# The Value of Water Power during the American Industrial Revolution

Todd Guilfoos*

**Abstract**

This work measures the historical value of water power during the Industrial Revolution in the United States. I use the variation in agricultural land prices in 1880 to identify the aggregate value of water power. County-level water-power estimates are based on the 1880 Water Power Census to measure the aggregate value of water power and the importance of natural endowments in economic growth. The aggregate value of one horsepower of water power is valued at $294. The aggregate value is decomposed into direct values (power as a prime mover) and indirect values (attracting infrastructure); at least 65% of the total value is the direct effect of water power as a prime mover. Indirect value is gained by water-power sites attracting railroad infrastructure, affecting the endogenous growth of transportation networks. The validity of the direct value of water-power estimates is supported by estimating the elasticity of water power as an input into production using establishment-level production data from the manufacturing census rolls.

**JEL Codes: Q51, Q57**

*Department of Environmental and Natural Resource Economics, University of Rhode Island, 219 Coastal Institute, 1 Greenhouse Road, Kingston, RI 02881. Email: `guilfoos@uri.edu` I thank Andrew Boslett for excellent research assistance.

# 1 Introduction

What drives the spatial dispersion of growth and industry? How important are natural geographic endowments to growth compared to market integration or infrastructure, such as railroads? Why did manufacturing in the United States take hold in the North and not the South during the Industrial Revolution? Both human-built infrastructure and natural advantages of geography play a role in economic development. The placement of ancient Roman roads had long-lasting effects on future development (Dalgaard et al., 2018). In America, the railroad and steam engine were strong influences on the location and speed of economic development (Donaldson and Hornbeck, 2016; Crafts, 2004; Atack et al., 2019). Just as the railroad and the dispersion of steam power across the country were paramount to economic growth, I hypothesize that natural endowments of water power were just as important. Crafts and Wolf (2014) finds that water power and market access predict the location of textile mills in Great Britain, which explains the initial growth of industrialized cities and a "lock-in" effect of agglomeration after the primary benefits of water power are gone. Recent research on spatial economic growth demonstrates the importance of place, based on natural advantages or endowments (Bleakley and Lin, 2012; Desmet and Rossi-Hansberg, 2014; Martin and Sunley, 2006; Ellison and Glaeser, 1999; Holmes and Lee, 2012). In this paper, I identify the aggregate value of water power in 1880. I then use two sets of data from 1880 to decompose the aggregate value of water power into the production value of water power and its indirect value, through agglomeration.

Labor-saving technologies are the primary feature of the first Industrial Revolution (Atack et al., 2019). The technological advances during that period depended on both innovation in production machines and prime movers, machines that convert natural energy into mechanical energy. In the nineteenth century, economic growth depended on the local availability of power (Stern and Kander, 2012). Prime movers such as waterwheel turned water energy into energy to power machines critical to America's manufacturing. The earliest prime movers were human and animal-driven, which did not allow a large concentration of power in one location. The harnessing of water power, and later steam power, connected to innovative machines, drove the development and growth of the factory system. The beginning of this process in America began in Rhode Island, where Samuel Slater established the first cotton spinning mills, which grew into a concentration of activity in the Northeastern United States. Large mill towns appeared across New

England–Lowell, Lawrence, Saco, Holyoke, and Manchester–that harnessed the immense water power available in the region. Famously, the Lowell factory system transformed the work system from piecework made in homes to an integrated factory system. The early mills and factory systems critically depended on natural endowments of water power.

The use of waterwheels goes back over two thousand years; it was a feature of the Roman Empire (Reynolds, 1983). From antiquity to 1790, the waterwheel's value was primarily in grinding grain.[1] Flour mills, gristmills, sawmills, and fulling mills populated much of Colonial America. It was common for populations to live close to a local mill so that harvested grain could be cheaply brought to the miller and made into flour. It was also common in colonial New England to offer inducements to build water mills to attract settlers and stimulate land values (Hunter, 1979). Water-power sites would often determine the location of villages, especially in New England. As historian Ulysses Hendrick writes, "The happy accident of waterpower in river or stream determined the location of most of the towns of inland New York as a thousand names attest."[2] Millwrights and wheelwrights came to America from Europe and practiced their trade based on training they received in the Old World. The knowledge of how to harness water power was well traveled; a guide to building water mills was published in 1795 (Evans, 1795).[3] This comprehensive guide for millwrights provided a rational basis for the planning, designing, and constructing water mills. This knowledge of watermills and natural endowments of water power provided the necessary starting point for industrialization.

Water power was very important to America in the nineteenth century. The US government commissioned a census of water power across the country which was published in 1880. I measure counties' aggregate water power by digitizing the *Report on the Water Power of the United States* for 1880. Counties with a large endowment of water power are more productive at manufacturing, which is capitalized into land values. I measure the value of this capitalization using agricultural land values from 1880. The 1880 water-power report provides detailed records of horsepower estimates that are hydrologically available and feasible to exploit in 1880 along all major streams recorded. For instance, some slightly sloped rivers are not beneficial because of the small power potential and sig-

[1] There were other uses but none so widespread as the flour mill and the grist mill. In Persia, waterwheels were employed to lift water for irrigation, and lumber. Paper mills were also a common feature across Europe and early America.

[2] Hedrick (1933) p. 146.

[3] Oliver Evans, the author of this millwrights guide, also designed a high-pressure steam engine and wrote a guide for the steam engine as well in 1805 entitled *The Abortion of the Young Steam Engineer's Guide*.

nificant water displacement when dammed, which causes extensive flooding to farmland. Some additional context is available in the water census of major rivers that had not been developed. The report provides a valuable measure of feasible constraints on water-power development at the time. Water-power potential at the Niagara Falls dwarfs the estimate of used horsepower for the rest of the United States in 1880, yet it remained largely undeveloped due to the engineering challenges involved and the inability to transmit power with water turbines over distance.[4] This 1880 report is the first uniform accounting of water power across the country that enables such comparisons to be made.

The 1880 report on water power has been utilized in other research in economic history. Rosenberg and Trajtenberg (2004) used a portion of the report to measure the effect of the adoption of steam engines on urban agglomeration and the attraction of population growth. Bleakley and Lin (2012) use it to investigate how portage sites with significant water power attract economic development long after the sites are useful. Portage sites are places where there are natural blockages to the navigation of a river, such as falls. These sites were naturally advantageous for settlements. Bleakley and Lin (2012) find that portage sites have path dependency on population and can predict population densities long after the natural advantages of portage sites became obsolete. A growing literature has been investigating how the history of particular places influences economic outcomes (Proost and Thisse, 2019; Martin and Sunley, 2006). The economics literature, building on the economic-geography models, is increasingly making use of spatial models to explain regional differences in economic growth and trade (Desmet and Rossi-Hansberg, 2014; Trew, 2014; Desmet and Henderson, 2015; Allen and Arkolakis, 2014). Geographic endowments may also play a role in market infrastructure. Railroads, roads, and canals are endogenous sources of growth that combine with harbors, waterfalls, and natural waterways to provide access to markets and growth (Donaldson and Hornbeck, 2016; Trew, 2020).

The transition from water power to steam power is the focus of many studies of prime movers in the Industrial Revolution (Atack et al., 2019; Atack, 1979; Atack et al., 2008a, 1980; Kim, 2005; Temin, 1966; Crafts, 2004). Steam engines were a notable technological advancement. Steam power has key advantages over water power. It is available in every season and can be procured where natural waterfalls are scarce. The adoption

[4] These constraints were short-lived. A hydroelectric power plant was built at Niagara Falls in 1895 and became a major source of power for electricity in the region.

of steam thus transformed the location and size of the power that was available.[5] On the other hand, water power in many cases had advantages of cost and could rely on widespread knowledge of watermills. Water power used in manufacturing is a useful measure of value because of its place in a power system. It drove the machinery in the factory to make goods in a market economy. Prime movers naturally limited advances in automation. The value of automation in the factory is therefore closely related to the value of power in manufacturing. Atack et al. (2019) find that significant productivity gains accompanied automation of products in the late nineteenth century by comparing hand labor to automated production.[6] Further, the aggregate value of water power may attract economic activity for gathering, trading, and building additional infrastructure. Mokyr et al. (2019) argues that in England water power may have acted as a place where human capital accumulated at mill sites, increasing future adoption of technologies. Large water-power sites are connected to rivers that provide water for agriculture, drinking water, and transportation infrastructure. These factors suggest that water power acts as a source of economic agglomeration through industrialization.

I find the aggregate value of water power to be \$294 per horsepower. I decompose its aggregate value using estimates of market access and railroad construction. The direct value of water power, as a prime mover, is approximately 65% of the aggregate value, or \$191. The remaining indirect values are the value provided by water-power endowments that act as a source of agglomeration, most notably of transportation infrastructure. These indirect values account for 1.4% to 6.9% of the land price changes through increases in market access driven by natural endowments of water power.

I validate the value of water power as a prime mover by using establishment-level data from the 1880 manufacturing census rolls. Employing a nationally representative sample of establishments using water power in 1880, I find that one horsepower was worth \$12 in value-added production from water power per year. Using a sample of textile mills from New England, I find a much higher value of water power of \$55, suggesting that automation in the factory system and regional location adds a significant premium to the industrialized value of prime movers. Using a 6% discount rate suggests that the production value of water power is the dominant component of its aggregate value and is

[5]One spatial limitation for steam engines is the distance to sources of coal for powering steam engines and the need for mechanics to maintain them.

[6]These authors find that production tasks using steam power reduce the time of the task more than water-powered tasks. They attribute this to the seasonality of limitations on water power. Either way, automation had a dramatic effect on production efficiency, regardless of power source.

worth at least \$200 per horsepower.

I perform a counterfactual analysis to estimate the total impact of water power on land value across space. Counterfactual analysis has been used previously to estimate historical changes in infrastructure (Donaldson and Hornbeck (2016); Atack et al. (2008b); Baum-Snow (2007); Michaels (2008)). I implement a similar strategy to estimate the impact of removing water-power endowments from the county-level analysis. The baseline counterfactual analysis finds a significant reduction in the value of agricultural land with the loss of water power. The total value of water-power endowments is significant and comparable to estimates of the value of market access provided by all railroads. Removing 50% of water power in 1880 is equivalent to a 54% loss in agricultural land values.

# 2 Empirical Models

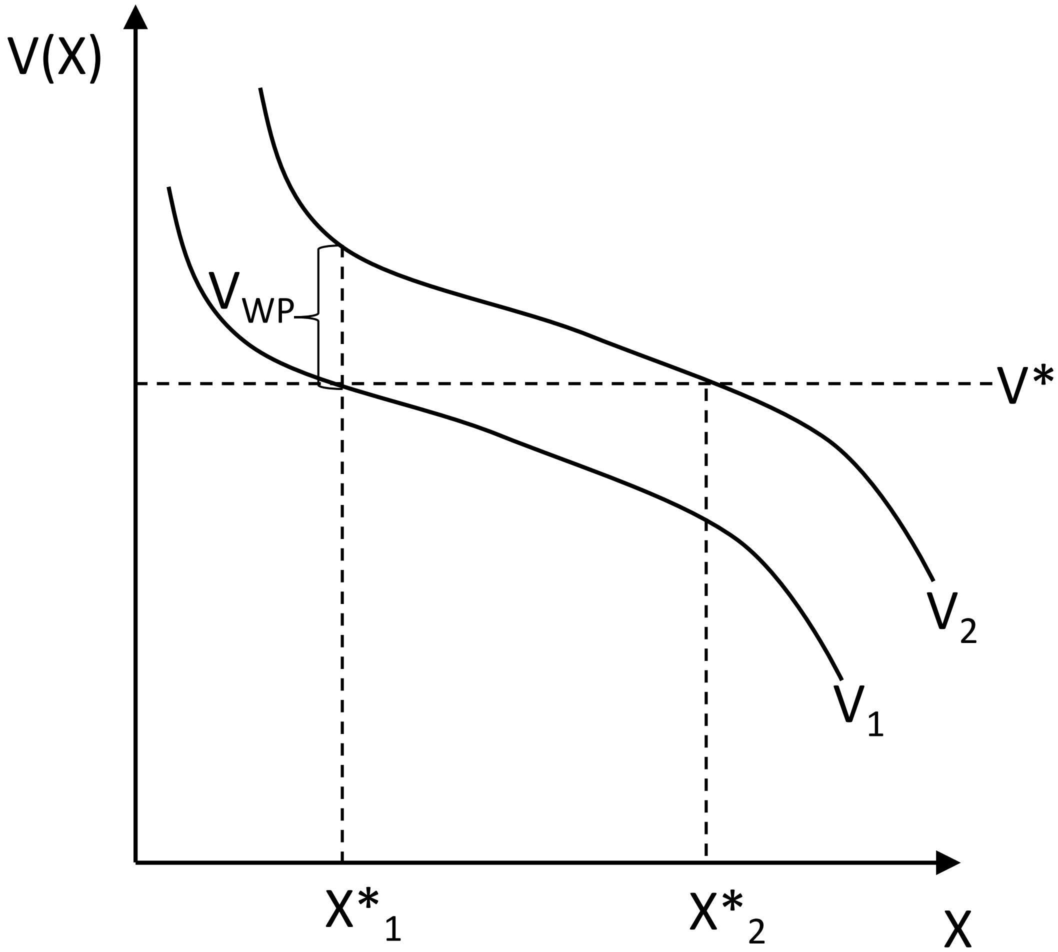
## 2.1 The Value of Water Power

I use the equilibrium analysis of a standard economic-geography model to interpret the main empirical findings of this paper in the style of Helpman (1998). The long-run equilibrium analysis in an economic-geography model is characterized in Figure 1, which is similar to analyses in Helpman (1998) and Bleakley and Lin (2012). Households and firms are mobile and can relocate without cost. Locations exist with fixed factors, with the factor of interest being water-power endowments. The value for a location of a mobile household in the model is conceptualized by the indirect value V(). The density of a location, X, and fixed factors determine the value of V() at a location. The downward sloping V() curve shows that the costs of congestion decrease the indirect value of households.[7] V*() indicates some level of indirect value that can be achieved at different locations in the economy. The long-run equilibrium for a location is given where V() intersects V*().

In figure 1, consider two locations, 1 and 2, in the economy that are identical except for their endowments of water power. Mobile households optimize locations based on their utility. Location 2 has a larger endowment of water power than location 1. The value of water-power endowments can be visualized by the vertical distance in Figure 1 and notated as $V_{WP}$. In the long-run equilibrium, the utility from each location is the same; when household utilities are not equal, then the marginal mobile household moves to the

[7] With increasing returns, the indirect value curve can be both upward and downward sloping along the gradient, which creates opportunities for multiple equilibria. The issue of increasing or decreasing returns is not critical to the valuation question.

Figure 1: Long-run Equilibrium in Model with Natural Advantages




Note. This figure shows the indirect household utility V(X) for two locations with different water power endowments and population densities, X. Location 1 has less water power than location 2. The equilibrium density for both locations is given where V* intersects the indirect household utility. This level of utility is achieved across locations at V*. The vertical distance, $V_{WP}$, is the value of the differential of water power between the two locations.

location with the greater utility until the densities are such that household utilities are equal.

Sites with large endowments of water power attract population, capital, and infrastructure, and households tolerate higher densities at these sites. The natural advantages of these locations, which are immobile, are measured in aggregate. I use a reduced-form model to estimate the value of water-power endowments through agricultural land prices. Locations that have larger endowments of water power attract higher land prices. The aggregate value of water power is estimated using equation 1.

$$ln(P_o) = \gamma_0 + \gamma_1 ln(WP_o) + \zeta X_o + \mu + \epsilon_o \tag{1}$$

The rental rate of land in county $o$ (P) is regressed on water power (WP) expressed in horsepower, a series of other spatial controls (X), and state fixed effects ($\mu$). This reduced-form equation is consistent with the long-run equilibrium of the economic-geography model described above. I use cross-sectional variation to estimate the value of water power since the endowment of water power does not change over time. Controls include several spatial controls; the most important is a measure of market access to other counties that captures the costs of trading goods weighted by population. Market access is defined in equation 2.

$$MA_o = \sum_{d \neq o} \tau_{od}^{-\theta} N_d \tag{2}$$

To assess the effects of trade and spatial economic activity, I construct the 1880 measure of market access (MA) used in Donaldson and Hornbeck (2016). This measure is based on an general equilibrium model of trade. Market access is constructed using the networks of railroads, harbors, canals, and roads to construct a cost of shipping goods to markets weighted by population. Equation 2 shows the approximation used to construct market access for county $o$. The variable $N_d$ is population of county $d$, $\tau_{od}$ are the trade costs between county $o$ and county $d$, and $\theta$ captures the trade elasticity. The $\theta$ parameter comes from a distribution that captures how productivity differences across counties give incentives to trade, where these incentives are inversely related to $\theta$. The parameters $\tau$ and $\theta$ need to be assigned to calculate the approximation of MA. I use an estimate from Donaldson and Hornbeck (2016) of $\theta = 8.22$ as the baseline value for trade elasticity.[8] The

[8] I find that the estimates of the value of water power are robust to a wide variety of values for $\theta$ in the Appendix. Donaldson and Hornbeck (2016) use a nonlinear least squares routine to find the best fit on $\theta$ to

parameter $\tau$ is also based on the county-by-county transportation costs and average price per ton of goods from the Donaldson and Hornbeck (2016) for 1880.

To understand the role of water power on market access, I look at two measures: (1) indirect measures of water power on market access, defined by the network of costs between counties, and (2) railroad mileage. More productive counties with larger endowments of water power attract more market access because they produce more goods, attract households, and increase demand for connected infrastructure. I regress water power on the constructed measure of market access and railroad mileage by county to understand the indirect pathways in which water power agglomerates infrastructure. By interacting the coefficients of water power on market access and market access on land values, I arrive at an indirect value of water power as a source of agglomeration of infrastructure.[9]

One limitation of the data is that natural endowments of water power do not change over time, which makes it difficult to separate the pathways for economic value. While I include many spatial controls in the models, it is still a limiting factor in identification. Another limiting factor is the lack of availability of data from this time period. In particular, I lack detailed information on steam power adoption by county during the period. To address this shortcoming, I use a smaller sample of my data that contains steam power estimates from establishment-level data (Atack and Bateman, 1999). I also utilize information about the use of the Corliss steam engine in 1869 as a separate control for steam power gathered from a petition to Congress by George Corliss for an extension of patent rights for the engine.

## 2.2 Production Value of Water-Power Model

To measure the value of water power as a factor of production, I estimate a Cobb-Douglas production function. This model allows the decomposition of production and measures the elasticity of water power to value-added production. Value-added output (VA) is a function of technology (A), labor (L), capital (K), and power (HP). In the Cobb-Douglas form, it is represented in equation 3

$$VA = A\dot{K}^{\alpha}L^{\beta}HP^{\delta} \tag{3}$$

their data. Their empirical specification focuses on 1870 to 1890 and includes more counties, and I use their range of $\theta$s in this work.

[9]This method is sometimes called mediation analysis and is used in experimental economics and psychology to identify mediators, or pathways, to treatment effects in experimental data.

Transforming equation 3 using natural logs provides the specification used to estimate the elasticities of the inputs to production. This specification is provided in equation 4 and is indexed by establishment $i$.

$$ln(VA_i) = \kappa + \alpha ln(K_i) + \beta ln(L_i) + \delta ln(HP_i) + \epsilon_i \tag{4}$$

The Cobb-Douglas production function has been used extensively in estimates of production function, but in the historical use of the data, the estimates of power have not been included in most of the work on production; see, for instance, Sokoloff (1984). The lack of reliable power data from this early period is one reason why water power or steam power would be excluded from the estimates at an establishment or aggregate level. Another reason is that investments in water power are likely captured in capital invested, and therefore, they are integrated into the elasticity of capital. This simple production model provides a different approach in which to value water power from its most obvious economic benefit, a prime mover in manufacturing.

As an alternative, I also investigate the cost of water power in Section 4.5, though it is not clear that water-power prices are set competitively. Many water-power corporations have a local monopoly on water power and bundle water power with other goods and services. Therefore, to validate the estimation of water-power value as a prime mover, I look both at (1) the estimated benefit of water power to production explicitly using establishment-level production data and at (2) water prices at major water-power sites.

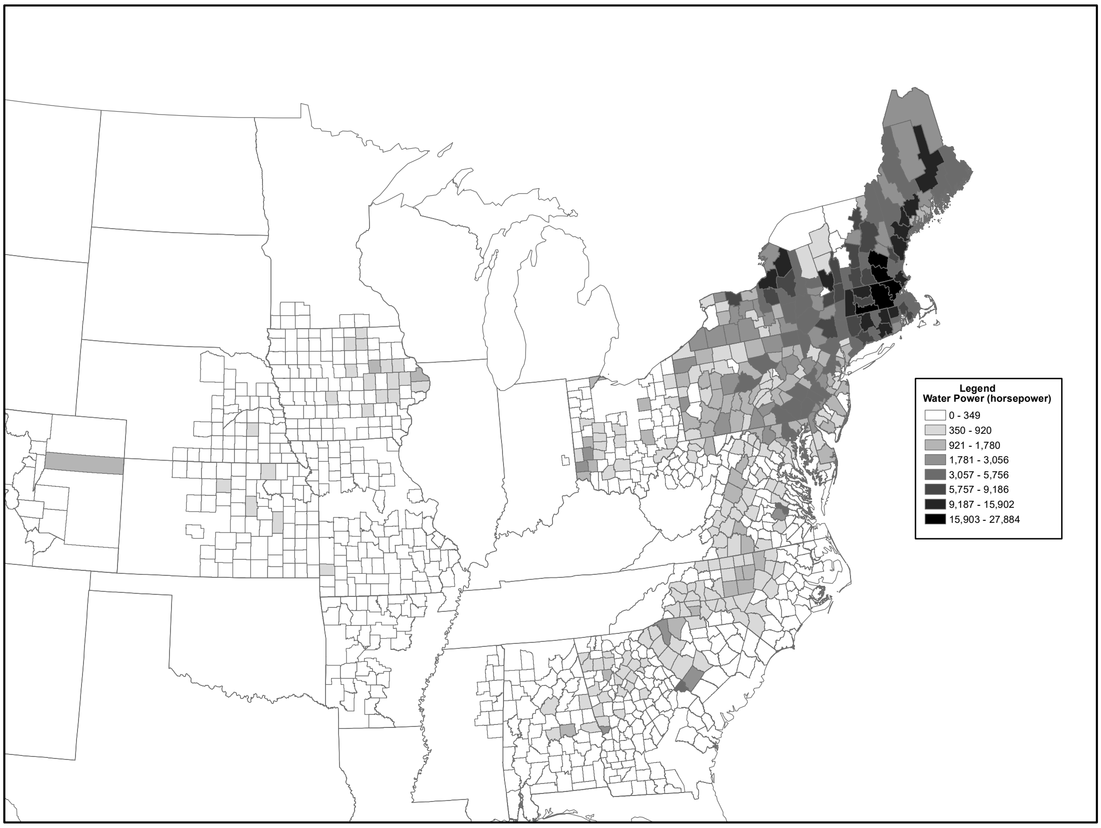
# 3 Data

## 3.1 The 1880 Report on Water Power

The water-power census was undertaken in the latter part of the nineteenth century and was the first of its kind in America. The enumerators of this report took on the arduous process of identifying and recording water power sites. Even though steam power had made its appearance long before 1880, water power was still a critical factor in manufacturing. The efforts to compile such an extensive report detailing American hydrology, the development of water power, and potential sites for water-power development demonstrate how important the government thought water power was to future generations.

The report was developed under the direction of Professor W. P. Trowbridge of

Figure 2: 1880 Water Power Census Data by County




Note. This map shows the county-level totals of water power from the 1880 Water Power Census. It contains 982 counties.

Columbia College. Enumeration was largely undertaken by three civil engineers in the field who traveled across America East of the Rocky Mountains to compile the report. They traveled extensively and estimated water power across many watersheds, speaking to the engineers who managed water power at large sites.

In 1880, the United States had 55,404 water wheels in use and approximately 1,225,379 horsepower used in manufacturing. No other country's water-power sites were so extensively developed.[10] Figure 2 shows the county-level totals of water power in horsepower from the digitized records. Darker shades indicate a greater amount of horsepower from water. There is considerable variation by county and clear regional differences in water-power endowments. Water power is concentrated in the north and drops off toward the South along the coastal plains on the eastern seaboard. The geography of the relatively flat coastal plains leads to a dramatic reduction in water-power sites. New England contains a high concentration of water power up through Maine and benefits from a number of smaller artificial reservoirs that regulate flow. The flows from south of Delaware are not regulated by any large lakes, which reduces seasonal low flow.

By 1880, steam power had also flourished in the United States. The aggregate power generated by steam had surpassed water power before 1870, yet water power had still grown modestly between 1870 and 1880. The primary difference between steam power and engines and water power is that steam power is mobile. Steam power is mobile in manufacturing or in the service of moving goods and people. Water power is constrained to a location with limited conveyance of water or power transfers. The natural landscape, the provision of water from nature, and the limits of engineering determine the potential power of a water-power site. 1880 was also on the cusp of the arrival of electricity, which further separates the value of a particular place for energy generation. By 1880, steam power costs were likely less than water-power costs on average (Atack et al., 1980) though the trade-offs were not always in favor of steam power. Fuel availability, mechanical expertise, and the availability of water power could make water power more attractive to a firm.

There is a strong correlation between water and steam power at the regional and state level, for several reasons. Many manufacturing firms that started with water power adapted to using steam at the same location. This inertia in the placement of industry and human capital is the first factor. Steam power is often used as a backup for water power

[10] Reports on the Water-Power of the United States p.11

when power needs are more significant than water power can provide. Depending on the fuel cost, water can be much cheaper than steam, though when streams are at a low flow or frozen during the winter, a firm with steam power can continue production while one running solely on water power must shut down. Without steam power, the seasonality of water flows in some regions dictated partial-year operations. Many locations suffered from the problem of water wheels that could not operate due to ice or because of low flows in the drier months.

The data from the 1880 water report was recorded at the site of water power being assessed. Each entry recorded the number of firms, county, state, stream, type of industry, and estimated horsepower utilized at that location. I aggregate this data by county and use it as the variable of interest in this analysis. The report also lists the major water-power sites that were developed, with estimates of the amount of horsepower theoretical available, in excess of the horsepower actually utilized. A gap exists between theoretical power and utilized power, for multiple reasons. The efficiency of water use is lower than optimal due to the management of a large power site, with many firms drawing water from power canals. Water wheels and turbines have friction and potentially inefficient design and construction, and correctly sizing a wheel means that there will be additional inefficiencies during high and low flows. Leakage and overflows are common in the operation of water wheels, dams, and power canals. Additionally, low flows can hinder the potential power at a site. A range of power is available given the seasonal variation in rainfall and snowmelt and the watershed's storage capacity. Water-power companies may have reserved some rights to compensate for the natural variation and low flows in river systems. Lastly, at some major powers there is excess water power available.

In the primary analysis, I use the utilized horsepower to measure water power and use excess theoretical power in a robustness check. I exclude counties that do not have estimates of water power from the 1880 report. The report is geographically incomplete due to a lack of funds available to finish it. The report also notes that some areas are excluded due to unremarkable water power or lack of regular flow. Yet, given the lack of data over large areas, I do not impute data over the missing counties. Some power sites may not be developed due to high costs or other trade-offs, such as minimal flows, transportation networks, and capital necessary to develop the sites. I consider the report complete for the areas included and incomplete for areas not enumerated.

### 3.2 Other County-level Data

County-level data of population and the total value of agricultural land are drawn from the U.S. Censuses of Agriculture and Population (Haines, 2005). A variable of interest, the dependent variable, is the total value of agricultural land from 1880 by county. The total value of agricultural land combines land, buildings, and improvements.[11]

Market access data is constructed from 1880 data using the networks of railroads, harbors, canals, and roads and associated costs of shipping goods to markets weighted by population. I use market access to capture the economic trade connections between counties in the empirical specification.[12]

To complement the census and water-power data, I collect a number of other environmental controls. I use measures of soil quality (Ph, soil depth, organic matter, water in soil) and climate (mean temperature, average annual precipitation) to control for differences in land productivity.[13] These variables, state fixed effects, and cubic functions of latitude and longitude are the controls in the baseline regressions.

### 3.3 Establishment Level Data

I also use data collected from the census rolls of the 1880 Federal Census of Manufacturers to estimate production functions. The data is a sample of nationally representative establishments collected by Atack and Bateman (1999).[14]

1,034 records have water-power reported from the nationally representative 1880 sample.[15] I use capital invested, the count of workers as labor, the value-added output, and horsepower.[16] The large majority of establishment observations with complete power

[11] Fogel makes an adjustment by state to exclude the value of buildings and land improvements to estimate the "true" value of agricultural land by state Fogel (1964) for 1890. The regression results are unaffected by the unadjusted land values because they contain state fixed effects.

[12] There is a concern that market access is endogenous with land prices since population is in the definition of market access, and the own county MA is excluded from the definition of market access. Several robustness checks in Donaldson and Hornbeck (2016) demonstrate that their baseline definition of market access is robust to shocks in neighboring counties, population adjustments, and adjustments for international ports.

[13] Soil quality data is from the U.S. General Soil Map developed by the National Cooperative Soil Survey, available through https://www.nrcs.usda.gov/. Long-term climate variables were attained by the U.S. Forest Service for the period from 1975 to 2005 from https://www.fs.fed.us/rm/boise/AWAE/projects/national-forest-climate-change-maps.html.

[14] The manufacturing census data are available online at http://www.vanderbilt.edu/Econ/faculty/Atack/atackj.htm

[15] The extent of power estimates by establishment that are missing is unclear, though I expect some power estimates to be missing because in some cases no horsepower estimates are reported, whereas sizable labor and capital categories are. In earlier national samples from this same source, there are more considerable disparities in reporting power. The 1850 and 1860 censuses are not practicable to use for power estimates due to missing data.

[16] To account for entrepreneurial labor, I use the Sokoloff adjustment and add a count to labor for to each firm.

records are of grain and grist mills and sawmills. There are 548 grain and grist mills and 293 sawmills; all other industries have a small number of records.

The sample of textile establishments in the nationally representative data is too sparse on its own to enable estimation. I supplement this analysis with a collected sample of textile establishments from the manufacturing census rolls of 1880 from Massachusetts and New Hampshire. Textiles are a well-known industry that was relatively automated by 1880. This sample is gathered by recording every textile establishment in the manufacturing rolls in those two states with inputs, outputs, and horsepower estimates. I obtain 94 textile establishment-level records.

One limitation of using water power in the estimates of production functions is that capital invested in real estate typically includes the cost of water-power sites. Establishment owners would pay a premium for land with good prospects for water power.[17] The values of land and water power are not separable from the records available. I therefore expect that some of the variation attributable to prime movers is captured by capital. This variation should have a downward bias effect on the elasticity of water power in the production function, suggesting that estimates would be a lower bound on the actual estimates.

# 4 Results

## 4.1 Aggregate Value of Water Power

Table 1 reports the estimates of the aggregate value of water power. These results use equation 1 to estimate the effect of the logarithm of water power on the logarithm of agricultural land prices of County $o$. Column (1) reports the baseline results without additional spatial controls, but includes state fixed effects. Column (2) includes state fixed effects and market access as a control for spatial economic activity. Column (3) includes cubic functions of latitude and longitude. Column (4) includes soil and environmental controls (Ph, soil depth, organic matter, water in soil, mean temperature, mean annual precipitation). Column (5) uses spatial and environmental controls but excludes market access as a control. Column (6) includes all of the controls and is the most comprehensive and will be referred to as the baseline estimate going forward.

These estimates suggest that water power is highly valued. To put the value into

[17] I find explicit rights to water power only at major water-power sites. Yet smaller mill firms would also be expected to pay a premium to be able to locate their mills at better and more reliable water-power sites. A suitable micro-level data set of land sales and water power is difficult to obtain for this period.

Table 1: Impact of Water Power on Agricultural Land Prices

| | Log Value of Agricultural Land | | | | |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) |
| log WP | 0.268 | 0.228 | 0.216 | 0.211 | 0.232 |
| | (0.032) | (0.031) | (0.032) | (0.034) | (0.035) |
| Market Access | N | Y | Y | Y | N |
| Spatial Controls | N | N | Y | Y | Y |
| Environmental Controls | N | N | N | Y | Y |
| $N$ | 982 | 982 | 982 | 982 | 982 |
| $R^2$ | 0.724 | 0.777 | 0.789 | 0.812 | 0.799 |

Notes. Clustered standard errors by state are in parentheses. All regressions include state fixed effects.

monetary units, I evaluate the change in land prices at the means of the data. I find the aggregate value of one horsepower of water power is $294.[18] This substantial value reflects the permanent value of one horsepower of water power in 1880. This value includes value derived from manufacturing and the indirect value of agglomeration of economic activity. The elasticity of market access is 0.639, which is very similar to the estimates of market access from Donaldson and Hornbeck (2016). The indirect value of agglomeration is investigated in Section 4.3.

## 4.2 Robustness to Steam Engine Adoption, Population, and Railroads

To control for the use of steam power, I use data from the nationally representative sample of manufacturing establishments from 1880. I sum the steam power at the county level and use the total reported steam power as an additional control in the regression. While the national sample reduces the likelihood of bias in selection spatially, there still may be bias in reporting of power estimates that sampling does not eliminate. I use the manufacturing census for steam power data because the 1880 water power report is highly incomplete. The enumerators did not consistently record steam power at water-power sites and the data is severely limited. Another source of steam power data is the aforementioned petition to Congress submitted by George Corliss in 1869 to ask for an extension of patents for the Corliss steam engine, a high-pressured version of the steam engine. The petition included 256 owners of Corliss steam engines across the country.

[18] This is obtained by applying the marginal change in water power from Table 1, column (4) evaluated at the means of log-adjusted land value and the mean of water power. The adjustment to land values follows Fogel (1964) to eliminate buildings and improvements in order to reflect solely the value of the land. I take the adjustment factors from 1890 by state and apply them to the 1880 land values in order to estimate the true value of the land.

This source contains roughly 15% of all Corliss or Corliss-type steam engines in the country (Hunter, 1985; Rosenberg and Trajtenberg, 2004) and may also be biased, given that Corliss engines were not nationally representative of all steam engines and were concentrated in the northern and mid-Atlantic states.

Table 2: Robustness of Impact of Water Power on Agricultural Land Prices

| | Log Value of Agricultural Land | | | | |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) |
| log WP | 0.211 | 0.201 | 0.314 | 0.157 | 0.195 |
| | (0.034) | (0.040) | (0.087) | (0.026) | (0.036) |
| Railroads | N | N | N | Y | N |
| Steam power | N | Y | N | N | N |
| Corliss engines | N | N | Y | N | N |
| Population | N | N | N | N | Y |
| $N$ | 982 | 689 | 209 | 982 | 972 |
| $R^2$ | 0.812 | 0.806 | 0.616 | 0.846 | 0.821 |

Notes. Clustered standard errors by state are in parentheses. All regressions include state fixed effects, cubic functions of latitude and longitude, and environmental controls (Ph, soil depth, organic matter, water in soil, mean temperature, mean annual precipitation). Railroad controls use number of miles of railroad within a county with a buffer of 1 mile. Steam power controls uses the national representative sample of reported steam power by horsepower by county. Corliss engines controls use the horsepower of Corliss engines by county.

Table 2 shows my baseline result in column (1). Column (2) reports the results with the additional control of steam power as a control. Column (3) uses the Corliss engines estimates of horsepower as a control and restricts the sample to states listed in the Corliss petition to Congress. Column (4) reports the addition of railroad mileage by county as a control for infrastructure.[19] Column (5) includes the population of counties as a control. There is a slight decrease in water-power elasticity with the population as a control variable, but it does not appear statistically significant.

The addition of these controls does not significantly change the estimated elasticity of water power. Steam power, in particular, does not reduce the estimates of the value of water power. Column (3) finds a higher value of water power with Corliss steam engines as a control. The increase in the value of water power is due to the regional restriction of the sample, which focuses on the mid-Atlantic and New England. I do find that railroads reduce the elasticity of water power. Since railroads and water power are correlated

[19] While I rely on market access to capture infrastructure network dynamics, my estimate of market access may be imperfect, so I also explore railroad mileage.

factors in land value, I investigate, in the next section, whether water power affects land prices through attracting railroad infrastructure.

### 4.3 Indirect Effects on Value through Transportation Networks

One indirect pathway in which water power increases land values is through the agglomeration of infrastructure. I measure the indirect value and estimate the effect of water-power endowments on market access and railroad miles. Table 3 shows the effect of water power on railroad mileage in columns (1) and (2). Columns (3) and (4) report the effects of water power on market access. The results suggest water-power endowments increase market access, likely through increases in railroad construction.

The economic significance of indirect pathways can be estimated by combining the coefficients of the log of water power (log HP) from Table 3 and the coefficients of market access or railroads on the value of agricultural land from Table 2.[20] The indirect effect of one additional horsepower of water power on the value of agricultural land through railroad mileage is 5.5%. This comports with the aggregate value being largely made up of a direct effect of water power for manufacturing of approximately 15.7%, and an indirect value through transportation networks of 5.5%. The aggregate effect is almost identical to my baseline estimates of a 21.1% increase in agricultural land for an additional horsepower of water power. The indirect effect of one additional horsepower of water power on the value of agricultural land through market access is 1.4%.[21]

Table 3: Water-Power Effects on Transportation Networks

| | Railroad Mileage | | Market Access | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| log WP | 16.551 | 13.452 | 0.025 | 0.022 |
| | (3.785) | (3.827) | (0.009) | (0.009) |
| Population | N | Y | N | Y |
| Spatial Controls | N | Y | N | Y |
| $N$ | 982 | 972 | 982 | 972 |
| $R^2$ | 0.626 | 0.677 | 0.602 | 0.605 |

Notes. Clustered standard errors by state are in parentheses. All regressions include the controls of state fixed effects and the cubic functions of latitude and longitude.

There is a potential issue of endogeneity of railroad infrastructure and land prices.

[20] The coefficient from Table 2, column (4) for railroads mileage is 0.004.

[21] I am using the baseline estimate of market access on land values of 0.639 from column (4) of Table 1. This value fluctuates significantly with the value of theta as reported in the Appendix.

While natural endowments are exogenous to land prices, the choice of where to build railroads is likely to include aspects of choice based on local land prices, which creates the endogeneity issue. While the primary aggregate estimates of water power are not affected by this issue, the indirect effect of market access on land prices could be affected by endogeneity.

The natural substitutability of railroads and water infrastructure is used as an instrument for the estimates of the indirect effects on market access. Since natural waterways should reduce the need for railroad infrastructure, they may act as an instrument for changes in the railroad network.[22] It is expected that counties with natural waterways will naturally have greater market access and less need to build railroads over time.

Table 4: Market Access Impacts on Land Value: Instrumenting with Waterways

| | log MA 1880 | Log Value of Agricultural Land | |
|---|---|---|---|
| | (OLS) | (2SLS) | (OLS) |
| log WP | 0.030 | 0.180 | 0.212 |
| | (0.009) | (0.025) | (0.034) |
| log MA | - | 2.290 | 0.096 |
| | - | (0.524) | (0.020) |
| Waterways (miles) | 0.003 | - | - |
| | (0.001) | - | - |
| $N$ | 973 | 973 | 982 |
| $R^2$ | 0.619 | 0.714 | 0.812 |

Notes. Clustered standard errors by state are in parentheses. All regressions include the controls of state fixed effects and the cubic functions of latitude and longitude.

Table 4, column (1) reports the first-stage results of the IV regression. The second stage results are reported in column (2), and for comparison, the baseline results are reported in column (3).

The size of the effect of market access is larger using the IV regression.[23] Correcting for endogeneity increases my estimate of the indirect effects of water power on attracting market access, so that the indirect effects are now 6.9%. The aggregate effect of water power on land values is 24.9%, which is in the same range as the main results. The size of the effect of market access is rather large compared to the baseline results. It may be that

[22] Donaldson and Hornbeck (2016) use the market access of natural waterways as an instrument for the effect of the change in market access on land values in a similar exercise. The main difference is that they are instrumenting on market access and using the change in market access from 1870 to 1890. I am estimating in the cross section of the data in 1880.

[23] This finding is similar to that of Donaldson and Hornbeck (2016), so it is expected.

the size is an indication that the necessary assumption of non-exclusion is violated.

I conclude that the indirect effects of water power have significant effects on the development of transportation networks, though these effects are smaller than the direct effects of water power on land values derived from manufacturing. I explore a validation of this conclusion by inspecting establishment-level production data to estimate the direct value of water as a prime mover in manufacturing.

### 4.4 Production Value of Water Power

I present the estimates of water power as a function of production in Table 5 using the national samples from Atack et al. (2008a) and my collected sample of textile establishments from 1880 in Massachusetts and New Hampshire. Table 5 includes results of 1880 data in column (1) with all establishments given water-power estimates from the nationally representative sample; a steam power fixed effect is included for establishments that have recorded that some or all of their power comes from steam. Column (2) excludes establishments that record using steam power. Column (3) uses the sample of textile establishments from Massachusetts and New Hampshire, and includes a fixed effect for steam power. Column (4) excludes establishments that record using steam power using the textile-only sample.

The elasticity of water power to value-added output is approximately 0.188 in 1880. This translates to a mean value of $12 per horsepower. This estimate is in line with the lower end of prices for water power at many major power sites, as discussed in Section 4.5. Table 5, column (3) suggests that the factors of production for water power are much higher for the textile industry than for other industries. The nationally representative sample is primarily composed of grain and lumber mills. The estimates in column (3) also show a hefty premium for establishments with steam power, which follows from the intuition that they have more flexibility in production and can remain open all year. The value of one horsepower in water power is $55 in the textile industry using column (3) from Table 5. This value is much higher than the average value using the nationally representative sample. The rate of $55 per horsepower is more in line with the rates of surplus power at major power sites and suggests an even higher value to water power at major industrial centers such as Lowell and Lawrence.

Since the estimates are an annualized price, I transform them to obtain the permanent value of water power. I use a 6% rate to discount future periods into 1880 dollars (Swain, 1888; Fogel, 1964).[24] At a 6% interest rate, the permanent right to a horsepower of water is approximately $200 based on the nationally-representative sample. The textile establishments have a larger value of $916. These estimates comport with the main estimates of the value of water power. The estimate of the nationally-representative sample supports the estimate of the direct effects of water power being close to 68% of the aggregate value, with indirect values making up the rest of the $294 of the value of one horsepower of water-power endowment. Provided that the mix of industries in the national sample may exclude more automated industries with a higher direct value as a prime mover, the 68% is a lower bound of the value of water as a prime mover.

I suspect the complementary nature of power and high automation in an industry such as textiles makes water power more valuable in production. There are regional differences driving this value as well, since concentrations of water power are greater in the Northeast than in other regions. The considerable heterogeneity in the value of water power in production by industry could be caused by automation and regional constraints on the supply of water power.

I surmise from these estimates and the aggregate estimates in Table 5 that water power provides the most value through manufacturing as a prime mover, and second as an agglomerate of economic infrastructure.

It is difficult to speculate on the value of water power earlier than 1880 due to the lack of high-quality data. There is evidence of an increasing capital deepening during the Industrial Revolution Atack et al. (2005). As manufacturing moved from artisan workshops into more automated processes and specialized production processes, the factors of production relied more heavily on water power. Over time, as water power was used more aggressively to help automate factories, the value of water would increase with automation. Moreover, the amount of automation and reliance on water power as a prime mover by industry and region should vary the value of water in manufacturing. This is supported by the higher elasticity I find for water power in the textile industry.

However, with the onset of steam power, the importance of water would likely decline. These estimates may be an upper bound on the value that water power had as the prime mover in production.[25] As steam power continued to spread and electricity spread, the

[24]Capital is priced at 6% in locations that leased water power according to the water-power report. Fogel (1964) uses a national mortgage rate of 7.84% to capitalize railroad values.

[25]This is also supported anecdotally by the fact that the Lowell water-power supplier, the Lake Company, located in New Hampshire, was sold off in 1890 as more steam power allowed for companies in Lowell to maintain power during low flows.

Table 5: Production Function Elasticity Estimates of Water Power

| | Log of Value Added Output | | | |
|---|---|---|---|---|
| | (1) All Industries | (2) All Industries | (3) Textiles | (4) Textiles |
| lnK | 0.317 | 0.308 | 0.250 | 0.174 |
| | (0.035) | (0.037) | (0.098) | (0.147) |
| lnL | 0.699 | 0.684 | 0.364 | 0.330 |
| | (0.057) | (0.063) | (0.123) | (0.190) |
| lnHP | 0.183 | 0.188 | 0.445 | 0.652 |
| | (0.046) | (0.048) | (0.126) | (0.227) |
| Steam | -0.062 | - | 0.241 | - |
| | (0.115) | - | (0.198) | - |
| $N$ | 1034 | 942 | 94 | 35 |
| $R^2$ | 0.666 | 0.599 | 0.729 | 0.768 |

Notes. Clustered standard errors by state are in parentheses. All regressions include the controls of state fixed effects and the industry classification fixed effects. Column (1) uses the nationally representative sample of establishments. Column (2) is a restricted sample of establishments with water power but without steam power reported from the nationally representative sample. Column (3) includes a sample of textile establishments from 1880 in Massachusetts and New Hampshire. Column (4) includes the sample of textile establishments from 1880 in Massachusetts and New Hampshire but restricts the sample to firms that do not report steam power.

old water wheel became more obsolete in relation to the needs of manufacturers.

### 4.5 Water-Power Prices

There is ample evidence of the cost of water power during the Industrial Revolution from major power sites, such as Lowell, Massachusetts. In Lowell, twenty miles from Boston, the Proprietors of Locks and Canals company held and sold water rights to the mills. The first mills bought water rights with the land. Major power sites would then sell permanent water rights or lease water power. In Lowell, the first issuance of water rights was from the Proprietors of Locks and Canals to the mills' owners, who were the same. The capital stock of the Proprietors of Locks and Canals was owned by ten large manufacturing companies using the power. The ownership of water rights were permanent leases proportional to the ownership of capital stock in the power company. Cash payments for mill powers were made at incorporation at the rate of \$10,000 and a reserved rent of \$300 per mill power per annum. Mill power is equal to 85 theoretical horsepower or 25 cubic feet of water at a 30-foot fall, established as a water rights unit from the Waltham experiment. Similarly, at Lawrence, MA, a mill power was originally valued at \$15,000.[26]

The costs of water rights represented a share of building and maintaining the dams and canals that provided power. It was thought that the terms of these agreements were quite generous for the times. In 1890, the hydraulic engineer Joseph P. Frizell stated in a report to the City Council of Austin about the value of water power for a proposed dam site across the Colorado River: "It is not easy to state the rental received for water power at the great manufacturing centers in New England, as grants of water are usually covered with grants of land, the water being regarded as an easement of the land. A round sum was paid for the land and a nominal rent for the water, which was intended as the fund for the maintenance of the appliances of the water power. When manufacturers draw in excess of their grant, they are charged all the way from \$3 to \$12 a day for a mill power for water terminable at will. My opinion is that \$1,200 per annum fairly represents the value of mill power."[27] This value would make the costs at Lowell a fairly low value. The value of the leases for water power was favorable. However, the Proprietors of Locks and Canals

[26] There were slight differences in the definition of mill power between Lawrence and Lowell, as well as other major power sites. The approximation to 85 gross or 62 net horsepower is fairly accurate. Other reasons for variation in the actual horsepower delivered are the efficiency of waterwheels at the mills, the efficiency in water use and backflow in power canals, and the efficiency of water use during operations and storage during downtimes.

[27] Quoted by Thomas U. Taylor, Taylor (1900) p. 15

earned back favorable conditions on the sale of real estate, machinery, and equipment.[28] These conditions suggest that the value of water power was greater than the lease prices for water power.

Table 6 shows the costs of water power across different sites, adapted from Swain (1888). Surplus rates represent water used above a company's permanent water rights per day. A chief engineer regularly measured the water levels in the canals to ascertain how much water power each establishment used and notified the companies of surplus charges to each user. This exacting recording of water use was in place to ensure that mill power was available to the allotted establishments and waste did not occur. While the initial cost of water power from the Proprietors of Locks and Canals may have been favorable, the surplus charges exceeded this cost by a substantial amount. Table 6 shows a considerable variation in water costs across the United States. Even where the cost of water power remained high in New Jersey, all the available power was in use.

In Lowell, the prices did not change often, yet rate increases did occur. Initially, rates of \$3.50 per mill power per day and \$7.00 for a mill power per day of surplus power. Through three additional rate changes, the daily rates of surplus power changed to \$5.00, \$10, and \$20 per mill power per day for less than 40%, 40% to 50%, and greater than 50% of water power used. In Holyoke, when power supplies became limited due to demand, the rate of surplus water was increased, and additional regulatory controls were enacted.[29] These actions suggest that the permanent rights were generously priced and that the actual value exceeded the base rates at which water power was procured.

The management of flows in the water-power system was complex. When floods threaten to damage equipment or overwhelm the infrastructure, a condition known as "backwater," companies at Lowell were allowed to draw unlimited excess water above their permanent right for \$1.00 a day per mill power of original lease, a fraction of the permanent mill power cost. Conversely, when low flows and droughts threatened the water supply, companies were restricted from taking excess water(Hunter, 1979). When restrictions were in place for surplus water use in Lowell, any company using an excess of what is allowable was charged \$75 per mill-power per day. These pricing mechanisms suggest that external costs and benefits were priced into the daily water use.

[28] Hunter (1979) p.215.
[29] Hunter (1979) p. 229

Table 6: Annual Cost of Water Power at Major Power Sites

| Location | Type | Cost per HP |
|---|---|---|
| Lawrence, MA | Original | $15 |
| "" | Surplus up to 20% | $20.61 |
| "" | Surplus 20 to 50% | $41.22 |
| Lowell, MA | Original | $15 |
| "" | Surplus up to 40% | $25.75 |
| "" | Surplus 40 to 50% | $51.50 |
| "" | Surplus 50 to 60% | $103.00 |
| Manchester, NH | Surplus power | $25.75 |
| Saco and Biddford, ME | Surplus power | $15.45 |
| Lewiston, ME | Ordinary leases | $2.50 to $12.50 |
| Windor Locks, CT | according to fall | 8.00 to $27.00 |
| Holyoke, MA | | $12.87 |
| Bellows Falls, VT | | $7.50 |
| Rochester, NY | | $25.00 |
| Passaic, NJ | | $47.50 |
| Paterson, NJ | | $51.00 |
| Trenton, NJ | | $53.00 to $71.00 |
| Fredericksburg, VA | | $5.00 to $15.00 |
| Augusta, GA | | $5.50 |
| Dayton, OH | | $43.00 |
| Lawrence, KS | | $20.00 |

Note. Source: Water Power Census of 1880.

Table 7: Annual Cost of Water Power at Canals

| Canal or Company | Cost |
|---|---|
| Delaware and Raritan Canals | $3 per square inch |
| Lehigh Canal and Navigation Company | $1-$4 per square inch |
| Schuykill Navigation Company | $6-$7.50 per square inch |
| Pennsylvania canal | $2-$5 per horsepower per annum |
| Chesapeake and Ohio canal | $2.50 per square inch |
| James River and Kanawha canal | $6-$20 per horsepower per annum |

Note. Source: Water Power Census of 1880.

Mills located at smaller water-power sites sometimes leased part of the power available or rented floor space in the mill building. For instance, the Slater Mill in Rhode Island rented the upper floor of their yarn mill for $100 per horsepower.[30]

Another source of water-power prices is from water leased from canals. Excess water not needed for navigation can often be diverted at dams and locks along the canals for sale to manufacturers. Table 7 lists the major canals with rates of horsepower listed in the 1880 report. Many of the rates at canals are variable to conditions, meaning that only surplus water is leased as the water levels for canal traffic are the priority. The rates are similar to many of the rates at major power sites where conversions to horsepower are available[31].

These water-power prices, especially at the higher end of the range, support my estimates of water-power elasticities from production as the full value of water power for production in textiles. The surplus rates at Lowell that are greater than $100 per horsepower likely represent a scarcity rent when water power is at full capacity and overuse generates significant externalities on other establishments with permanent rights to water. The centralization of water-power companies in mill towns appears to have resolved the complex externalities between establishments using the same water-power supply.[32] The higher end of water-power costs show the economic value that water continued to play in manufacturing in 1880.

While there is a wealth of price information in 1880 from the water-power report,

[30] Water Power Report pg. 14.

[31] The Lehigh Canal and Navigation Company provide data to compute these conversions which vary between $7 and $27 per horsepower.

[32] This does not presume that externalities across the watershed did not exist, especially when considering the fluctuations in supply by the use or capture of water at dam sites.

some water rates and land sales can be traced from earlier periods. In Paterson, New Jersey, the cost was $51 per horsepower cost in 1880, but the rates for water rights that came with a lot in 1792 were most likely lower Fries (1975).[33] The initial prices seem to be set based on the cost of building the infrastructure rather than any demand for water power. Atack et al. (1980) show in simulations that the costs of providing water power decreased between 1830 and 1880. This decrease in the cost of water power was slower than the decrease of the cost of steam power over the same period, explaining the increased adoption of steam power. At Biddeford and Saco, Maine, the price of water-power rights varied between $2.50 and $12.00 per horsepower per annum, with favorable rates afforded to the original corporations. It appears that the price to obtain water rights may have increased during this period though the cost of procuring and maintaining water-power equipment decreased over time. Prices at major water-power sites were set favorably to the original lessees, who were sometimes the owners of the water-power companies, and then raised after the original business concern was well underway. Surplus rates were used to contain overuse of the available water power. It could be that favorable prices were set to attract companies to establish themselves or that other services were sold in conjunction with water rights, such as equipment, to make the enterprise profitable.

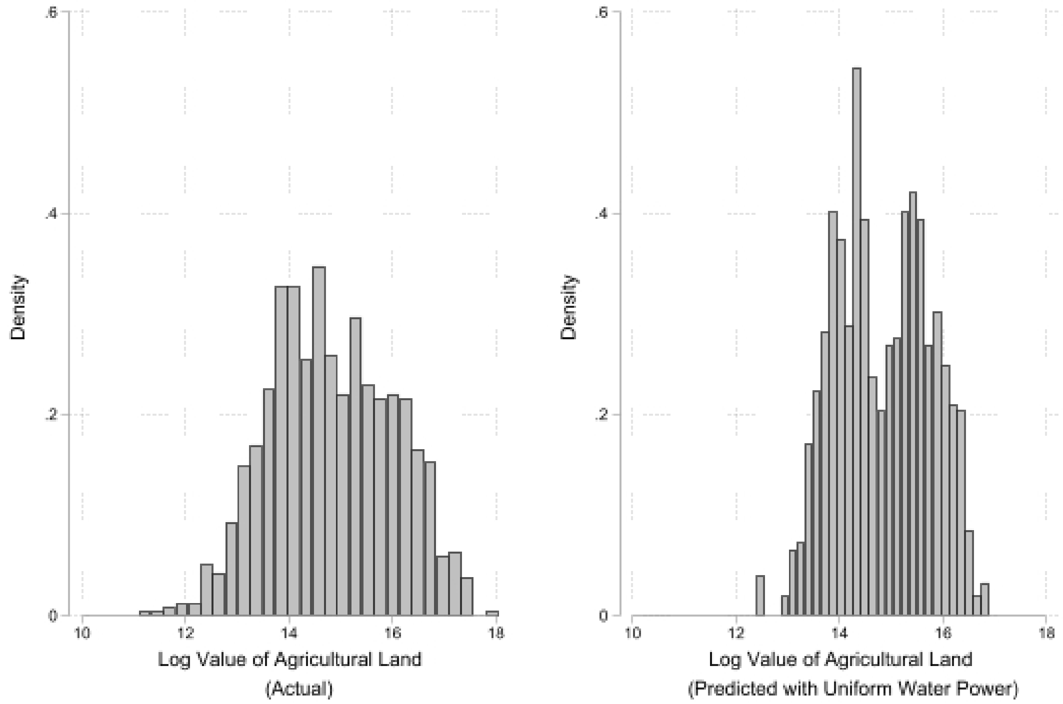
# 5 Counterfactual Analysis

Some simple counterfactual analyses are done using the above results. First, I calculate the reduction of economic value if water power were dispersed evenly across the country. This analysis estimates how much of the dispersion of economic growth is due to the natural dispersion of water-power endowments. Second, I compute reductions in water power to understand the relative importance of water-power endowments compared to railroads. Comparisons between water power and market access are made with the estimates of the elimination of all railroads in Donaldson and Hornbeck (2016), which they find is equivalent to a 60% loss in agricultural land values.

The dispersion of economic activity is one of the motivations of this paper. I use the Column (4) of the model in Table 1 to predict land prices with uniform water-power dispersion in order to create a counterfactual of what land prices would look like if there was no concentration of water power in the Northeast. Figure 3 compares the actual

[33] Lots were sold for $400, which included water power to turn two millstones, one half square foot of water and a twenty-foot head, which would take approximately 10 horsepower.

Figure 3: Histogram of U.S. Land Values at 1880

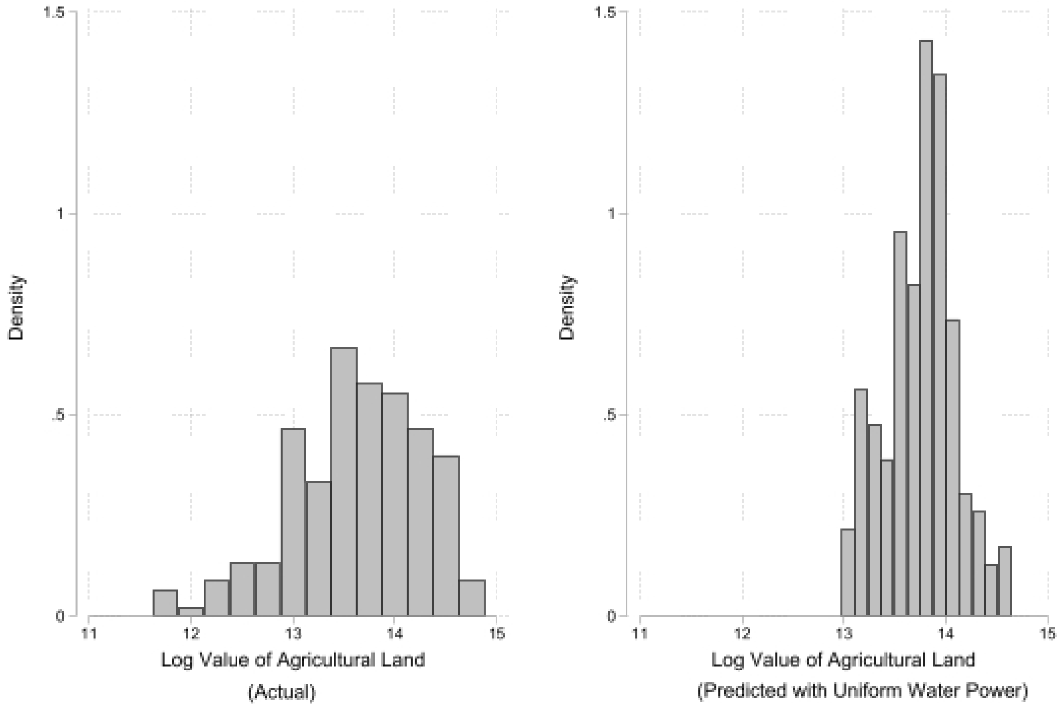



histogram of the log of agricultural land prices with the predicted agricultural land prices, assuming the average water power is dispersed evenly across the counties in my sample. This figure shows a significant shift and tightening of the distribution with a uniform water-power distribution. The uneven dispersion of water power has a considerable economic effect on the distribution of land values.

Figure 4 shows the histogram of the logarithm of land prices for Georgia, Mississippi, and Alabama to demonstrate the regional distribution effects of a uniform distribution of water power. The uniform distribution of water power shifts land prices significantly upward. It benefits rural counties with low water-power endowments, shifting the mean and median upward.

The second counterfactual analysis estimates the economic value lost if water power endowments were lost. Using the prediction of land prices from Column (4) of Table 1 suggests a 75% loss in agricultural land prices occurs when all water-power endowments are lost. This is a considerable portion of value that is lost. The estimate must be considered with caution since it is predicting out of sample with water power being projected at 0 for all counties, something that does not occur in the data. Losses of water power of 25%, 50%, and 75% generate a 37%, 54%, and 66% loss in agricultural land

Figure 4: Histogram of Southern State Land Values in 1880




Note. The states included in this figure are Alabama, Mississippi, and Georgia.

value, respectively. The main estimate of the loss of railroads is 60% (Donaldson and Hornbeck, 2016), using a similar valuation method. These considerable losses suggest that water-power endowments are just as valuable as railroads as measured through market access.

In the above counterfactual analysis, I make several assumptions. First, that population and infrastructure do not change in response to water-power endowments. I assume that market access and water-power endowments are separable in this analysis. The change or loss in water power affects the distribution of railroads and market access. Some portion of market access may therefore be lost, or differ, with a loss in the natural endowments of water power. I also assume that steam power develops at the same speed and distribution across space. It is likely that, without the abundance of water power, the industrialization of America would not have occurred in the same way or would have been delayed significantly. On the other hand, without significant water-power endowments, it is possible that manufacturers would have adopted steam power faster and perhaps increased the speed of technical development of safe high-pressure steam engines and human capital in repairing engines. Both in America and Great Britain, areas endowed with less water power lagged in the process of industrialization(Gordon, 1983), suggesting that development would probably have been slower without water power. Identifying the causal influence of natural endowments on the adoption of the steam engine is beyond the scope of this analysis. However, the counterfactual analysis depends on how a vacuum of water power would have changed the composition of industry and how new technologies would have been developed and adopted by manufacturers. Perhaps the distribution of manufacturing and specialization in production would have shifted to industries less reliant on power and machine automation.

## 6 Discussion

Natural endowments of water power were valuable–potentially more valuable than the railroad system. Even so, natural endowments can go undeveloped and be less valuable to economic activity for a variety of reasons. In the South, there are several underdeveloped water-power sites. The South had fewer large power sites to develop, yet still left significant available horsepower unused. One reason is that capital was more readily available in the Northeast, based on generations of earnings from overseas trade. The availability of power is thus not the only factor involved in recognizing the gains enabled by water-power endowments. The employment of capital to realize the gains from automation and from developing large amounts of water power, when advantageous and close to trade infrastructure, is critical to the value of water power. A significant amount of capital was needed to build a dam and power canals to distribute power to mills effectively. At Augusta, Georgia, the development of water power along the Savannah River of over 3,600 horsepower required an investment of over $800,000. For reference, the cost of the power plant at Lowell, Massachusetts was approximately $2,500,000, and the primary companies using the Lowell power system were well capitalized. Nevertheless, at some developed sites, such as Richmond, Virginia, a significant amount of horsepower went unused. There are factors beyond natural endowments of water power that led to the growth of Lawrence and but not Richmond as a center for manufacturing.

The infrastructure developed to increase market access to water-power sites is a critical aspect of the aggregate value of water power. Before the Industrial Revolution, sites of villages were often chosen based on closeness to a mill site, especially in the New England region where many such sites were available. As major water-power sites began to be developed, such as Lowell, Manchester, and Lawrence along the Merrimack River, these water-power locations attracted the additional infrastructure to carry goods to markets. New England has the natural advantages of the fall lines being closer to the coast than in the South, which provides a shorter distance to ship goods to the coast.[34] Before railroads, natural navigable waterways played an essential role in bringing goods to market. The endogenous growth of railroads increased the value of existing mill towns when expanding market access and reduced the dependency on natural navigable waterways.

Water-power sites were valuable, and the land around developed water-power endowments became more valuable as a result. This paper provides estimates of this value to give context and comparisons with it. Further, the actions of manufacturers give further support to the value of water found here. The benefits from production suggest a higher value of water power than the leased prices. Water-power companies took great pains to secure land that guaranteed a consistent supply of water power, which could be used or leased out. The Essex Company, a power company in Lawrence, Massachusetts, and the Proprietors of the Locks and Canals in Lowell, bought the water rights of the Merrimack River up to Lake Winnipesaukee in New Hampshire in order to secure a consistent supply of water for power. The Lock and Canals company spent approximately $430,000 to acquire an additional supply of water power from the reservoirs in New Hampshire. In turn, they sold water-power leases worth over $500,000 from the additional capacity.[35]

# 7 Conclusion

This work estimates the historical value of water-power endowments in America during the Industrial Revolution using the water-power report of 1880. This approach uses agricultural land prices to value the direct and indirect values of water-power endowments, water as a prime mover, and water as a factor in the agglomeration of transportation infrastructure. The aggregate value of one horsepower is valued at $294. The value as a prime mover is at least 65% of this value. The agglomeration of people and infrastructure that expanded the access to markets also provides significant value to areas endowed with water power. I validate the direct value of water power by using establishment-level production data and water-power prices at major water-power sites.

Water-power endowments are arguably just as important as the railroad to economic

[34] "The head of navigation on the Alabama River is over 300 miles from the Gulf,.....while in New England navigation on the rivers is not carried over 50 miles from the coast, and rarely that." Reports on the Water-Power of the United States p.20.

[35] Hunter (1979) p. 264.

growth during the nineteenth century. I find that the estimated value of lost water-power endowments is similar to that of lost railroad infrastructure from Donaldson and Hornbeck (2016). The loss of the railroad is estimated to cost 60% of agricultural land value, while a 50% loss of water-power endowments cost 54%. Though the focus of historical inquiry on steam and automation has eclipsed water power in the literature, the Industrial Revolution in fact relied on the widely available and well understood prime mover, water power, to power the automation revolution in the factory system. This work highlights the aggregate value of geographic endowments to the economy.

The spatial dispersion of industry depended on water-power endowments to a great extent. Even after steam power emerged as a widely adopted source of power, water power persisted as a significant influence in the location of factories, railroads, and population. The distribution of land values is heavily dependent on water-power endowments. The re-distribution of water power would have considerable implications for the locations of industry and railroads. The northern states' natural hydrologic advantage played a critical role in the way America industrialized.

## References


Allen, T. and Arkolakis, C. (2014). Trade and the topography of the spatial economy. *The Quarterly Journal of Economics*, 129(3):1085–1140.

Atack, J. (1979). Fact in fiction? the relative costs of steam and water power: a simulation approach. *Explorations in Economic History*, 16(4):409–437.

Atack, J. and Bateman, F. (1999). Nineteenth-century us industrial development through the eyes of the census of manufactures a new resource for historical research. *Historical Methods: A Journal of Quantitative and Interdisciplinary History*, 32(4):177–188.

Atack, J., Bateman, F., and Margo, R. A. (2005). Capital deepening and the rise of the factory: the american experience during the nineteenth century 1. *The Economic History Review*, 58(3):586–595.

Atack, J., Bateman, F., and Margo, R. A. (2008a). Steam power, establishment size, and labor productivity growth in nineteenth century american manufacturing. *Explorations in Economic History*, 45(2):185–198.

Atack, J., Bateman, F., and Weiss, T. (1980). The regional diffusion and adoption of the steam engine in american manufacturing. *Journal of Economic History*, pages 281–308.

Atack, J., Haines, M. R., and Margo, R. A. (2008b). Railroads and the rise of the factory: Evidence for the united states, 1850-70. Technical report, National Bureau of Economic Research.

Atack, J., Margo, R. A., and Rhode, P. W. (2019). " automation" of manufacturing in the late nineteenth century: The hand and machine labor study. *Journal of Economic Perspectives*, 33(2):51–70.

Baum-Snow, N. (2007). Did highways cause suburbanization? *The quarterly journal of economics*, 122(2):775–805.

Bleakley, H. and Lin, J. (2012). Portage and path dependence. *The quarterly journal of economics*, 127(2):587–644.

Crafts, N. (2004). Steam as a general purpose technology: a growth accounting perspective. *The Economic Journal*, 114(495):338–351.

Crafts, N. and Wolf, N. (2014). The location of the uk cotton textiles industry in 1838: A quantitative analysis. *The Journal of Economic History*, pages 1103–1139.

Dalgaard, C.-J., Kaarsen, N., Olsson, O., and Selaya, P. (2018). Roman roads to prosperity: Persistence and non-persistence of public goods provision.

Desmet, K. and Henderson, J. V. (2015). The geography of development within countries. In *Handbook of regional and urban economics*, volume 5, pages 1457–1517. Elsevier.

Desmet, K. and Rossi-Hansberg, E. (2014). Spatial development. *American Economic Review*, 104(4):1211–43.

Donaldson, D. and Hornbeck, R. (2016). Railroads and american economic growth: A "market access" approach. *The Quarterly Journal of Economics*, 131(2):799–858.

Ellison, G. and Glaeser, E. L. (1999). The geographic concentration of industry: does natural advantage explain agglomeration? *American Economic Review*, 89(2):311–316.

Evans, O. (1795). The young mill-wright and miller's guide. 1990 reprint.

Fogel, R. W. (1964). *Railroads and American economic growth: Essays in econometric history*. Baltimore: Johns Hopkins Press.

Fries, R. I. (1975). European vs. american engineering: Pierre charles l'enfant and the water power system of paterson, nj. *Northeast Historical Archaeology*, 4(1):9.

Gordon, R. B. (1983). Cost and use of water power during industrialization in new england and great britain: a geological interpretation. *Economic History Review*, pages 240–259.

Haines, M. R. (2005). Historical, demographic, economic, and social data: The united states, 1790-2000.

Hedrick, U. P. (1933). history of agriculture in the state of new york.

Helpman, E. (1998). The size of regions in david pines, efraim sadka, and itzhak zilcha, eds 'topics in public economics: Theoretical and applied analysis'.

Holmes, T. J. and Lee, S. (2012). Economies of density versus natural advantage: Crop choice on the back forty. *Review of Economics and Statistics*, 94(1):1–19.

Hunter, L. C. (1979). *A History of Industrial Power in the United States, 1780-1930. Volume One: Waterpower in the Century of the Steam Engine*. University Press of Virginia, Charlottesville.

Hunter, L. C. (1985). *A History of Industrial Power in the United States, 1780-1930. Volume 2: Steam Power*. University Press of Virginia, Charlottesville.

Kim, S. (2005). Industrialization and urbanization: Did the steam engine contribute to the growth of cities in the united states? *Explorations in Economic History*, 42(4):586–598.

Martin, R. and Sunley, P. (2006). Path dependence and regional economic evolution. *Journal of economic geography*, 6(4):395–437.

Michaels, G. (2008). The effect of trade on the demand for skill: Evidence from the interstate highway system. *The Review of Economics and Statistics*, 90(4):683–701.

Mokyr, J., Sarid, A., and van der Beek, K. (2019). *The Wheels of Change: Human Capital, Millwrights, and Industrialization in Eighteenth-Century England*. Centre for Economic Policy Research.

Proost, S. and Thisse, J.-F. (2019). What can be learned from spatial economics? *Journal of Economic Literature*, 57(3):575–643.

Reynolds, T. S. (1983). *Stronger than a hundred men: a history of the vertical water wheel*, volume 7. JHU Press.

Rosenberg, N. and Trajtenberg, M. (2004). A general-purpose technology at work: The corliss steam engine in the late-nineteenth-century united states. *The Journal of Economic History*, 64(1):61–99.

Sokoloff, K. L. (1984). Was the transition from the artisanal shop to the nonmechanized factory associated with gains in efficiency?: Evidence from the us manufacturing censuses of 1820 and 1850. *Explorations in Economic History*, 21(4):351–382.

Stern, D. I. and Kander, A. (2012). The role of energy in the industrial revolution and modern economic growth. *The Energy Journal*, 33(3).

Swain, G. F. (1888). Statistics of water power employed in manufacturing in the united states. *Publications of the American Statistical Association*, 1(1):5–36.

Taylor, T. U. (1900). *The Austin Dam*. Number 40. US Government Printing Office.

Temin, P. (1966). Steam and waterpower in the early nineteenth century. *Journal of Economic History*, pages 187–205.

Trew, A. (2014). Spatial takeoff in the first industrial revolution. *Review of Economic Dynamics*, 17(4):707–725.

Trew, A. (2020). Endogenous infrastructure development and spatial takeoff in the first industrial revolution. *American Economic Journal: Macroeconomics*, 12(2):44–93.

# Appendix

## A Market Access Parameters

To assess if the baseline result is sensitive to trade elasticity parameters I calculate market access across a wide range of trade elasticities, $\theta$. Table 8 shows that the baseline result does not depend on the value of the trade elasticity. But, in the cross sectional results the value of market access is sensitive to trade elasticity. Care must thus be taken when extrapolating comparisons or interpreting the indirect effects of estimation of the impact of natural endowments through man-made infrastructure.

Table 8: Robustness of Impact of Water Power on Agricultural Land Prices to Trade Elasticities

| | Log Value of Agricultural Land | | | | | | |
|---|---|---|---|---|---|---|---|
| | ($\theta = 1$) | ($\theta = 3.73$) | ($\theta = 3.6$) | ($\theta = 3.8$) | ($\theta = 6.74$) | ($\theta = 12.86$) | ($\theta = 26.83$) |
| log WP | 0.212 | 0.211 | 0.212 | 0.211 | 0.211 | 0.211 | 0.210 |
| | (0.034) | (0.034) | (0.034) | (0.034) | (0.034) | (0.034) | (0.034) |
| log MA | 5.205 | 1.409 | 1.460 | 1.383 | 0.779 | 0.407 | 0.196 |
| | (0.893) | (0.238) | (0.246) | (0.233) | (0.131) | (0.068) | (0.033) |
| $N$ | 982 | 982 | 982 | 982 | 982 | 982 | 982 |
| $R^2$ | 0.812 | 0.812 | 0.812 | 0.812 | 0.812 | 0.813 | 0.813 |

Note. Clustered standard errors by state are in parentheses. All regressions include the controls of state fixed effects and the cubic functions of latitude and longitude.

## B Theoretical Power Estimates

As discussed in the Data section, the primary measure of water power I use is *utilized* water power. The water-power report also notes developed water sites and their theoretical power available. In Table 9, I report the results of the regression of the theoretical water power available on the log of agricultural land prices. These results use the same specifications that is reported in Table 1 as the main results.

I find that the estimate of the horsepower of water is not affected by the inclusion of excess unused power at major sites.

## C Robustness to Outliers

In this section, I test how the main estimates perform when removing the tails of the distribution of the logarithm of the value of agricultural land and the logarithm of water

Table 9: Impact of Water Power on Agricultural Land Prices: Theoretical Power

| | Log Value of Agricultural Land | | | | |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) |
| log WP | 0.250 | 0.212 | 0.202 | 0.196 | 0.217 |
| | (0.028) | (0.028) | (0.030) | (0.032) | (0.032) |
| Market Access | N | Y | Y | Y | N |
| Spatial Controls | N | N | Y | Y | Y |
| Environmental Controls | N | N | N | Y | Y |
| $N$ | 982 | 982 | 982 | 982 | 982 |
| $R^2$ | 0.722 | 0.775 | 0.788 | 0.811 | 0.798 |

Note. Clustered standard errors by state are in parentheses. All regressions include state fixed effects.

power. One potential concern is that there are very different dynamics in the rural, less settled regions, which have less water power and land values, and that those differences could be driving the baseline results. In Table 10, I compare my baseline result in Column 1 to the samples excluding the top and bottom 1% of land prices (Column 2), excluding the top and bottom 5% of land prices (Column 3), excluding the top and bottom 1% of water power (Column 4), and excluding the top and bottom 5% of water power (Column 5).

I find that the estimates are consistent with the more selective samples and that outliers of land prices and water power are not responsible for the baseline results.

Table 10: Robustness of Impact of Water Power on Agricultural Land Prices to Outliers

| | Log Value of Agricultural Land | | | | |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) |
| log WP | 0.211 | 0.211 | 0.190 | 0.211 | 0.233 |
| | (0.034) | (0.032) | (0.036) | (0.034) | (0.041) |
| $N$ | 982 | 962 | 882 | 962 | 880 |
| $R^2$ | 0.812 | 0.807 | 0.772 | 0.810 | 0.801 |

Note. Clustered standard errors by state are in parentheses. All regressions include the controls of state fixed effects and the cubic functions of latitude and longitude and spatial controls.