“All is Water”: Technological Complementarities and Path Dependence in Indian Agriculture

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Abstract

What are the myriad ways in which history impacts economic development? I examine this question in the context of structural transformation in Indian agriculture which dramatically improved food production but has led to an environmental crisis. I find that districts with colonial investments in irrigation i.e. a canal built before 1931 were associated with successful adoption of ‘Green Revolution’ practices between 1955-1985. Additionally, districts where canals were proposed in 1857 but never built continue to have worse agricultural outcomes more than a century later, despite having similar land suitability. Finally, I show that places that adopted modern practices are, paradoxically, facing depleting groundwater today. The findings suggest that control over water is an important mechanism through which history has persisting effects.

Keywords: Agricultural development, Canal irrigation, Colonial legacies, Green revolution, Multiple equilibria, India **JEL codes:** Q25, Q32, Q56, Q18

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1 Introduction

"History matters" for economic growth, and it could play a role via geography: disease (Gallup and Sachs, 2001; Diamond, 1999), crop endowments (Engerman and Sokoloff, 1997; Nunn and Qian, 2011), terrain (Nunn and Puga, 2012); or culture (Alesina and Giuliano, 2015); or genetics (Ashraf and Galor, 2013), or institutions: legal system (Porta et al., 2007), property rights (Acemoglu et al., 2002), land tenure system (Banerjee and Iyer, 2005), labor coercion (Dell, 2010), medieval trade (Jha, 2013) etc. But what are the mechanisms through which history can have persisting effects? Figure 1 illustrates that there is a strong spatial association between irrigation and economic development. In this paper, we examine long run agricultural development in one specific country (India) and ask whether colonial investments in surface irrigation were critical in kick-starting the 'Green Revolution'.

India is an excellent site to conduct this inquiry because: (a) the diversity of the country in terms of geography and institutions allow us to study the role of water infrastructure which hasn't received sufficient attention in the literature; (b) as a largely agricultural dependent country, it has been at the forefront of adoption of modern seed varieties that spurred structural transformation of the economy within only a couple of decades of gaining independence, thus allowing us to study the long run effects of colonial investments in canal irrigation; and (c) the availability of rich sub-national panel data and archives allow us to better understand the fundamental causes of agricultural development, and compare and contrast them against other explanations.

Using district-level data on agricultural outcomes between 1955 and 1987 we find that districts that had a canal in 1931 are associated with better adoption of modern agricultural technology and higher crop yields. The effect exists on both the extensive and intensive margin (measured by area equipped under irrigation in 1920). The results are robust to controlling for existing theories that previous scholars have found to be relevant such as land tenure (Banerjee and Iyer, 2005; Iversen et al., 2013) and agro-ecological factors (Palmer-Jones and Sen, 2003). Results also indicate that the same districts today are under severe ecological stress, and the rate at which groundwater is depleting is faster in these areas with colonial investments in canal irrigation. The findings suggest that control over water is an important channel through which history has persisting effects.

This paper makes three contributions. First, it adds to the small but burgeoning literature exploring the role of water in the long run (Alsan and Goldin, 2019; Bleakley and Lin, 2012). Current evidence is mixed: Haber (2012) argues that rainfall is conducive to democracy but in an empirical test of Wittfogel's "Hydraulic empire" hypothesis, Bentzen et al. (2012) note that, "Irrigated agriculture makes societies more likely to be ruled by an authoritarian elite". In a similar vein, Chaney (2013) shows that "Nile-induced economic crises" appear to have increased the political influence of the incumbent religious authority in Egypt. Second, the paper contributes to the literature on economic impacts of colonialism, which has focused, inter alia, on either public investments (Huillery, 2009) or transportation infrastructure such as railways (Jedwab et al., 2017; Donaldson, 2018) but has neglected the role played by irrigation networks. A notable exception is Chanda and Le (2019) who examine the long run effects of navigable waterways in Vietnam. Third, by describing the complementarities between surface and groundwater irrigation, the paper provides novel evidence on how history sets up countries on path dependence and multiple equilibria (Nunn, 2009). The impressive gains of the Green revolution in terms of improving food grain production was unfortunately achieved at the cost of exacerbating the regional divide and deepening environmental crisis. Thus, India moved from one low-level equilibrium to another, and the same places that adopted improved agricultural practices are, today, paradoxically, facing depleting water tables.

The remainder of the paper is organized as follows: Section 2 provides the historical background on Green revolution in India and describes the data that is used in the analysis. In Section 3 we discuss the empirical strategy that is used to establish the relationship between canal irrigation and agricultural outcomes. Section 4 presents the results and robustness checks. Finally, Section 5 concludes by addressing the scope conditions and discussing policy implications of this study for present day challenges.

2 Context and data

In a seminal paper, Banerjee and Iyer (2005) argued that agricultural development crucially hinges on the security of property rights and that places where this right was historically assigned directly to cultivators were in much better shape to exploit gains from technological progress. On the other hand, in areas where the land tenure system was given to the elite when an opportunity for change presented itself the non-inclusive political institutions constrained technological adoption leading to worse economic outcomes. While persuasive, however, the argument fails to resolve some of the following puzzles in India's agricultural growth experience: One, why did some *zamindari*/landlord areas in Bihar, Bengal and Orissa adopt high yielding varieties of seeds (HYVs)? Two, why did not some *ryotwari*/non-landlord districts in Maharashtra and Karnataka not adopt HYVs? Three, how and why did HYV wheat adoption succeed in parts of dry and arid parts of Rajasthan (most of which was under indirect colonial rule before independence)?

In order to answer these questions, one needs to understand the historical circumstances under which the Green revolution succeeded in India. When India gained independence in 1947, it had lost some of the most productive agricultural regions to Pakistan (and present day Bangladesh). The Soviet-styled planning process prioritized industrialization over agriculture and this urban bias meant that India had to rely on foreign aid to import food for its growing population. Dwindling foreign exchange reserves, a war with China in 1962, and back-to-back droughts in 1964 and 1965 forced India to experiment with a 'New Agricultural Strategy' (NAS) which aimed at improving food security. By advocating for increasing the intensity of cropping, use of improved high yielding varieties of seeds (HYVs), fertilizers and expansion of irrigation facilities, NAS laid the foundations of the Green revolution. Given resource constraints, the policy was implemented in select districts: “In late 1965, a conference on Intensive Agricultural programme, called by the Union Government, recommended the following norms for the selection of HYV areas: (1) The selected areas should, as far as possible, be under the IADP [Indian Agricultural District Program] or IDA district blocks where necessary organization and facilities have already been built up. (2) The selected blocks must have about 80 per cent of the cultivable area under irrigation, of which substantial portion should be under minor irrigation - as the latter permits better control over water supply. (3) Other than IADP/IAA, districts may be selected provided they have substantial area under irrigation and are important wheat growing tracts.” (Vyas, 1975)

The emphasis on irrigation meant that adoption of HYV rice and wheat over the years was reported in Tamil Nadu, Andhra Pradesh, Bihar, West Bengal, western Uttar Pradesh, Punjab and Haryana (Economic Survey of India, 1968). It is also worth pointing out that HYV wheat was adopted in the irrigated areas of Bihar, Punjab and Haryana but not in areas where wheat was grown on dryland such as Gujarat and Madhya Pradesh (Vyas, 1975). The above anecdotal evidence thus provides a strong case to empirically examine the contribution of irrigation to Indian agricultural development. We focus on the role of surface irrigation because at the time of independence it was the predominant source of irrigation.

2.1 Data

The data on agricultural outcomes comes from Banerjee and Iyer (2005) and ICRISAT (2013). Banerjee and Iyer (2005)’s replication archive provides a district-year panel data which records information on various agricultural practices such as area under cultivation that is irrigated, adoption of fertilizer and modern HYVs, alongside crop area and production. It also has information on a district’s colonial experience, recording the proportion of the district that was under the landlord/*zamindari* system, year of British conquest, geographic factors such as latitude, longtitude, soil characteristics and rainfall. The panel runs from 1956 to 1987 and covers 271 districts in major Indian states (that were under British rule). This data was mapped to 1966 district boundaries, so that variables from ICRISAT (2013) could be merged in (the latter has a richer set of covariates and the current analysis uses information on agro-ecological sub-regions (AESR) and source wise irrigated area).

The data on historical irrigation networks comes from Schwartzberg et al. (1992). The map of canal network in 1931 (Figure 2c) was digitized and overlaid with a district boundaries map of India to identify which districts had a canal in 1931. This variable captures the extensive margin of the effect of canals. Additionally, a continuous measure of irrigation was also calculated from a geospatial data of recently available sub-national statistics on area equipped under irrigation in 1920 (Siebert et al., 2015).

3 Empirical Strategy

The empirical strategy compares agricultural outcomes in districts which had a canal with those that didn't. The estimating equation is as follows:

$$y_{it} = \theta + \beta Canals_i + X_i + u_s + v_t + w_a + e_{it} \tag{1}$$

where, y_{it} is proportion of gross cropped area irrigated, proportion of rice/wheat/other cereals area under HYV, ln(rice/wheat/major crop yields) in district i at time t; $Canals_i$ is either a dummy for whether a district had a canal before 1931 or a continuous measure that is defined as ln(area equipped under irrigation in 1920); X_i are time-invariant geographic controls (average rainfall, type of soil, latitude, longitude, coastal dummy) and also include type of land tenure system (proportion of district that is under nonlandlord tenure) and length of British rule; u_s are state fixed effects; w_a are AESR fixed effects; v_t are year fixed effects and e_{it} is the idiosyncratic error term. Standard errors clustered at district level (1991 boundaries).

The coefficient of interest in equation (1) is β which captures the average difference in adoption of agricultural practices and outcomes in districts with and without canals. Year fixed effects absorb any country-level time-varying characteristics such has changes in macroeconomic conditions that might affect agricultural growth across districts, shocks to agricultural technology that do not vary with districts and other national policy changes that could bias the effect of canal irrigation. Adding state fixed effects allows for within state comparisons and adding AESR fixed effects further controls for potential confounding factors that are not included in X_i such as length of growing period, potential evapotranspiration etc. that are common across sub-regions. There are 13 states in the estimating sample and 18 AESRs.

The estimates from equation (1) provide, at best, an association between historical canal irrigation networks and present-day outcomes because of potentially unobserved factors such as productivity (that is not captured by X_i). Ideally, one would have liked to have some exogenous variation in the placement of canals and one could have exploited such a natural experiment to estimate the causal impact of canals. In 1857, Arthur Cotton, irrigation engineer (and chief architect of the Godavari anicut that transformed the region into 'rice bowl' of the country after independence) proposed a plan to tap into the 'undeveloped wealth in India'. His plans couldn't come into fruition because the influential steel lobby in London preferred investments in railways instead. I use Cotton's map (in Figure 3) to identify districts where a canal was proposed to be built but wasn't and use the plausibly exogenous variation to estimate:

$$y_{it} = \phi + \gamma UnbuiltCanals_i + X_i + u_s + v_t + w_a + e_{it} \tag{2}$$

where, $UnbuiltCanals_i$ is dummy for whether a districts had a canal that was proposed but not built, and the other definitions are same as earlier. The coefficient of interest in equation 2 is γ and we expect this to be negative.

4 Findings

Table 1 presents results from the baseline model in equation (1), without including state fixed effects. Panel A reports the coefficient on β for each of the 8 outcome variables when the independent variable is a dummy for whether a district had a canal in 1931. Districts with colonial investments in surface irrigation were 47 percent more likely to have area under irrigation (col 1), 29 percent greater fertilizer usage (col 2), 14 percent higher area under HYV rice (though the estimate in col 3 was not statistically significant) and 20 percent higher area under HYV wheat (col 4). Overall, crop yields for major crops (cereals, pulses and oilseeds) were 18 percent higher, rice yields were 22 percent higher and wheat yields were 10 percent higher. We observe qualitatively similar results when using a measure of the intensive margin: Panel B presents the coefficients when the independent variable is ln(area equipped under irrigation in 1920). We also obtained similar results using an alternative measure of ln(area equipped under irrigation in 1940) (results not shown). We prefer to report results using ln(AEI 1920) since it is relatively more exogenous compared to ln(AEI 1940). (The Government of India Act, 1935 devolved some power from the crown to state/provinces who could, in principle, differently invest in irrigation infrastructure in their regions under their jurisdiction.)

[TABLE 1 HERE]

We now discuss competing explanations and potential threats that could confound the above estimation. First, one obvious concern with the results in Table 1 is that they could simply reflect differences between states' initial conditions. North-western India had many more canals compared to the rest of the country and the estimates could be capturing this broad geographic difference. We address this by adding state fixed effects to the baseline specification in equation (1). Although the effect sizes drop by 40-60 percent, estimates from Panel A and B in Table 2 taken together show that the effect of long-run effect canals continues to persist even after accounting for state-level time-invariant unobservables. (This result is in stark contrast to Banerjee and Iyer

(2005) who find that state policy/adding state FE washes away the effect of the land tenure system.)

[TABLE 2 HERE]

Second, Palmer-Jones and Sen (2003) have argued that underlying agro-ecological conditions are crucial for agricultural growth, and it is possible that some of these agro-climatic factors could be driving the results. Table 3 adds agro-ecological sub-region (AESR) fixed effects, over and above state FE, and the overall results are only marginally different from those in Table 2.

[TABLE 3 HERE]

Third, one may be concerned that results could be driven by how canal irrigation might be interacting with peculiar unobserved characteristics of the land tenure system. Even though all regressions control for the proportion of the non-landlord tenure system, we conduct a stricter test by re-estimating 1 after dropping group of states where the effects of the land tenure are 'known' to be key. Table 4, Panel A drops Bihar and West Bengal, arguably the two states which bore much of the brunt of the *zamindari*/landlord system. Panel B drops Punjab and Haryana, the two states that are said to have been at the forefront of the Green revolution. Panel C drops Madhya Pradesh in response to a critique by Iversen et al. (2013) who claim that districts in the formerly Central Provinces are driving the positive results in Banerjee and Iyer (2005). Results in Table 4 depict that the association between colonial investments in canal irrigation and agricultural outcomes is not sensitive to the choice of states.

[TABLE 4 HERE]

Fourth, it is also possible that the average treatment effect in equation (1) is driven by unobserved factors other than canal irrigation, such as more recent policy developments. If this was the case then time-varying disaggregated estimates should pick up the effect of canals in the latter part of the sample period. Estimates from cross-sectional regressions, run separately for each year from 1966 to 1987, in Figure 4 illustrate that this is not true. For the sake of completeness, a comparison of the effect on both the land tenure system and canal is shown. The results for gross irrigated area (GIA), fertilizer and HYV wheat show a gradual divergence between districts which had a canal in 1931 and those that did not. These results illustrate that irrigation investments played an important role in the adoption of modern agricultural technology, much more than the role assigned to the land tenure system.

[FIGURE 4 HERE]

Fifth, Figure 5 illustrates cross-sectional estimates, year by year, for the effect of colonial canals on the source of irrigation. Observers of South Asia have documented how, despite its advantages, the colonial canal irrigation project was besieged with collective action problems. Since the institutional arrangement for canal irrigation had become restrictive by the mid-70s, most of the subsequent spread of the green revolution was primarily driven by the unregulated use of groundwater (Shah, 2010). The results in Figure 5 provide some suggestive evidence in favor of this theory. The area under irrigation via canals (and surface irrigation) is broadly constant/declines marginally, whereas area irrigated via tubewells and groundwater dramatically takes off.

[FIGURE 5 HERE]

Taken together, all these findings suggest that the success of the green revolution was biased towards places which had pre-existing investments in canal irrigation. As a final piece of evidence, we present results from equation (2). If Arthur Cotton's map of proposed canal was made keeping in mind productivity concerns, then districts where canals were planned to be built but never built would make for an interesting counterfactual experiment. Table 5 shows that land suitability for cultivation of cereals in these districts is similar which further lends credence to a causal interpretation of these results. Table 6 depicts that districts with unbuilt canals are the real ones who have experienced a 'reversal of fortunes' as they have worse agricultural outcomes more than a century after which Cotton first proposed his grand ambitious project.

[TABLE 5 AND TABLE 6 HERE]

Finally, I consider the environmental effects of the colonial canals. Figure 6 illustrates the severity of the groundwater problem in the country today. Table 7 shows water tables are depleting at a faster rate in places which had a canal in 1931 compared to others that did not, implying that agrarian progress was achieved at significant environmental cost.

[FIGURE 6 AND TABLE 7 HERE]

5 Discussion

The ancient Greek philosopher, Thales of Miletus[1], believed that originating principle of nature was a single material substance: water. Much of the academic literature examining the role of history in long run development has only paid cursory attention to the crucial importance of water infrastructure. Inspired by Thales' "All is water" thesis, this paper documents that colonial investments in canal irrigation were crucial for the successful adoption of the Green revolution in India. Showing that the initial take up of modern inputs (HYVs, fertilizers and tubewells) was biased towards places where investments in surface irrigation were historically made implies that control over water is an important mechanism through which history has persisting effects. The findings of the paper also sheds light on the nature of path dependence that history sets countries on, as evident from the development-environment trade off.

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[1] Aristotle called Thales the 'first' philosopher because he gave answers that were not just mythical cosmogonies.

Recognizing that the "process of expanding the real freedoms that people enjoy" (Sen, 1999) is fundamentally fraught with challenges would allow policy makers to build safeguards and navigate messy tradeoffs. The findings of this study might be relevant for Africa, where more than 90 percent of the land continues to be rain-fed and yet the debate on an African green revolution predominantly focuses on adoption of modern seed varieties. A recent review by the Consultative Group for International Agricultural Research (CGIAR) noted that irrigation and water management are under-evaluated areas.

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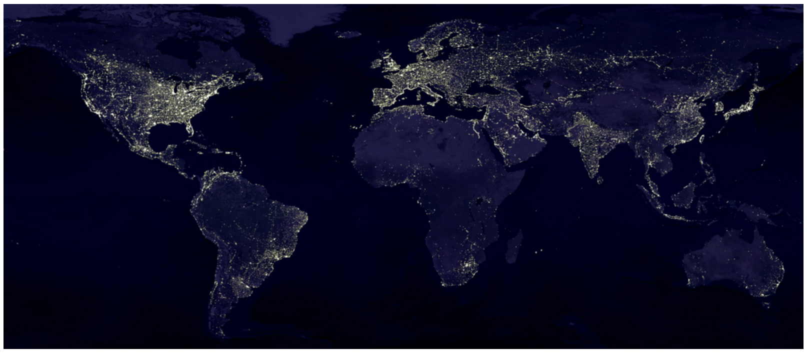
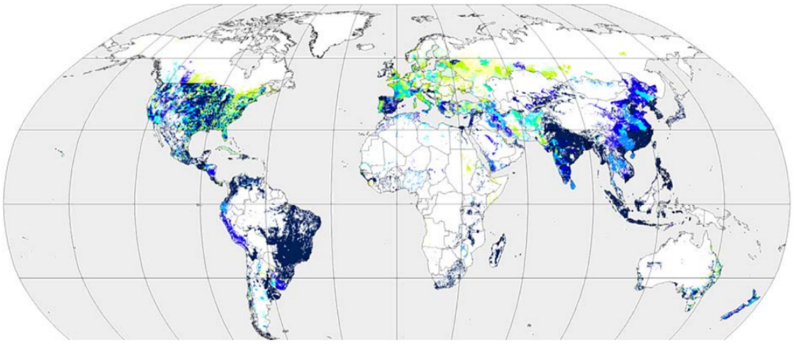
6 Figures

Figure 1: Economic development and irrigation across the world (circa 2000)



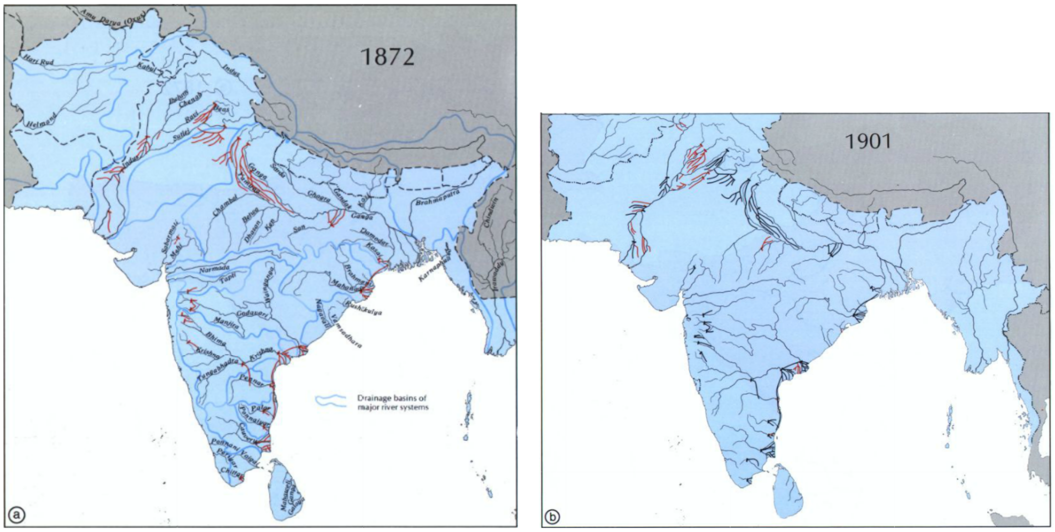
(a) Earth at night, as seen from outer space



(b) Global Map of Irrigation Areas (GMIA)

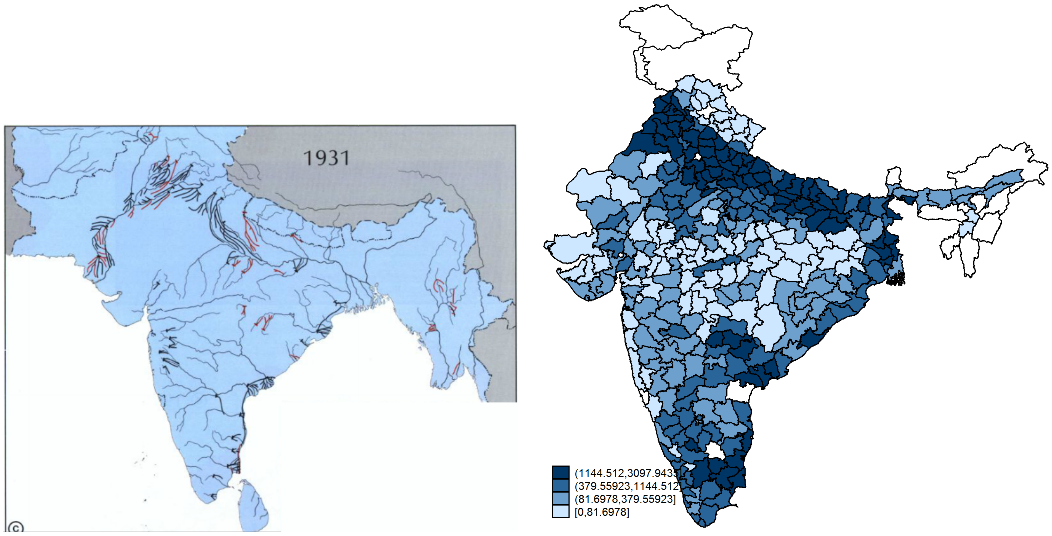
Note: Figure 1 shows the association between the levels of satellite night-time lights (a proxy for economic development) and area under irrigation. The nightlights map in Figure 1a is sourced from the National Geophysical Data Center. (Image and data processing by NOAA's National Geophysical Data Center. DMSP data collected by US Air Force Weather Agency.) Source of the irrigation map in Figure 1b is FAO (2016) AQUASTAT website.Food and Agriculture Organization of the United Nations (FAO).

Figure 2: Coverage of surface irrigation in the Indian subcontinent, 1872-1931



(a) Canal network in 1872

(b) Canal network in 1901

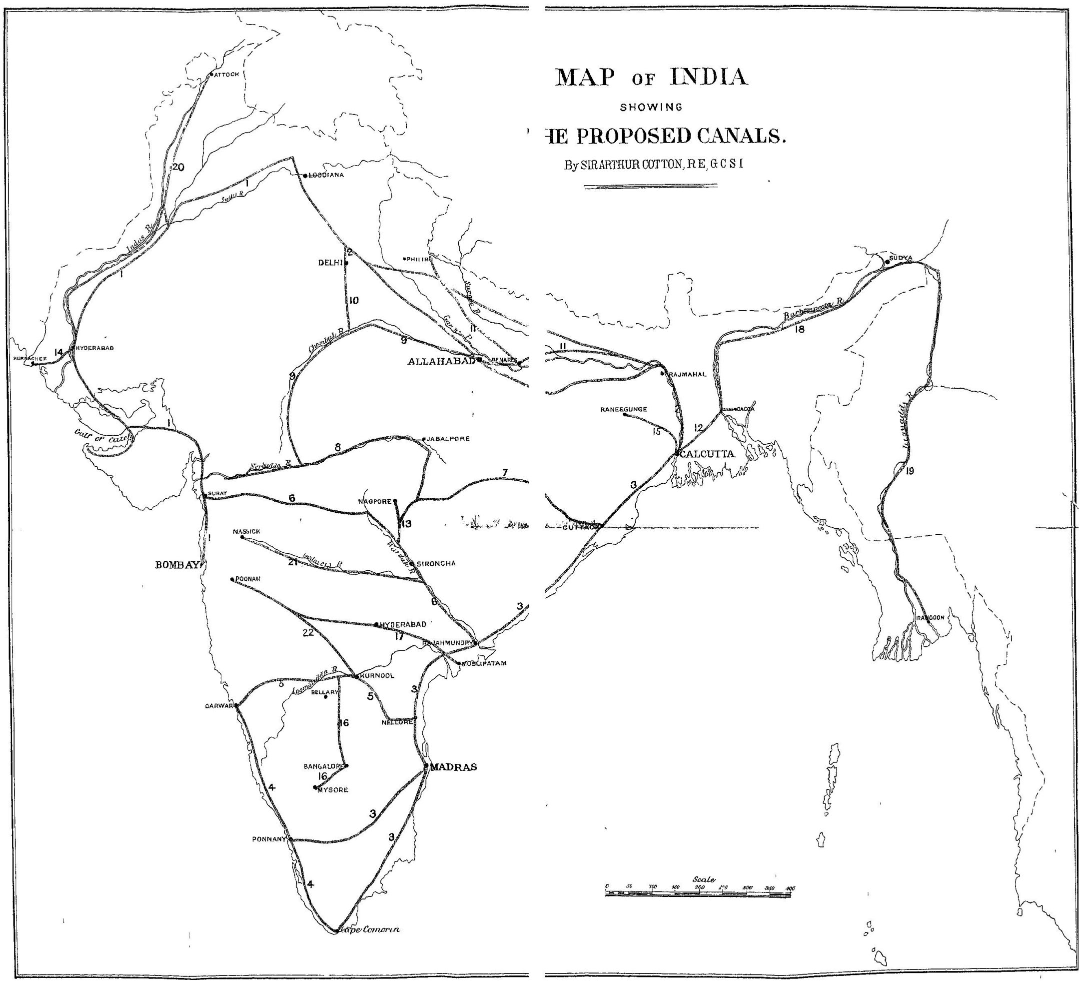


(c) Canal network in 1931

(d) Area equipped under irrigation in 1920

Figure 2 shows the evolution of the canal network in the Indian subcontinent from late 19th century to early 20th century. In Figure 2a, 2b and 2c the lines in blue represent rivers, while those in red and black depict canals. The map in Figure 2c (bottom left) was digitized and overlaid with the district map of India to identify the districts which had a canal in 1931. This indicator variable is the primary independent variable that is used in the analysis. Additionally, a continuous measure of historical irrigated area was also constructed using high resolution sub-national gridded data. Figure 2d (bottom right) represents the mean area equipped under irrigation (AEI) in 1920 in a given Indian district. Dark blue polygons correspond to districts which had relatively higher levels of AEI. Source: Schwartzberg et al. (1992), p. 127 (for the canal maps) and Siebert et al. (2015) Historical Irrigation Dataset (for the AEI 1920 map)

Figure 3: Network of canals proposed in 1857 by Arthur Cotton



Source: Undeveloped Wealth In India And State Reproductive Works (1874)

Figure 4: Cross-sectional estimates for modern agricultural inputs, 1965-87

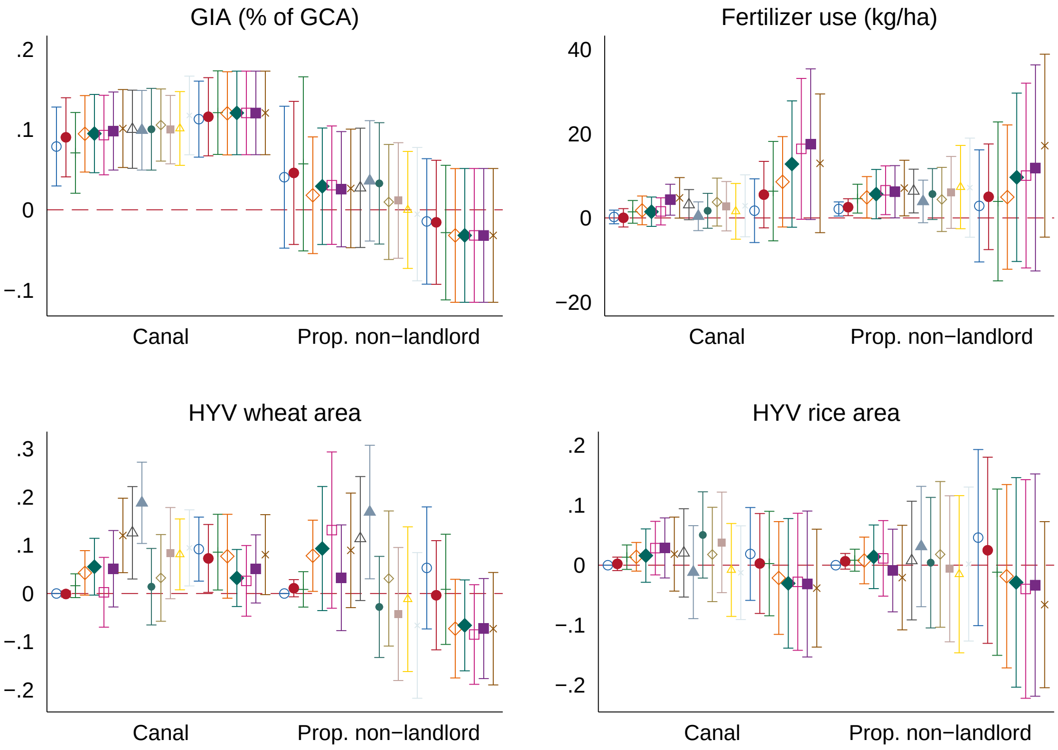


Figure 4 illustrates that colonial investments in canal irrigation played an important role in the adoption of modern agricultural technology (irrigation, fertilizer and seeds). It compares the estimates on canal (β) and land tenure (α) in cross-sectional regressions run year-by-year i.e. $y_i = \alpha Nonlandlord_i + \beta Canal_i + X_i + u_s + e_i \; \forall t \in \{1965...1987\}$, where y_i refers to agricultural outcome in district i in year t such as gross irrigated area (GIA) as a proportion of gross cropped area (GCA); fertilizer use in kg/ha; and proportion of cropped area of rice and wheat that is cultivated using high yielding varieties of seeds of the respective crop; $Canal_i$ refers to an indicator variable of whether a district had a canal in 1931; $Nonlandlord_i$ refers to the proportion of district which did not have landlord/*zamindari* land tenure system; X_i include controls for year of British conquest, altitude, latitude, mean annual rainfall, and dummies for soil type and coastal regions; u_s refers to state FE; and e_i is the idiosyncratic error term that is clustered at the district level.

Figure 5: Cross-sectional estimates for sources of irrigation, 1966-87

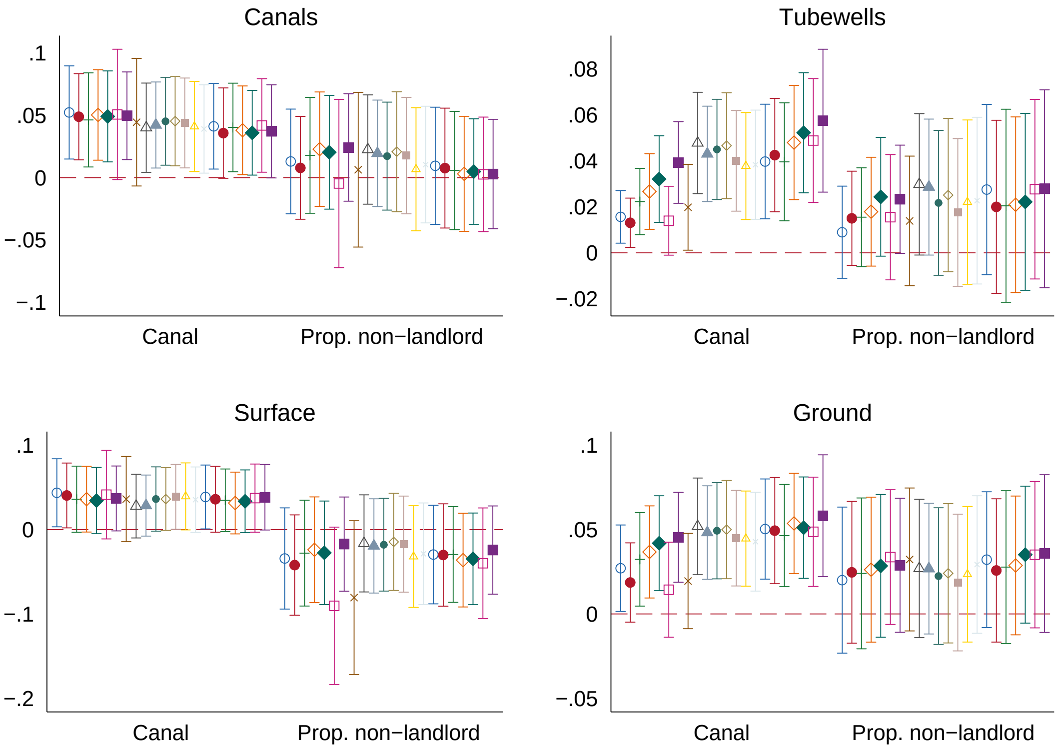
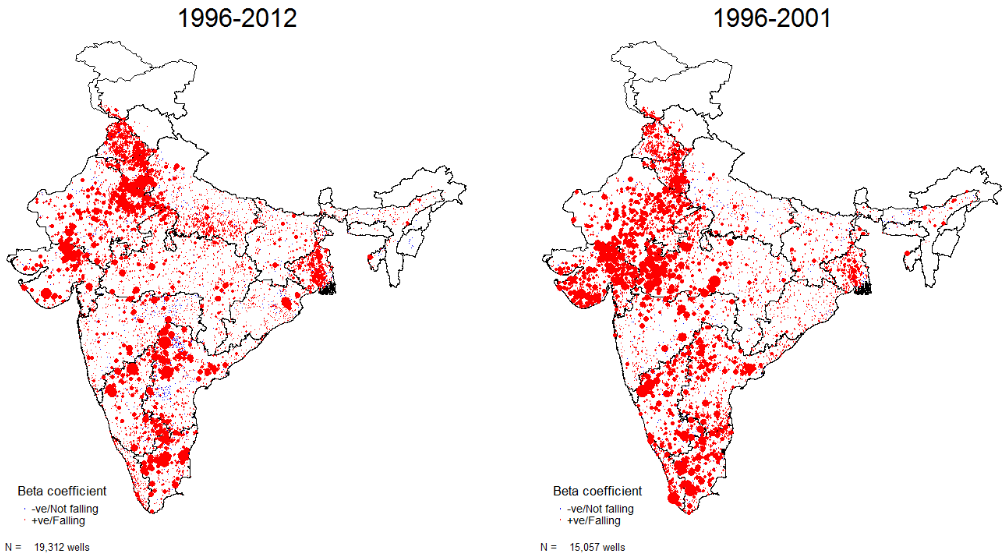
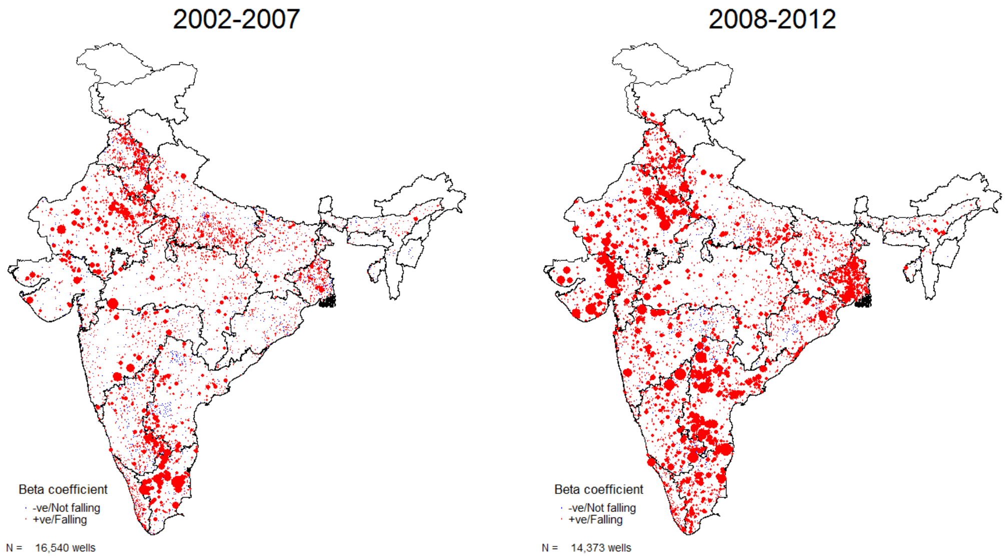


Figure 5 depicts that colonial investments in canal irrigation played an important role in the spread of both surface and groundwater irrigation. It compares the estimates on canal (β) and land tenure (α) in cross-sectional regressions run year-by-year i.e. $z_i = \alpha Nonlandlord_i + \beta Canal_i + X_i + u_s + e_i \; \forall t \in \{1965...1987\}$, where z_i refers to source of irrigated area (via canals, tubewells, surface or groundwater) as a proportion of gross cropped area in district i in year t; $Canal_i$ refers to an indicator variable of whether a district had a canal in 1931; $Nonlandlord_i$ refers to the proportion of district which did not have landlord/*zamindari* land tenure system; X_i include controls for year of British conquest, altitude, latitude, mean annual rainfall, and dummies for soil type and coastal regions; u_s refers to state FE; and e_i is the idiosyncratic error term that is clustered at the district level.

Figure 6: Severity of groundwater depletion



(a) Full period (b) Concentration phase



(c) Diffusion phase (d) Resurgence phase

Note: Map reproduced from Dar, Fishman and Jain (2016). It emphasizes the magnitude of groundwater depletion with the size of the dot scaled to depict the severity of the problem. The map plots magnitude of only those δ coefficients that are statistically significant in the following regression: $D_t = \delta timeperiod + \gamma_s + e_t$, where $timeperiod$ is a $(year, season)$ tuple and γ_s are seasonal dummies. The regression is run for each well separately and statistical significance was calculated at the 5-percent level. The colors correspond to: (a) blue: negative β/water table not falling, and (d) red: positive β/falling water table.

7 Tables

Table 1: Effect of canals on agricultural outcomes, without state fixed effects

	Inputs		Input: HYV seeds			Ln(Yields)		
	(1) Irrigation	(2) Fertilizer	(3) Rice	(4) Wheat	(5) Others	(6) All	(7) Rice	(8) Wheat
Panel A: Whether district had canal in 1931								
Canal	0.135^{***}	7.245^{**}	0.028	0.071^{***}	-0.033^{*}	0.178^{***}	0.224^{***}	0.097^{*}
	(0.028)	(3.014)	(0.023)	(0.023)	(0.018)	(0.054)	(0.045)	(0.058)
Panel B: Ln(Area equipped under irrigation in 1920)								
Canal	0.062^{***}	4.840^{***}	0.023^{***}	0.022^{***}	0.001	0.061^{***}	0.064^{***}	0.069^{***}
	(0.008)	(0.779)	(0.005)	(0.005)	(0.004)	(0.023)	(0.017)	(0.018)
N	5,280	5,293	5,201	5,034	5,049	5,311	5,293	4,484
Mean	.29	25	.2	.35	.13	.013	.0082	-.082

Table 1 shows that districts where colonial investments in canal irrigation were made are associated with better agricultural outcomes. Each estimate represents results from the following equation $y_{it} = \beta Canal_i + X_i + v_t + e_{it}$ where, y_{it} refers to agricultural outcomes in district i in year t such as percentage of gross cropped area irrigated (col 1); fertilizer use in kg/ha (col 2); proportion of cropped area rice (col 3), wheat (col 4) or other cereals (col 5) cultivated using high yielding varieties of seeds of respective crop; natural log of yield of major crops (col 6), rice (col 7) and wheat (col 8); $Canal_i$ refers to an indicator variable of whether a district had a canal in 1931 or a continuous variable that is defined as the natural log of the area equipped under irrigation in 1920; X_i include controls for land tenure system, year of British conquest, altitude, latitude, mean annual rainfall, and dummies for soil type and coastal regions; v_t refers to time FE; and e_{it} is the idiosyncratic error term. The sample period is 1956-1987. Standard errors are clustered at the district level. * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table 2: Effect of canals on agricultural outcomes, including state fixed effects

	Inputs		Input: HYV seeds			Ln(Yields)		
	(1) Irrigation	(2) Fertilizer	(3) Rice	(4) Wheat	(5) Others	(6) All	(7) Rice	(8) Wheat
Panel A: Whether district had canal in 1931								
Canal	0.093***	3.579*	0.004	0.043***	−0.032***	0.131***	0.165***	0.060
	(0.022)	(2.150)	(0.019)	(0.016)	(0.012)	(0.045)	(0.036)	(0.042)
Panel B: Ln(Area equipped under irrigation in 1920)								
Canal	0.039***	2.861***	0.029***	0.029***	0.003	0.012	0.031*	0.037**
	(0.010)	(0.673)	(0.008)	(0.006)	(0.005)	(0.023)	(0.018)	(0.015)
N	5,280	5,293	5,201	5,034	5,049	5,311	5,293	4,484
Mean	.29	25	.2	.35	.13	.013	.0082	-.082

Table 2 shows that districts where colonial investments in canal irrigation were made are associated with better agricultural outcomes. Each estimate represents results from the following equation $y_{it} = \beta Canal_i + X_i + v_t + u_s + e_{it}$ where, y_{it} refers to agricultural outcomes in district i in year t such as percentage of gross cropped area irrigated (col 1); fertilizer use in kg/ha (col 2); proportion of cropped area rice (col 3), wheat (col 4) or other cereals (col 5) cultivated using high yielding varieties of seeds of respective crop; natural log of yield of major crops (col 6), rice (col 7) and wheat (col 8); $Canal_i$ refers to an indicator variable of whether a district had a canal in 1931 or a continuous variable that is defined as the natural log of the area equipped under irrigation in 1920; X_i include controls for land tenure system, year of British conquest, altitude, latitude, mean annual rainfall, and dummies for soil type and coastal regions; v_t refers to time FE; u_s refers to state FE; and e_{it} is the idiosyncratic error term. The sample period is 1956-1987. Standard errors are clustered at the district level. * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table 3: Effect of canals on agricultural outcomes, including agro-ecological sub-region fixed effects in addition to state fixed effects

	Inputs		Input: HYV seeds			Ln(Yields)		
	(1) Irrigation	(2) Fertilizer	(3) Rice	(4) Wheat	(5) Others	(6) All	(7) Rice	(8) Wheat
Panel A: Whether district had canal in 1931								
Canal	0.095^{***}	4.980^{*}	0.045	0.048^{**}	-0.051^{***}	0.207^{***}	0.232^{***}	0.038
	(0.022)	(2.895)	(0.028)	(0.021)	(0.019)	(0.046)	(0.040)	(0.046)
Panel B: Ln(Area equipped under irrigation in 1920)								
Canal	0.049^{***}	5.781^{***}	0.052^{***}	0.030^{***}	-0.003	0.074^{***}	0.097^{***}	0.048^{***}
	(0.009)	(0.972)	(0.009)	(0.010)	(0.009)	(0.017)	(0.016)	(0.018)
N	3,768	3,777	3,685	3,518	3,591	3,795	3,784	3,238
Mean	.31	33	.29	.49	.19	.094	.08	.07

Table 3 shows that districts where colonial investments in canal irrigation were made are associated with better agricultural outcomes. Each estimate represents results from the following equation $y_{it} = \beta Canal_i + X_i + v_t + u_s + w_a + e_{it}$ where, y_{it} refers to agricultural outcomes in district i in year t such as percentage of gross cropped area irrigated (col 1); fertilizer use in kg/ha (col 2); proportion of cropped area rice (col 3), wheat (col 4) or other cereals (col 5) cultivated using high yielding varieties of seeds of respective crop; natural log of yield of major crops (col 6), rice (col 7) and wheat (col 8); $Canal_i$ refers to an indicator variable of whether a district had a canal in 1931 or a continuous variable that is defined as the natural log of the area equipped under irrigation in 1920; X_i include controls for land tenure system, year of British conquest, altitude, latitude, mean annual rainfall, and dummies for soil type and coastal regions; v_t refers to time FE; u_s refers to state FE; w_a refers to agro-ecological sub-region (AESR) FE; and e_{it} is the idiosyncratic error term. The sample period is 1956-1987. Standard errors are clustered at the district level. * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table 4: Effect of canals on agricultural outcomes, dropping states

	Inputs		Input: HYV seeds			Ln(Yields)		
	(1) Irrigation	(2) Fertilizer	(3) Rice	(4) Wheat	(5) Others	(6) All	(7) Rice	(8) Wheat
Panel A: Drop Bihar and Bengal								
Canal	0.132^{***}	7.966^{**}	0.052^{**}	0.081^{***}	-0.011	0.176^{***}	0.243^{***}	0.112^{*}
	(0.030)	(3.388)	(0.025)	(0.024)	(0.016)	(0.059)	(0.048)	(0.065)
N	4,544	4,557	4,465	4,298	4,373	4,575	4,557	3,751
Mean	.29	25	.21	.31	.12	.0073	.013	-.099
Panel B: Drop Punjab and Haryana								
Canal	0.120^{***}	3.989	-0.004	0.068^{***}	-0.046^{***}	0.154^{***}	0.177^{***}	0.078
	(0.028)	(2.814)	(0.020)	(0.023)	(0.017)	(0.057)	(0.038)	(0.059)
N	4,928	4,941	4,864	4,700	4,706	4,959	4,941	4,132
Mean	.27	23	.19	.34	.13	-.013	-.028	-.14
Panel C: Drop Madhya Pradesh								
Canal	0.135^{***}	6.847^{**}	0.015	0.068^{***}	-0.038^{*}	0.183^{***}	0.211^{***}	0.152^{***}
	(0.029)	(3.084)	(0.025)	(0.023)	(0.020)	(0.060)	(0.044)	(0.055)
N	4,800	4,813	4,721	4,586	4,571	4,831	4,813	4,004
Mean	.31	27	.21	.36	.14	.048	.045	-.034

Table 4 shows that association between colonial investments in canal irrigation and positive agricultural outcomes is not sensitive to choice of states. Each estimate represents results from the following equation $y_{it} = \beta Canal_i + X_i + v_t + e_{it}$ where, y_{it} refers to agricultural outcomes in district i in year t such as percentage of gross cropped area irrigated (col 1); fertilizer use in kg/ha (col 2); proportion of cropped area rice (col 3), wheat (col 4) or other cereals (col 5) cultivated using high yielding varieties of seeds of respective crop; natural log of yield of major crops (col 6), rice (col 7) and wheat (col 8); $Canal_i$ refers to an indicator variable of whether a district had a canal in 1931; X_i include controls for land tenure system, year of British conquest, altitude, latitude, mean annual rainfall, and dummies for soil type and coastal regions; v_t refers to time FE; and e_{it} is the idiosyncratic error term. The sample period is 1956-1987; panel A restricts the data to all states except Bihar and Bengal where the landlord land tenure system was most severe; panel B drops Punjab and Haryana, the two states that were at the forefront of the Green Revolution in India; and panel C drops Madhya Pradesh as there is scholarly disagreement on the type of land tenure system in that region. Standard errors are clustered at the district level. * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table 5: Cross-sectional relationship between districts with unbuilt canals on land suitability

	No state FE		With state FE	
	(1) Low	(2) High	(3) Low	(4) High
Unbuilt	-4.717^{**}	-2.298	-0.005	0.049
	(2.037)	(2.538)	(0.050)	(0.034)
N	177	177	177	177

Table 5 shows that districts where colonial investments in canal irrigation were proposed to have been originally made were similar in terms of suitability for growing cereals. Each estimate represents results from the following cross-sectional regression $y_i = \gamma Unbuilt_i + e_{it}$ where, y_i refers to land suitability for rainfed cereals in district i corresponding to low or high inputs; $Unbuilt_i$ refers to an indicator variable of whether a district was proposed to have a canal built in 1857 but wasn't; and e_{it} is the idiosyncratic error term. Heteroskedasticity robust standard errors are presented. * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table 6: Effect of unbuilt canals on agricultural outcomes

	Inputs		Input: HYV seeds			Ln(Yields)		
	(1) Irrigation	(2) Fertilizer	(3) Rice	(4) Wheat	(5) Others	(6) All	(7) Rice	(8) Wheat
Panel A: No FE								
Unbuilt	-0.137^{***}	-8.034^{*}	-0.038	-0.083^{***}	0.032	-0.185^{**}	-0.221^{***}	-0.151^{**}
	(0.041)	(4.778)	(0.026)	(0.030)	(0.023)	(0.077)	(0.054)	(0.074)
Panel B: (A) + State FE								
Unbuilt	-0.102^{***}	-3.382	-0.002	-0.038^{*}	0.018	-0.148^{**}	-0.138^{***}	-0.086^{*}
	(0.031)	(3.546)	(0.022)	(0.023)	(0.015)	(0.062)	(0.052)	(0.051)
Panel C: (B) + AESR FE								
Unbuilt	-0.101^{***}	-3.062	-0.026	-0.068^{**}	0.028	-0.223^{***}	-0.188^{***}	-0.065
	(0.031)	(4.441)	(0.035)	(0.031)	(0.024)	(0.052)	(0.060)	(0.060)
N	2,641	2,650	2,581	2,473	2,524	2,668	2,668	2,250
Mean	.33	35	.29	.49	.19	.073	.06	.041

Table 6 shows that districts where colonial investments in canal irrigation were proposed to have been originally made, but none were eventually built are associated with worse agricultural outcomes. Each estimate represents results from the following equation $y_{it} = \gamma Unbuilt_i + X_i + v_t + e_{it}$ where, y_{it} refers to agricultural outcomes in district i in year t such as percentage of gross cropped area irrigated (col 1); fertilizer use in kg/ha (col 2); proportion of cropped area rice (col 3), wheat (col 4) or other cereals (col 5) cultivated using high yielding varieties of seeds of respective crop; natural log of yield of major crops (col 6), rice (col 7) and wheat (col 8); $Unbuilt_i$ refers to an indicator variable of whether a district was proposed to have a canal built in 1857 but wasn't; X_i include controls for land tenure system, year of British conquest, altitude, latitude, mean annual rainfall, and dummies for soil type and coastal regions; v_t refers to time FE; and e_{it} is the idiosyncratic error term. Panel A presents results from the baseline specification specification; panel B adds u_s refers to state FE; and panel C adds w_a agro-ecological sub-region (AESR) FE. The sample period is 1956-1987. Standard errors are clustered at the district level. * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table 7: Effect of canals on groundwater depletion, 1996-2015

	All India		British India	
	(1)	(2)	(3)	(4)
Year	0.028***	0.033***	0.080***	0.086***
	(0.009)	(0.009)	(0.019)	(0.018)
Canal × year	0.038	0.040*	0.070**	0.070**
	(0.024)	(0.024)	(0.034)	(0.034)
N	822,026	822,026	3,823	3,823
Mean	8	8	7.9	7.9
Rainfall	No	Yes	No	Yes

Table 7 shows that districts with colonial canals witness a faster reduction in groundwater depletion. The estimates in col (1) and (2) represents results from the following equation $y_{wit} = \delta Year + Canal_i \times Year + u_w + v_s + e_{wit}$ where, y_{wit} refers to the depth of the watertable in well w in district i in quarter t wheat; $Canal_i$ refers to an indicator variable of whether a district had a canal in 1931; u_w are well fixed effects; v_s refers to seasonal dummies (one for each quarter); and e_{wit} is the idiosyncratic error term. Estimates in col (3) and (4) are from an analogous regression that is run at the district level and is only restricted to districts under direct British rule. The sample period is 1996-2015. Standard errors are clustered at the well and district level in col 1/2 and 3/4 respectively. * p<0.10, ** p<0.05, *** p<0.01.

A Appendix

Table A1: Canals built in India before 1947

S.No.	State	Name	Year	Type
1	AP	Kurnool-Cudappah canal	1870	Diversion
2	AP	Godvari delta system	1890	Diversion
3	AP	Penner river and canal system	1894	Diversion
4	AP	Krishna delta system	1898	Diversion
5	AP	Nizamsagar	1930	Storage
6	BR	Sone canals	1875	Diversion
7	HR	Western yamuna canals(ex. Tajewala)	1886	Diversion
8	HR	Western yamuna canal (extension)	1892	Diversion
9	MP	Tandula reservoir	1923	Storage
10	MP	Mahanadi canal and Murrum-silli reservoir	1923	Storage
11	MH	Godavari canal (Nandur Madhmeshwar Weir)	1916	Storage
12	MH	Pravara river works (Bhandardara)	1926	Storage
13	MH	Nira left bank canal and Sheptal tank	1927	Storage
14	MH	Nira right bank canal	1927	Storage
15	KA	Krishnarajasagar dam and Visveswaraya canal	1930	Storage
16	OR	Orissa canal	1895	Diversion
17	OR	Rushikulya system (in Ganjam)	1901	Storage
18	PB	Upper bari doab canal	1879	Diversion
19	PB	Sirhind canal	1887	Diversion
20	PB	Eastern canal	1933	Diversion
21	RJ	Gang canal	1928	Diversion
22	TN	Periyar system	1897	Storage
23	TN	Cauvery mettur project	1934	Storage
24	UP	Upper ganga canal	1854	Diversion
25	UP	Agra canal	1873	Diversion
26	UP	Lower ganga canal	1878	Diversion
27	UP	Betwa canal	1878	Diversion
28	UP	Ken canal	1886	Diversion
29	UP	Garai & Ghaggar canal	1917	Storage
30	UP	Sarda canal	1926	Diversion
31	WB	Damodar canal project	N.A.	Diversion

Note: Year denotes year of completion; N.A. stands for data not available. Gokak canal and Mhaswad tank in Maharashtra; Tribeni and Dhaka Canals in the Champaran district in Bihar, the Chankapur Tank in Bombay; Khairabanda Tank in the Central Provinces were also protective works. Source: RIC Appendix 4.1 and Chapter IV; Irrigation and Soil Salinity in the Indian Subcontinent: Past and Present By N. T. Singh, Chapter 4