotiation with local knowledge, see C.A. Bayly, *Empire and Information: Intelligence Gathering and Social Communication in India, 1780–1870* (Cambridge, 1996), pp. 151–65.

[26] C.S.C. Harrison, 'Hints to Engineers in Charge of Irrigation in Sind', 31 October 1931, London, British Library, OIOC, MSS Eur/F239/34, p. 8.

[27] Clibborn, *Irrigation Work*, p. 304.

[28] *Punjab Irrigation Manual Vol. I*, p. 202.

[29] Medley, *Irrigation Works*, 94.

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As one Punjab technical paper candidly suggested, both natural and human variability generated variable supply:

Gauge-readings . . . as is well known, vary from time to time for *the same discharge*, owing to changes in the channel, e.g. silt on bed, condition of bed and inner slopes, and draw-off near the head. Further, entire trust must be placed in the gauge-writers being constantly on the watch day and night to regulate the headgates as the canal rises or falls, or as the demand varies—a trust which is but seldom justified.[30]

Variable demand, meanwhile, entailed in charging by area irrigated rather than by fixed volumetric delivery, complicated the difficult assessment of the water used by a given area: the 'duty' of the canal, measured in acres per cusec. As a term borrowed from the vocabulary of steam engineering, some historians have argued that 'duty' measurements indicated engineers' scientific conception of a water 'machine . . . calculating its efficiency much in the same way as that of a steam-engine.'[31] In fact this overestimates both the assured scientific status of mechanical engineering in this period and, more significantly, the scientific precision of duty measurement itself. Certainly by the late 1860s more precise attempts to measure this quantity were being sought. The revenue department's 'rude and unscientific . . . . purely empirical management of the supply and distribution of water' was to be replaced by scientific planning for demand in advance, fixing experimentally-determined duties for different regions and crops.[32] Once again, though, both human and natural unreliability hampered scientific precision:

The actual duty for any given tract must be determined by experience, the nature of the soil, the climate, the system of cultivation, and the arrangements for distribution . . . . [T]here are other disturbing influences which may at

[30] R.G. Kennedy, *On the Distribution of Water for Irrigation by Measurement* (Punjab Irrigation Paper No. 12, 1906), p. 7 (*original emphasis*).

[31] J.S. Beresford (1875), quoted in D. Gilmartin, 'Imperial Rivers: Irrigation and British Visions of Empire', conference paper presented to 'How Empire Mattered: Imperial Structures and Globalization in the Era of British Imperialism', University of California, Berkeley, April 4 2003, http://www.ias.berkeley.edu/southasia/Gilmartin.doc, last accessed 30 May 2004. Cf. R.G. Kennedy, 'Memorandum', Cd. 1851, p. 520 for a similar description of the 'irrigation machine'. According to the Oxford English Dictionary, the etymological provenance of the word 'duty' is from James Watt's analysis of the efficiency of steam engines, describing the weight lifted through one foot per bushel of fuel.

[32] R. Strachey (Inspector General of Irrigation Works), *Report on Irrigation Works in India, May 1869* (Parliamentary Accounts and Papers, 1870, LIII) pp. 46–62, at p. 53.

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times modify the results of the best arranged systems, such as variations in rainfall, caste of cultivators ... In India the influence which race and caste has on cultivation is most marked, and the hired labourers which enriched canal farmers often employ are not nearly such economical workers as self-cultivating tenants.[33]

Thus the 'disturbing' factors of climate and caste evidently made it much more difficult to measure duty than to measure the efficiency of a steam engine, challenging the scientific status of irrigation engineering in a period when other branches of engineering were being self-consciously scientised by moving measurement and experimentation out of the workshop and into the controlled conditions of mechanical laboratories.[34] An early programme of duty experiments proposed by the Chief Engineer for Irrigation in Madras in the 1890s exemplifies these problems.[35] Although established on a controlled experimental farm, the Superintendent was to 'consult experienced ryots of the [neighbouring] village ... on all points connected with the efficient management of the water-supply to the seed-beds or growing crops', requesting local knowledge not just about local conditions but about the actual agricultural knowledge supposedly being sought through impersonal experiment:

All crops require some variation of treatment at different stages of their growth, and what is desired is to secure the utmost health and vigour .... Experienced ryots will be able to give valuable advice, therefore, as to whether the crops need more or less water at any particular time, and especially as to the proper times for draining off the water ... the depths of water to be maintained on the plots, &c.[36]

Contrary to the standards of universally-applicable scientific results, to ensure the replicability of an experiment dependent on such local knowledge, as well as on reliable empirical measurement, the Superintendent could not be changed: 'The experiments should be

[33] Medley, *Irrigation Works*, pp. 117–18.

[34] R. Fox and A. Guagnini, *Laboratories, Workshops, and Sites. Concepts and Practices of Research in Industrial Europe, 1800–1914* (Berkeley 1999); G. Gooday, 'Teaching Telegraphy and Electrotechnics in the Physics Laboratory: William Ayrton and the Creation of an Academic Space for Electrical Engineering in Britain 1873–1884', *History of Technology 13* (1991), pp. 73–111. Cf. the records of the pioneering mechanical laboratory at the PWD training college at Cooper's Hill, established in 1882: London, British Library, OIOC, IOR/L/PWD/8/80, 183, 231, 329.

[35] Lieut.-Gen. J. Mullins, *Irrigation Manual* (Madras 1890), pp. 81–91.

[36] Mullins, *Irrigation Manual*, p. 88.

repeated on the same ground for at least three seasons or years in succession and, if possible, under the same superintendent, supposing him to be in all respects trustworthy and efficient.'[37]

Of course, control of the experimental environment would be expected in any rigorous scientific experiment. The quantity of water supplied to the plots, for example, was to be precisely measured by adjustable measuring modules. Seed quantities and soil types were to be rigorously apportioned.[38] Yet this control was to include both physical *and social* conditions, bringing the requirements of experiment closer to the exigencies of canal administration itself. The success of the experiment relied heavily, Mullins insisted, upon the harmonious agrarian relations of the experimental farm. Under the heading 'Arrangements with the Owner of the Land Selected', Mullins stipulated that '[t]he terms should be liberal, so that the owner may be induced to take an interest in and assist the experiments. He should be guaranteed a full return at least from the land .... All cattle, labour, &c., made available should be paid for at the full current rates.'[39] Indeed, controlling such relations effectively involved the political process of land settlement:

> the terms arranged and agreed upon ... should be clearly laid down in writing and signed by the owner, and by the Divisional Officer .... The assistance of the Revenue Authorities should, if necessary, be obtained in the settlement of the arrangements, and the removal of any difficulties of detail which may arise.[40]

Even at their at their most self-consciously scientific, duty measurements on an experimental farm thus encountered precisely the same agrarian and human 'disturbances' as the agrarian assessments of the *zilladars*, and involved precisely the troublesome combination of local knowledge, social discretion and reliable personnel of the imprecise art of canal management itself. As with Mullins' reliable experimentalist conversant with local agrarian expertise, the *Roorkee Treatise* advised against moving canal personnel, particularly subordinate staff, between irrigation circles, moves which 'render it difficult to apply past experience or to trace and check irregularities. They deprive a good man of much of his interest in his work and of

[37] *Ibid.*, p. 88.
[38] *Ibid.*, pp. 81–3.
[39] *Ibid.*, p. 82.
[40] *Ibid.*

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his acquired local knowledge.'[41] Social reliability and local knowledge were thus personal, experiential expert characteristics: attached not to the ideal of the universal expert knowledge of European hydraulic science, but respectively to the tact and integrity of the European administrator supervising the unruly *chokidar*, and to his authentic practical experience. These qualities were required not simply to manage agrarian relations, as the ICS revenue officers argued, but in the experimental and observational skill, and the 'professional knowledge', involved in making the measurements and assessments necessary for canal engineering itself.

III. 'The Science of Distribution'

Against these local and contingent practices, however, can be discerned an alternative vision of 'scientific' canal administration, allied to a new political economy of resource management. A series of technical innovations from the late 1840s, which gained renewed discussion from the late 1850s just as more civil engineers were being introduced into the PWD, sought explicitly to minimise the social sources of both unreliable demand and unreliable supply.[42] Supply was ensured on newer perennial canals by government-built irrigation channels (*rajbuha*s) feeding off from the main canal, instead of the pipes and cuts inserted into the canal channel by riparian cultivators. *Rajbuha* systems promised to replace distribution through privately-constructed village watercourses, a 'most objectionable method . . . . [owing] as little to science as possible', with standardised masonry-lined channels of known water discharge, built by PWD engineers.[43] These were first instituted on the Eastern Jumna and other North-West Province canals, and enshrined in the 1873 Canal Act, which insisted upon government construction and management of any distribution channel longer than a mile.[44]

[41] Medley, *Irrigation Works*, pp. 95–6.

[42] For discussions of rajbuhas, modules and associated systems of water charging and distribution management, see *Indian Famine Commission Report, Pt. III, Appendices*, pp. 515–32; Cd. 1851, pp. 111–18.

[43] Cautley, *Ganges Canal Works Vol. I*, 426–7.

[44] See C.C. Anderson, Note by Officiating Chief Engineer, Irrigation Works, NWP, 21 December 1878 No. 1285W, in *Indian Famine Commission Report, Pt. III, Appendices*, pp. 523–34; Stone, *Canal Irrigation,* pp. 195–8.

In part, of course, government control aimed simply to correct the perceived lack of constructional expertise on the part of cultivators who had previously built their own outlets and watercourses with varying slope, causing stagnation or excessive wear; with long, often duplicated, and porous private water-courses which increased water loss; and with differing capacities.[45] But it also enabled, in theory, a more equitable system of managing distribution. With known discharges on the various channels, equity could be ensured by preventing excessive take-up of water near the head of canals, 'without the slightest reference to the equal claims of villages situated lower down.'[46] Instead of numerous perpendicular cuts from the main water-course, a closed network of distributaries helped to equalise supply in lower parts of the network, 'the surplus water, which reaches the tail of each line, [being] thrown into that next below it, and so brought into use.'[47]

In a metaphor repeated in engineering manuals and public enquiries throughout this period, Cautley and others suggestively likened this closed system to the new municipal water systems expected to spread across urban Britain as the Ganges Canal was being constructed: 'the canal ... answering to the Reservoir or supply channel in the water-supply of towns; the rajbuhas or distributaries as the Mains, and the village water-courses as the Service channels'.[48] These municipal systems, as Christopher Hamlin has argued, were emblematic of the benign despotism of 'sanitary rationality', promising equitable freedom from dearth, disease and the 'bumbledom' of local authority disputes by replacing the political and economic choices of local municipalities with the dictates of modern scientific engineering.[49] The canal engineer's control of distribution, hard-wired into the

[45] W.E. Morton, *Professional Papers printed at the Civil Engineering College Roorkee No. II: On Rajbuhas* (Roorkee, 2nd edn. 1883), pp. 39–41. Morton was Superintendent Engineer on the Eastern Jumna Canal (EJC). His reference booklet was drawn up initially in 1853 to assist the engineers of the Ganges Canal, based upon the experience gained on the EJC. Morton, *Rajbuhas*, p. i.

[46] Morton, *Rajbuhas*, p. 43.

[47] *Ibid*., p. 44.

[48] A.T. Arundel, 'Irrigation and Communal Labour in the Madras Presidency', *Indian Famine Commission Report, Pt. III, Appendices*, pp. 572–9, at p. 572. Cautley used this analogy first: Cautley, *Ganges Canal Works Vol. I, p.* 423; repeated in Medley, *Irrigation Works*, p. 81.

[49] C. Hamlin, *Public Health and Social Justice: Britain, 1800–1854* (Cambridge, 1998), p. 302; Hamlin, 'Muddling in Bumbledom: on the enormity of large sanitary improvements in four British towns, 1855–1885', *Victorian Studies* 32, 1 (1988), pp. 55–85.

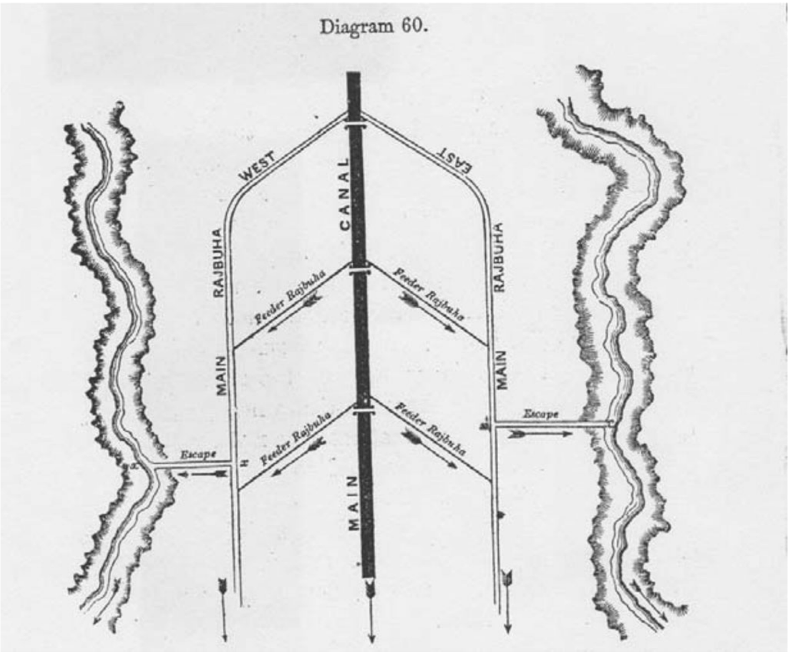

Fig. 1: Rajbuha schematic (Source: Cautley, *Report on the Ganges Canal Works Vol. I*, p. 434)

design of *rajbuha*s, promised similar freedoms from famine, quarrelling *zamindars*, and malaria.[50]

Several historians, including Gilmartin and Ian Stone, have correspondingly portrayed this period of canal building as one of heightened technological interventionism by the Raj.[51] There was certainly a substantial body of support both for government control of distribution channels and for their management by professional engineers. The irrigation lobbyist Sir Richard Strachey called for 'the substitution of a properly qualified special professional management of irrigation works, for the system of *laissez faire* . . . which, in my judgement, does not deserve the name of management at all'.[52] This combination of engineering and political economic preference was echoed as late as the 1920s by engineers who defended their expertise over the new Agricultural Department by evoking the utilitarian

[50] For rajbuhas' effects on famine, zamindars and malaria, see Morton, *Rajbuhas*, pp. 40–51.

[51] Stone, *Canal Irrigation*, pp. 204–18; Gilmartin, 'Imperial Rivers', passim.

[52] Strachey, *Report on Irrigation Works in India*, p. 57.

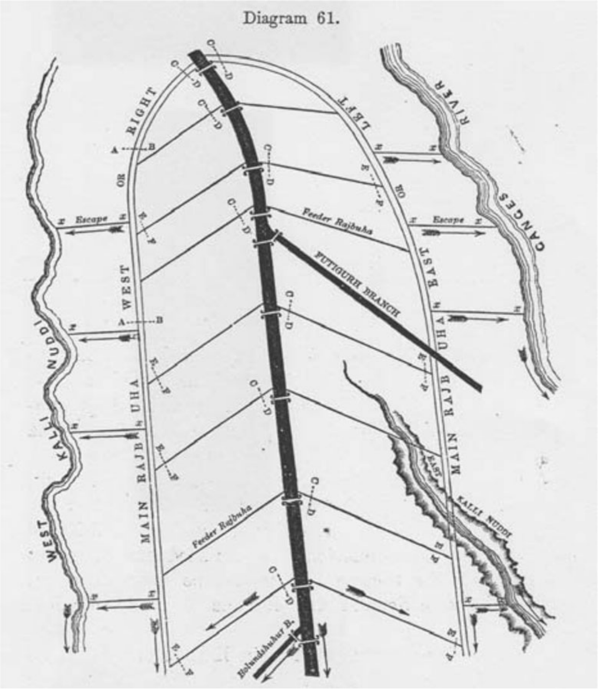

Fig. 2: Layout of rajbuhas on a section of the Ganges Canal (Source: Cautley, *Report on the Ganges Canal Works Vol. I,* p. 442)

values built into '[i]rrigation practice [which] should be based entirely on the greatest good of the greatest number, not on the greatest good of the individual cultivator. The Agricultural Department has very naturally viewed agriculture from the standpoint of the individual.'[53]

Importantly, though, Stone and Gilmartin overlook the fact that the dirigiste paternalism of the 'science of distribution' actually claimed to reduce 'all necessary interference . . . with the domestic details of the village' by minimising unreliable human involvement.[54] Its advocates thus sought to assuage provincial governments which had felt it 'desirable . . . to fix some limit beyond which State interference should not extend': set legally in Madras in 1873, for instance, at the point at which water left the regulation sluice.[55] By substituting a branching

[53] 'Evidence of Mr. C.C. Inglis, Executive Engineer, Special Irrigation Division, Bombay', *Royal Commission on Agriculture in India, Vol. II.i,* pp. 226–33, at p. 226.

[54] Cd. 1851, p. 111.

[55] 'Report of the Committee Appointed under the Famine Commission to enquire into the Management of Irrigation Works in Madras, Orissa, and Midnapur; together

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network of diminishing channels for the mass of cuts off the main canal, the very geometry of the rajbuhas reduced the number of nodes at which the supply had to be controlled, the necessary establishment being thus 'reduced to one-tenth or one-fifteenth of what it would be'.[56] This would reduce not only human labour, but also the possibility of fraud by the 'native' canal establishment:

> Canal Chokidars too, who would not hesitate to receive a bribe and permit a single water-course to run in disobedience of orders, are seldom hardy enough to keep a Rajbuha head open on a Tateel day. When so much water has to be stolen and so many receivers are implicated, it is not easy to avoid detection.[57]

In many cases distributary planning and remodelling aimed to remove the necessity of a *tatil* at all. Discharges to each part of the canal system would be known, and the self-recharging produced by the interlinked network of channels would reduce the problem of declining discharge along the length of the canal, allowing the uninterrupted, continuous delivery of water in the canal system.[58] The main canal would still 'require the constant interference of regulating establishment, but the ideal distributary should automatically control its supply once the head sluice has been opened and adjusted.'[59] Thus the perfectly constructed irrigation machine would operate largely without interference, like a self-scouring municipal water system, simply by regulating the appropriate influx of water at the headworks. Both local knowledge and unreliable surveillance would thus be minimised. As Clibborn's 1901 textbook proudly announced, 'the local investigation will [soon] be a thing of the past .... [reducing the] great personal influence in the district, which can only be secured by even the best men after long residence'.[60]

Dirigiste technological perfection was thus allied to economic *laissez-faire*. Proponents of this transparent scientific management argued that it would allow the market transparency of un-interfered volumetric supply, rather than the complex and discreet negotiations

with a Supplement on the Irrigation System of the Soane Canals, Behar', *Indian Famine Commission Report, Pt. III, Appendices,* pp. 615–61, at p. 618.

[56] Morton, *Rajbuhas,* p. 44.

[57] *Ibid*.

[58] Strachey, *Report on Irrigation Works in India,* p. 57.

[59] Clibborn, *Irrigation Work,* p. 172.

[60] *ibid.*, p. 306.

of area measurement.[61] Fixed outlets would permit long-term contracts between the Canal Department and the cultivator rather than yearly land surveys, and a resultant economy of water and improvement of cultivation was anticipated by harnessing the cultivator's individual self-interest in frugality, given a fixed supply.[62] The interference of the canal officer, his agricultural supervision and planned distributary closures managing the interests of the population over the interest and enterprise of the individual, would be replaced by a constantly flowing irrigation machine 'in which the interests of the cultivator are identical with those of Government, in the economical distribution of the water'.[63]

Well into the 1900s, engineering manuals also continued to preach an ideal engineering political economy in which profligate water use, even if fiscally remunerative, was condemned in favour of water economy, and an engineered equity nonetheless described in terms of market virtues, 'the fairest method of charging payment for water . . . sell[ing] it as one would sell any other article; that is, according to the quantity'.[64] Correspondingly, alongside rueful exhortations about the management of subordinate personnel, and the importance of liaising with local inhabitants' knowledge, they portrayed an ideal economy of expertise in which an irrigation machine designed by expert European science would replace human interference and local knowledge. Clibborn's 1901 *Roorkee Treatise* summarised this vision:

> Recently when discussing with an experienced Deputy Magistrate the improvements in the irrigation system introduced and contemplated of late, this official . . . remarked that the abolition of tatil and remodelling when properly carried out, had already extinguished the patrol as far as his ancient functions were concerned, and that he feared there would be no good reason for keeping on Deputies in the future. I consider this naïve expression of opinion the greatest praise that could be given in the way of efficient working.[65]

[61] The question of area vs. volumetric charging has a much larger history, which I do not cover fully here. See Strachey, *Report on Irrigation Works in India,* pp. 58–62; *Indian Famine Commission Report, Pt. III, Appendices*, pp. 515–52; Cd. 1851, pp. 111–18; *Report of the Royal Commission on Agriculture in India, Vol. II.i*, pp. 230–2, 241–4, 263–6; and *Vol. VII*, p. 141.

[62] 'Contract Irrigation in the NWP', *Indian Famine Commission Report, Pt. III, Appendices*, p. 529.

[63] *Ibid*., p. 524.

[64] Medley, *Irrigation Work*, p. 89.

[65] Clibborn, *Irrigation Work*, 310–11.

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Yet despite these confident ideals, during the 1860s and 1870s experiments with volumetric measurement and contract irrigation failed in most places. Engineers cited the unwillingness of cultivators to be tied to a fixed volume, and their suspicion of the PWD's measurements. In addition, although opposition was not explicitly stated on these grounds, the halving of canal revenue on contract land, clearly resulting not simply from the 18% discount on contract irrigation but also from greater economy of water use, suggested that the unity of interest between government and cultivator on a marketised irrigation machine was far from perfect.[66] By 1881 even the *rajbuha* apostles Baird Smith and Morton had, albeit reluctantly, abandoned volumetric delivery and contract irrigation on the EJC, returning to the detailed routines of local supervision, area measurement and agrarian inquiry.[67]

IV. The Personal Equation

It is easy to ascribe the failure of the human-free irrigation machine and its science of distribution to the resistance of Indian cultivators and Government revenue officers. In fact, however, much was due to the inability of hydraulic science itself to ascertain canal discharge, the key quantity of the irrigation machine. This inadequacy would ultimately invoke precisely the same social and racial hierarchies of expertise and reliability as were entailed in the imprecise and instinctive agrarian knowledge of duty measurements and area-based distribution.

Volumetric supply required above all a known and reasonably constant discharge along each channel. In theory, if the depth of the water was known, discharge could be calculated *a priori* using an equation combining the slope and dimensions of the channel. This basic discharge equation would ostensibly allow irrigation engineers to design or remodel channels to supply water at known rates.[68] While

66 'Contract Irrigation in the NWP', pp. 523–4; On the EJC in 1866–8, returns on the 24% of irrigated land managed by contracts fell from Rs. 2–8-4 per acre to Rs. 1–4-2 per acre: 'Chief Engineer's Review of Revenue Report of the Eastern Jumna Canal, 1866–7, No. 621 of 1868', *Indian Famine Commission Report, Pt. III, Appendices,* p. 530.

67 'Contract Irrigation in the NWP', p. 524.

68 The basic equation took the form $V = c\sqrt{mi}$: V denotes velocity, m the hydraulic mean depth (a function of the channel's dimensions and water depth), i is the canal's slope, and c is a coefficient. For presentations of this equation in various forms, see

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this predictivity did not solve the physical problem of variable supply from rainfall draining into the main canal, nonetheless even with variable supply, discharges into the distributaries should be calculable simply by reading the water's depth off a fixed gauge, and in any case the available water distributed equitably according to prior design.

Gilmartin argues that such mathematical certainty provided hydraulics with its late-nineteenth-century claims to scientific status, and geographically universal application. As the textbook used to train PWD superior staff after 1901 stated, hydraulics was 'the "practical application of the most important principles of natural philosophy"'.[69] Mathematised universal hydraulic principles allowed not only scientific precision, but also the production of tabulated data of coefficients and discharges, calculated from basic formulae, which could be used anywhere.[70] But not all hydraulicians shared this scientistic self-assurance. The standard British textbook, written by the Royal Indian Engineering College's longest-serving Professor of Hydraulics, W.C. Unwin, insisted cautiously that mathematical incertitude deprived it, as yet, of truly scientific status. The practical problems of hydraulics have 'recourse to comparatively simple mechanical principles and simplified assumptions which furnish rough formulae ... modified by empirical constants so as to be true to the necessary approximation over any required range of conditions.'[71] Thus against his more self-confident colleagues, Unwin argued that

> In the strict sense hydraulics is not a science. It is embarrassed by tangles of formulae, which, initially based on imperfect reasoning, have been modified

Medley, *Irrigation Works*, pp. 31–3; Clibborn, *Irrigation Work*, p. 92; Sergeant B.O. Reynolds, *College of Engineering Manual: Irrigation Works* (Madras 1896), p. 14; J.D. Stoddard, *Rules and Formulae for the Computation and Solution of the Various Hydraulic Problems, &c. required in the Irrigation Department* (Madras 1855), p. 7; C.W. Odling, 'Memorandum on the Different Methods of ascertaining the discharges of rivers, canals and open channels' (1897), London, British Library, OIOC, IOR/V/27/730/2, p. 1; Mullins, *Irrigation Manual*, p. 40; W.C. Unwin, 'Hydrodynamics', *Encyclopaedia Britannica Vol. XII* (9th ed., Edinburgh 1881), pp. 435–535, at pp. 492–3; Unwin, *A Treatise on Hydraulics* (London, 1907), p. 265.

[69] Thomas Tredgold, quoted in J.H.T. Tudsbery and A.W. Brightmore, *The Principles of Waterworks Engineering* (2nd ed. London, 1897), p. i. For the use of this textbook after 1901, co-authored by Cooper's Hill's second Professor of Hydraulics, compare the 1895–6 and 1901–2 editions of the *Calendar of the Royal Indian Engineering College* (London, 1873–1906), p. 49 (1895–6) and pp. 107–8 (1901–2).

[70] Stoddard, *Rules and Formulae*.

[71] Unwin, *Hydraulics*, p. v. This work was an update of Unwin's 1881 Encyclopaedia Britannica article.

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and adjusted to conform more or less accurately to the results of experiments, themselves affected to some extent by observational errors.[72]

This mathematical embarrassment was nowhere more acute than in discharge formulae, 'obviously based on an imperfect hypothesis', Unwin argued. Their coefficients, it gradually emerged over the course of the nineteenth century, varied recursively with the nature of the channel and its physical dimensions themselves.[73] Despite a series of large-scale experiments to refine them, standardised coefficients produced incorrect results in most cases. As became evident early on, when Sir Proby Cautley applied Du Buat's standard coefficients to the pioneering design of the Ganges Canal, resulting in several major structural failures, standardised discharge tables were rarely sufficiently precise even for calculating broad design tolerances, let alone for the precision needed to sell water volumetrically from small channels.[74]

In short, the precise water discharges necessary for local adjustment and volumetric supply could not be calculated using the resources of a hydraulic science providing universally applicable principles and equations. Instead, continual local observation by the PWD establishment was required, the discharges for different depths of water at different places in the canal system being measured empirically at discharge sites built into the canal network, and updated regularly as the roughness of the stream bed altered to update the calculated discharges corresponding to different readings on the depth gauges.[75] As late as 1931, despite the sophistication of discharge formulae having advanced substantially, engineers on the Lloyd Canals were still instructed to take bi-weekly discharge measurements on main branches, and weekly on other branches.[76] The un-interfered canal machine, therefore, continued to require the sort of detailed regime of local observation that had been condemned by more scientistic engineers for entailing the unaccountable experiential knowledge and uncertain social reliability of 'men-on-the-spot'.

[72] *Ibid*., p. 37.

[73] Unwin, 'Hydrodynamics', p. 492.

[74] For the Cautley/Ganges Canal controversy, see Brown, 'Sir Proby Cautley', pp. 77–89.

[75] Kennedy, *Distribution of Water*, p. 7.

[76] Harrison, 'Hints to Engineers', London, British Library, OIOC, MSS Eur/F239/34, pp. 9–10.

As with duty experiments, these problems were invoked even where canal administration ostensibly gave way to theoretical science. In 1874 a large series of discharge experiments begun on the giant Solani Aqueduct of the Ganges Canal by Captain Allan Cunningham, Professor of Mathematics at the Roorkee PWD college, sought to fit the colonial knowledge generated by India's unruly canals to a global standard. Using the regularised hydrodynamic conditions of what was then the largest artificial channel in the world, Cunningham hoped both to contribute to the global experimental programme, stretching from Mississippi to Paraguay, to determine discharge coefficients 'whose numerical values, have as yet been determined solely . . . in pipes and in small artificial channels'; and also to determine a refined 'System of Cubic Discharge-Measurement . . . for practical adoption [by the PWD]'.[77] Dismissing mechanical current meters as unreliable and difficult to calibrate, his method used rod floats whose transits, along a measured length of waterway demarcated with transverse ropes, were timed by observers with chronometers.[78] Such float-transit observations were a long-used, primitive technique.[79] But Cunningham sought new precision by dividing the labour of observation and timing:

> One observer sat with a chronometer in front of him midway between the two ropes: the second observer standing opposite the upper rope, warned the "time-keeper" of the approach of the float, and then shouted just as it passed under the upper rope; he then walked down to the lower rope, and standing opposite, shouted again just as the float passed under the lower rope. The time-keeper entered the number of chronometer-beats counted just as he caught each "shout" *to the nearest half-second*.[80]

By retaining the same observer for both observations, then swapping the observer and timekeeper, '[t]his is considered to

[77] A. Cunningham, *Hydraulic Experiments at Roorkee 1874–5* (Roorkee, 1875), p. 3; Cunningham, *Roorkee Hydraulic Experiments* (Roorkee, 1881), p. 348. See also the review of these experiments in *Engineering* 20 (1875), 31 Dec. 1875, pp. 517–18; and *Engineering* 21 (1876), 7 Jan 1876, pp. 10–11. Major programmes of discharge coefficient experiments were carried out by the Ponts et Chaussées engineers Darcy and Bazin on small French canals, 1855–1866; by Humphrey and Abbot of the US Corps of Engineers on the Mississippi 1850–61; by Cunningham; on the Irrawaddy River in Burma, 1872–73; and by a French team on the Parana River in Paraguay in the 1860s: see Unwin, 'Hydrodynamics', p. 438.

[78] Cunningham, *Hydraulic Experiments 1881*, pp. 348–50, 357.

[79] Unwin, *Hydraulics,* pp. 268–9.

[80] Cunningham, *Hydraulic Experiments 1874–5*, p. 20 (*original emphasis*).

reduce the effect of "personal equations" of the observers to a minimum.'[81]

The main object of Cunningham's concerns with precision measurement, then, was not the variability of the float's path, nor the conditions of wind, waves and so on, all of which surely had a far greater impact on accurate measurement than the imprecision of a visual observation, yet were recorded relatively haphazardly. Rather it was the observational reliability of the float observers themselves. Each was

> carefully trained for about a fortnight in the system of "eye-and-ear observing" just explained, and his trial-timings were repeatedly compared with those of the existing trained Staff. No new Observer was passed as a "trained Observer" until the *maximum* Discrepancy between the timings of many successive Floats done by himself and by one of the trained Staff was not more than one chronometer-beat (or half-second).[82]

Cunningham's method and vocabulary indicates that his concern with human observational error, and its solution, derived from the well-publicised problem of personal error in transit astronomy, whose analogous "eye-and-ear" method for timing the transit of stars (rather than floats) across a transversely-divided astronomical meridian (rather than a canal) was the *locus classicus* of observational discipline and psychometric measurement of the "personal equation" in the nineteenth century.[83] By coincidence, as Cunningham was commencing his experiments in 1874, Roorkee was playing host to a team from the global centre of 'personal equation' management, the Royal Observatory at Greenwich, to observe the rare transit of Venus from India.[84] Thus of several methods trialled, this 'was finally adopted (after taking advice of one of the Staff of the Transit of Venus Expedition)'.[85]

Observational skill, for both Greenwich's and Roorkee's observers, was highly personal, experiential expertise. Each recorded observation was initialled to make it attributable to observers with varying

[81] *Ibid*., p. 20.
[82] Cunningham, *Hydraulic Experiments 1881*, p. 60 (*original emphasis*).
[83] S. Schaffer, 'Astronomers Mark Time: Discipline and the Personal Equation', *Science in Context* 2, 1 (1988), pp. 115–45; R. Benschop and R. Draaisma, 'In pursuit of precision: the calibration of minds and machines in late 19th-century psychology', *Annals of Science* 57,1 (2000), pp. 1–25.
[84] J.F. Tennant, *Report on the preparations for, and observations of, the transit of Venus, as seen at Roorkee and Lahore on December 8, 1874* (Calcutta, 1877).
[85] Cunningham, *Hydraulic Experiments 1874–5*, p. 20.

'personal equations', which one trustworthy Royal Engineer was able to reduce to a quarter-second.[86] Just as Medley had recommended a fixed canal establishment in order to retain the local knowledge embodied in experienced canal officers, changes in Cunningham's habituated personnel were minimised to retain their observational skill, and so as not to disrupt the personal link between fixed pairs of observers.[87] Cunningham further made it clear that the accuracy of his observations depended upon the social, moral and racial pedigree of his observers. Certainly he wanted men with 'a practical knowledge of surveying', an operation for which other engineers felt 'the native mind is well adapted'.[88] Yet for such ostensibly routine work Cunningham required not simply the practical 'fresh clever lads from the country' promised by the Indian engineering colleges to fill the subordinate ranks of the PWD: the 'steady and regular' Indian engineers who, Roorkee's former principal insisted, although 'weak in taste and judgement . . . can carry out instructions with success'.[89] Instead,

> [t]he whole of the *responsible* observations of every sort—whether sounding, measuring distances, calling out instant of passage of floats, use of chronometers, &c.—and also the computation attending the reduction of the observations were (with the exception of a few done by the Author himself) performed by *the two Europeans*, trained in the first instance by the Author.'[90]

As the experiments progressed Cunningham used only European Overseers or ex-Overseers of the PWD; even 'men out of [PWD] employ proved . . . very unsatisfactory'.[91]

Cunningham's 'improved' method was repeated in PWD textbooks and manuals for at least the following fifty years, usually with similar

[86] *Ibid*., p. 20.

[87] Cunningham, *Hydraulic Experiments 1881,* pp. 19–21.

[88] Cunningham, *Hydraulic Experiments 1881*, p. 21; for native suitability for surveying, see *Selections from the Records of the Government, North West Provinces: Mr. Thomason's Despatches Vol. I* (2 vols., Calcutta, 1856), p. 385; cf. Raj, 'When human travellers become instruments'.

[89] Evidence of Maj. Gen. R. MacLagan, *Collection of Papers Relating to the Reservation of Engineer Appointments in India to pure Natives* (Calcutta, 1887), p. 43; Lt. George Winscom (Principal of Madras Engineering College) quoted in S. Ambirajan, 'Science and Technology Education in South India' in D. Kumar and R. MacLeod (eds), *Technology and the Raj* (New Delhi, 1995), pp. 112–36, at p. 121.

[90] Cunningham, *Hydraulic Experiments 1874–5*, p. 6 (*original emphasis*).

[91] Cunningham, *Hydraulic Experiments 1881*, p. 21.

strictures about the personal equation.[92] Although not as socially or racially limited as Cunningham's requirements, by 1931 canal engineers in Sind still measured discharges 'with velocity rods and stop watches', which were not to be taken 'by anyone of lower rank than Overseer and should be checked frequently by the Sub-Divisional Officer and Executive Engineer.'[93]

Proponents of non-interference and mechanistic reliability continued to hold out hopes that technology would overcome the inadequacy of hydraulic theory. Proposals were made throughout this period to replace the tedious regime of discharge measurements with mechanical modules that would automatically measure and control the water passing through irrigation outlets, regardless of the channel's discharge, thereby securing human-free volumetric distribution.[94] Such technological solutions explicitly targeted the familiar combination of social and scientific unreliability. The module designed around 1900 by R.G. Kennedy, for example, promised to replace both the moral unreliability of the subordinate establishment who read depth gauges, and the empirical uncertainty of human discharge measurements. While a guaranteed fixed discharge would supersede the 'entire trust [which] must be placed in the gauge-writers . . . seldom justified', a built-in pressure gauge would provide 'an exact index of the discharge passing', improving upon the measurements of the 'sub-divisional officer [who] is supposed . . . to keep continually checking the discharges of all his channels . . . too often based on obsolete discharge tables'.[95] Tellingly, Kennedy's promotional pamphlet describes managerial and observational skill with the same familiar phrase. The requisite supervision of "native" subordinates to prevent corruption depends upon the executive engineer's administrative assiduousness, 'the *personal equation* of the official in charge . . . . when he leaves, after putting things more or less straight, as likely as not they will lapse into their former condition,

[92] Unwin, 'Hydrodynamics' (1881), p. 505; Mullins, *Irrigation Manual* (1890), p. 12; Odling, 'Memorandum' (1897), pp. 7–8; Unwin, *Hydraulics* (1907), pp. 268–9; Harrison, 'Hints to Engineers' (1931), London, British Library, OIOC, MSS Eur/F239/34, p. 9.

[93] Harrison, 'Hints in Engineers', London, British Library, OIOC, MSS Eur/F239/34, p. 9.

[94] The technological history of Indian irrigation modules is a complex one, not dealt with fully here. See Baird Smith, *Italian Irrigation Vol. I*, pp. 47–54, 202–10; Cautley, *Ganges Canal Vol. I*, pp. 99–104; Kennedy, *On the Distribution of Water*.

[95] Kennedy, *On the Distribution of Water*, p. 7.

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his successor not taking any interest in this class of work'. Further on, it quantitatively compares the mensurative accuracy of 'the gate-module . . . found to be about +/- 2 per cent', with the 'mere discharge observations in a distributary [which] vary a great deal in their results . . . due to the *personal equation* of the observer, a very variable and undefined quantity . . . not likely less than 3 per cent'.[96]

Modules to measure and regulate discharge were generally thwarted in this period by the technical obstacles of silting, excessively varying supply and, it appears, the suspicions of cultivators that they were being short-changed.[97] Yet despite the introduction of more accurate and inexpensive current meters which were accepted by most hydraulicians, including Unwin; and despite the absurdity of attempting to reduce the human factor of observational error in a method involving a wandering float which might even be timed, Cunningham advised, with a make-shift pendulum using a bullet and string; Cunningham's rod-eye-ear method persisted. This is remarkable testimony to the continued premium placed on the social and racial charisma of experienced, trustworthy individuals to make the distribution of water both quantifiable and accountable.[98]

Moral, mensurative and economic reliability were inseparable on government canals throughout this period. They were not simply the qualities of the 'civilian' administrator, but constituted the professional practice of engineering itself, in ascertaining drainage lines, duties, water charges and discharges. Certainly two identities of Indian engineering ran through the manuals and reports of the PWD, each with its own economy of expertise, and arguably its own political economy: one envisaging a responsive and continually adjusted agrarian system in which local knowledge was gathered by the interference and surveillance of a practically experienced canal establishment; the other an impersonal, constantly flowing irrigation machine whose scientific design and management would obviate the need for interference, and underpin not only utilitarian equity but market transparency.[99] In practice, however, the operation of even

[96] *Ibid*., pp. 6, 30 (*my emphasis*).

[97] *Indian Famine Commission Report, Pt. III, Appendices*, pp. 523–24; Cd. 1851, pp. 111–18.

[98] Cunningham, *Hydraulic Experiments 1881*, p. 350.

[99] Simon Schaffer has suggested that these be characterized as 'georgic' and 'hydraulic' styles of engineering [S. Schaffer, personal communication, 11 May 2004]. For a comparable but less empirically-grounded late 20th-century typology of 'anthropocentric' and 'technocentric' engineering, see P. Brödner, 'The Two cultures

the most "scientifically" designed and managed canals continued to involve interference, adjustment, and the local knowledge and social reliability this entailed. Although by the 1930s canal engineers might not deign to wander across flood plains accompanied by village elders pointing out drainage lines and recalling notable monsoons, observations were still checked with personal initials on *khasras* and discharge sheets alike; and the 'personal equation' still mattered in both supervising subordinate *chokidar*s and observing velocity floats.

Ultimately it was precisely because the mathematical formulae of hydraulic engineering could *not* be transferred smoothly from 'California to the Indus Basin' that the racial and social prejudices of European engineers and administrators could continue to inhere in ideals of engineering competence.[100] The equations of an ostensibly mathematicised, predictive science thus need to be read as pieces of social technology: each algebraic quantity in fact requiring an individual to negotiate and measure India's agrarian landscape, thereby bringing the variability of social, racial and environmental relations to bear problematically on the abstraction and universalism of 'the science of distribution'. Both engineers and administrators could thus continue to argue that 'scientific' canal management did not involve universally applicable and acquirable theory, but the local "instinct" of the experienced irrigation engineer combined with the reliability and "character" deemed unique to European superior staff.

The theoretical uncertainty of hydraulic science also challenged the Raj's alliance of predictive European science, and political economic ideals that ambiguously combined both laissez-faire provision for resource use, and the state's equitable apportioning of water resources. Rajbuhas and irrigation modules were machines for markets, allowing known discharges of water to be delivered according to volumetric contracts; yet their supply was designed to be rigid, equal, equitable, and wholly unresponsive to dynamically varying demand and duty. The interventionist engineering that emerged in practice was both less perfectly equitable; and more responsive, in theory at least, to changing environmental and agrarian circumstances.

in Engineering', in B. Göranzon (ed.), *Skill, Technology and Enlightenment: On Practical Philosophy* (London 1995), pp. 249–60.

[100] Gilmartin, 'Scientific Empire', p. 1136.

https://doi.org/10.1017/S0026749X06002721 Published online by Cambridge University Press

The balance sheet of the successes and failures of colonial India's canals has yet to be settled.[101] Comparable debates, meanwhile, continue about the transformative political economy and exuberant scientific rationalism of independent India's giant hydraulic development projects, whose damaging proliferation shows no sign of abating. The contested results of colonial India's hydraulic transformations thus inform current political controversies.[102] If they are to enlist the colonial record in this way, participants in these debates will need to recognise the limits and compromises of imperial economic visions: limits generated not by the theoretical hubris of European knowledge, but by its uncertainties and weakness in colonial practice.

[101] For two broad surveys, the first highly pessimistic and the second more sanguine, see E. Whitcombe, *Agrarian Conditions in Northern India, Volume I: The United Provinces Under British Rule, 1860–1900* (Berkeley 1971); Stone, *Canal Irrigation*.

[102] See, for example, the colonial legacy invoked by opponents of the Narmada Valley development projects: 'The independent Indian state has to a large extent adopted the bureaucratic and extortionist habits of the British. Local systems continue to be neglected; huge reservoirs are built while feeder canals are left unfinished; top-down management is inflexible and impenetrable by the concerns of either those displaced or those excluded from water': Gail Omvelt, 'Harnessing Water', *The Hindu,* 19 September 1999, http://www.narmada.org/archive/hindu/files/hindu.19990919.13190614.htm [last accessed 4 February 2005].