The Value of Piped Water and Sewers: Evidence from 19th Century Chicago

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Our question(s)

- How did the massive investments in sanitation infrastructure in late nineteenth century U.S. cities impact land values and urban development?

- How much does sewer and piped water service contribute to land value? Does this contribution exceed the cost of service provision?

To address these questions we:

- Assemble parcel-level data describing price, date and location for a sample of Chicago real estate transactions, between 1870 and 1890.
- Match transactions to annual maps of sewer access.
- Exploit a natural experiment assigning water and sewer service to streets on the basis of imperceptible changes in elevation to;
  - Estimate marginal and average treatment effects in a quasi-experimental sample.
  - Extrapolate estimates of marginal treatment effect estimates to calculate ATE for all parcels receiving water and sewer service during our study period.
- Compare sewer and water construction and operation expenditures to relevant changes in real estate value.

Main findings

- Quasi-random assignment of water and sewer access about doubles the value of treated parcels on average (LATE $\approx$ ATE $\approx$ Relevant ATE).
- Applying this estimate to the area affected by Chicago's 1874-80 sewer and water expansion we find that increased land value exceeded construction cost by about a factor of 40.

Why is this important?

- Most existing evidence relates water quality to health and mortality at the city level Cutler and Miller [2005], Anderson et al. [2018], Ferrie and Troesken [2008], Alsan and Goldin [2019]. We relate water and sewer access to parcel transaction prices.
- Spatially-detailed water and sewer data are scarce. Transportation and power infrastructure are better studied.
- In 2020, 15%/40% of the world's urban population without safely managed water/sanitation. Many in developing world slums. Do expansions pass a cost-benefit test? Should policy makers expand access?
- Methodological contributions: (1) A new cross-sectional research design; (2) new method to extrapolate from local natural experiments to economically relevant areas.

Literature

Available evidence suggests huge effects of better water and sewers in the U.S. and Europe around 1900. For example,

- Alsan and Goldin [2019], water quality and sewers, Greater Boston, 1880-1915, $\Longrightarrow \frac{27}{1000}$ decrease in child mortality. Baseline $\frac{163}{1000}$. D-D design.
- Anderson et al. [2018], opening of H2O treatment in 25 big US cities 1900-40, $\Longrightarrow \frac{2.6}{1000}$ decrease in child mortality. Baseline $\frac{38}{1000}$. D-D design. Other public health interventions move estimates.
- Kesztenbaum and Rosenthal [2017], Paris sewer expansion. 10% more HH connections $\Longrightarrow$ 0.1 more year of life. Neighborhood-level panel data, 1881-1913.
- Literature in developing countries typically D-D for particular policies, e.g. water company privatization [Galiani et al., 2005], subsidy for household water connections [Devoto et al., 2012], service interuptions Ashraf et al. [2017]. Gamper-Rabindran et al. [2010] gives panel data estimator of water and sewer access on child mortality in Brazil.
- No evidence on land values.

Background: Chicago after the Civil War

- Chicago had 300,000 people in 1870 and 1.0 million by 1900.
- Land market is large and usually liquid. Booms, panics, and busts were routine (Hoyt 1933).
- Flat, swampy terrain complicated efforts to keep sewage and water separate. In 1860:

  The average Chicagoan... used the backyard pump dug 10-12 feet into the sand and clay. Excrements were emptied into privy vaults sunk into the same soil, often in close proximity... the vaults were seldom tight. (Cain 1978).

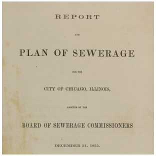
Background: Sanitation infrastructure in Chicago

- Chicago was first U.S. city to construct a comprehensive sewer system with systematic sewage disposal, mostly into local rivers.
- Piped water and sewers were installed together during our study period. Piped water without sewers caused cesspools to overflow.
- Drinking water came from Lake Michigan with no major water quality changes during our main 1874-1889 window; 2 Mile crib (1867), 4 Mile crib (1892), reversal of Chicago River (1900) [Ferrie and Troesken, 2008].

Sewer construction I

- Typical (gravity) sewers need 1:200 grade [Mara, 1996]. 1:70 is just perceptible on a playing field [Aldous, 1999].
- Chicago is too flat. The intersection of the Eisenhower Expwy (formerly Congress St.) and Halsted is about 2 miles from and 12 feet above the level of Lake Michigan, an average grade of about 1:880.
- Chicago's sewers relied on a system of manual flushing to allow them to function at a grade of 1:2500. This required widespread regrading of streets.

Sewer construction II



- The 1855 plan for sewerage from noted engineer Chesbrough described Chicago's topography and laid out a strategy for sewering the entire city.
- Beginning in 1863, the city regularly issued sewer ordinances that enumerated streets, block by block, to be sewered and their finished elevations in hundredths of an inch.
- Water mains and sewers were typically installed at the same time.
- Our study area was farmland in 1855 and 97% undeveloped during our main 1874-1880 study period (Hoyt [2000] and our data).

Sewer construction III

The assignment of sewers to neighborhoods and streets was probably not independent of land value.

> *... the unsewered portion of the city is that which, of all others, most needs it. ... These neighborhoods are densely populated by people who have not the means to adopt any sanitary measures. - Chicago Tribune (6/25/1873)*

The Southwest Triangle

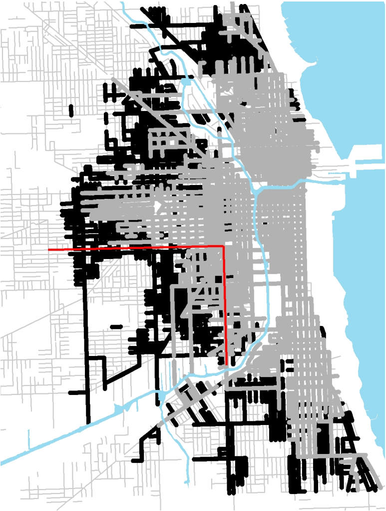
From the 1855 sewer plan:

- "It will be necessary to raise the grades of streets an average of eighteen inches per 2500 feet going west."
- "Extreme south-west part of city too low..." to provide sewers, the "depth of filling required to raise streets over it, would average two feet" (p. 16).
- This area was defined as the "triangle" south of Tyler Street (now the Eisenhower Expressway) and west of Halsted Street.
- "As this part of the city may not be improved for several years, it is deemed sufficient for present purposes to state the general depth of filling that would be required..." (p. 16).

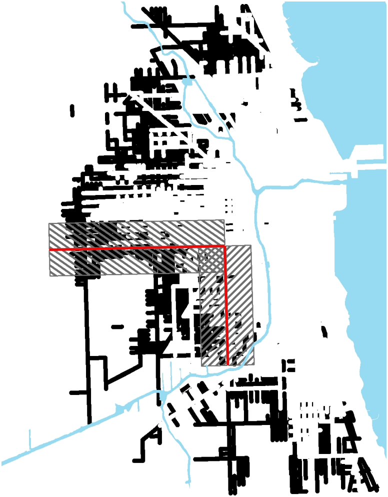
Sewer and piped water provision in this area is delayed ONLY due to the expense of 6" of marginal fill. Western edge of $\triangle$ is not given. We set it at 14000' from the CBD.

Data: Sewer networks by year

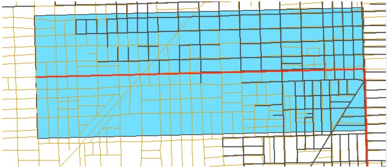
- The spatial sewer data we use was constructed from Annual Reports of the Chicago Department of Public Works by Fogel's Early Indicators Project.
- Files include ward boundaries and year by year GIS files showing build out of sewer and water system for 1830-1930.



Sewers before 1874, during 1874-1880, after 1880, and boundaries of the Southwest triangle.

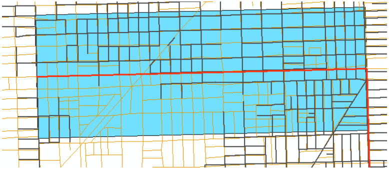


'Relevant" sample area (1874-1880 expansion) and "Quasi-experimental" sample areas.



1874

1876



1878

1880

Sewer extent in study area between 1874 and 1880. Tan ∼ 1930s street network. Red ∼ Southwest Triangle. Light blue ∼ Quasi-experimental area. Black ∼ sewer network.

Data: Real Estate Transactions

- The Chicago Tribune regularly published a record of every parcel sale that was filed at the courthouse the previous day, including price, dimensions, date of sale, and an indicator for "improvement," and nearest intersection.
- We collect the parcel transactions for every Sunday paper from 1874 to 1889, when the Tribune stopped reporting transfers less than $1000.
- We obtained around 700 observations per year in the 1870s and 1000 observations per year in the 1880s. We successfully geocoded 77% of transactions by matching street intersection names to the Logan 1880 street map and Google Maps API.

Parcel Transactions from the Tribune; Sundays, 1874-1889

SATURDAY'S TRANSFERS.

The following instruments were filed for record Saturday, April 10:

CITY PROPERTY.

Walnut st, 120 ft e of Western av, s f, 30x126 ft, dated April 10 (A. E. and C. M. Hemler to John T. Shannon).............$ 2,025

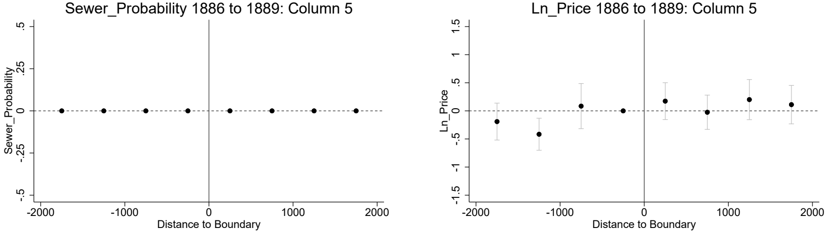
West Superior st, 49 4-10 ft e of Lincoln, n f, 25x128 ft, dated April 10 (B. F. Crosby to O. B. Olson)................... 600

Cleaver st, 225 ft s of Bradley, w f, 37½x125 ft, dated April 8 (Mat Schillo et al. to M. Kufel et al.)..................... 750

West Madison st, 428 ft w of Staunton, s f, undivided ⅓ of 24x126 ft, dated April 6 (Mary J. Seymour to C. L. Wehe)................................ 2,400

Each record reports location, price, area, "improved." houses

Sewer share and price by distance to boundary, **1886-9**

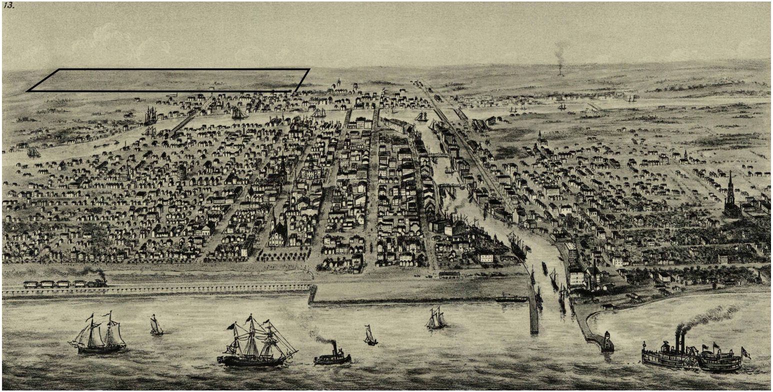


Left: Share of parcels sewered 1874-80 by 500' bins of distance to SW△ boundary, $x < 0$ is 'inside'. $x \in [-500, 0]$ is y intercept. Conditional on year, ln(area), ln(mi. to CBD).

Right: Same as left panel but y-axis is ln(Price).

Prices at the border are the same after sewer and water provision in the SW△.

The Southwest Triangle around 1853

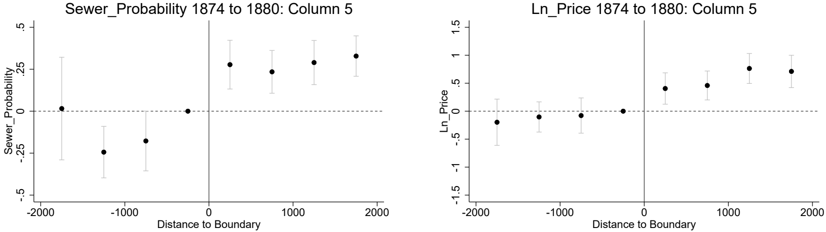


Our study area is approximately outlined in black. At the time the 1855 plan was made, the whole area was undeveloped.

Summary Statistics 1874-1880

	(1) SW$\triangle = 1$	(2) SW$\triangle = 0$	(3) t-test	(4) Relevant
Share Sewered	0.47	0.92	10.84	0.70
	(0.50)	(0.27)		(0.46)
Log Price	7.68	8.41	8.48	7.39
	(0.85)	(0.75)		(0.89)
Log Distance to CBD	9.13	9.10	-0.82	9.49
	(0.39)	(0.38)		(0.25)
Log Area	-9.02	-8.88	1.88	-8.97
	(0.62)	(0.69)		(0.54)
Share Corner	0.10	0.12	0.56	0.13
	(0.30)	(0.33)		(0.34)
Distance to Horsecar	0.17	0.08	-9.61	0.34
	(0.11)	(0.06)		(0.26)
Distance to Major Street	0.11	0.09	-2.27	0.09
	(0.08)	(0.07)		(0.07)
Year	1877.21	1877.42	0.87	1877.60
	(2.20)	(2.19)		(2.26)
Time to Sewer	3.38	2.69	-1.26	2.96
	(2.12)	(1.08)		(1.66)
Observations	146	205		1298

Sewer incidence and land price by distance to boundary, 1874-80



Left: Share of parcels sewered 1874-80 by 500' bins of distance to SW$\triangle$ boundary, $x < 0$ is 'inside'. $x \in [-500, 0]$ is y intercept. Conditional on year, ln(area), ln(mi. to CBD).

Right: Same as left panel but y-axis is ln(Price).

TSLS-LATE 1874-80

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
A: OLS.								
Sewer=1	.354***	.413***	.407***	.379***	-.080	.265***	.276***	.25***
	(.089)	(.086)	(.087)	(.144)	(.105)	(.084)	(.081)	(.079)
R^2	0.032	0.386	0.405	0.436	0.536	0.391	0.376	0.458
B: Red. Form								
$SW\triangle = 0$	.731***	.657***	.805***	.543***	.338*	.457***	.336***	.322***
	(.088)	(.072)	(.077)	(.106)	(.173)	(.072)	(.063)	(.059)
R^2	0.171	0.486	0.527	0.504	0.540	0.447	0.397	0.478
C. 1st Stage								
$SW\triangle = 0$	.449***	.432***	.440***	.320***	.187*	.432***	.259***	.259***
	(.045)	(.039)	(.042)	(.056)	(.097)	(.039)	(.031)	(.031)
R^2	0.252	0.451	0.451	0.454	0.469	0.451	0.333	0.334
F-stat	97.543	119.729	107.237	32.917	3.727	119.729	71.711	72.171
D. IV.								
Sewer=1	1.626***	1.522***	1.831***	1.699***	1.805	1.058***	1.296***	1.242***
	(.265)	(.220)	(.244)	(.425)	(1.323)	(.195)	(.277)	(.263)
Year FE & ln(Area)		Y	Y	Y	Y	Y	Y	Y
ln(mi. CBD)		Y	Y	Y	Y	Y	Y	Y
H.car & Maj. St.& Corner			Y		Y			Y
Distance to Congress St.					Y			
1886-1889 Trend Correction						Y		
Sample	Q.E.	Q.E.	Q.E.	Q.E. 1k'	Q.E.	Q.E.	E.Q.E.	E.Q.E.
Observations	351	351	351	172	351	351	533	533

N.B: $e^{1.3} \approx 3.7$.

Notation for MTE framework

$$
\begin{aligned}
Y &\sim \text{ln(Parcel Transaction Price)} \\
X &\subseteq \{\text{Transaction year}, f(\text{distance to CBD}), \text{ln(Area)}, \\
&\qquad\qquad \text{Corner, `Improved'}\} \\
D &\sim \begin{cases} 1 & \text{Sewer and water} \\ 0 & \text{Not} \end{cases} \\
Z &\sim \begin{cases} 1 & \text{Not in SW } \triangle \\ 0 & \text{In SW } \triangle \end{cases} \\
P &\sim \text{Quasi-experimental sample and} \\
&\quad \text{distribution of } (Y, X, Z, D, U_1, U_0, U_D) \\
P^* &\sim \text{Relevant sample and} \\
&\quad \text{distribution of } (Y^*, X^*, Z^*, D^*, U_1^*, U_0^*, U_D^*)
\end{aligned}
$$

MTE Framework,Carneiro et al. [2010]

$$\begin{aligned} Y_1 &= X'\beta_1 + U_1 \\ Y_0 &= X'\beta_0 + U_0 \\ D &= \mathbb{1}[v(X,Z) - U_D \geq 0] \\ (X,Z)&\perp(U_1, U_0, U_D) \end{aligned} \tag{1}$$

for Y_1 'treated', Y_0 'not treated'.

Assuming cubic control function in $\widehat{p}$.

$$\begin{aligned} \Longrightarrow p &= F(X,Z) \\ Y &= X'\delta_0 + \widehat{p}X'(\delta_1 - \delta_0) + \gamma_1\widehat{p} + \gamma_2\widehat{p}^2 + \gamma_3\widehat{p}^3 + \varepsilon \end{aligned}$$

$$\begin{aligned} \Longrightarrow & MTE(X, \widetilde{U}_D) = X'(\delta_1 - \delta_0) + \gamma_1 + 2\gamma_2 U_D + 3\gamma_3 U_D^2 \\ \Longrightarrow & ATE = E(X)'(\delta_1 - \delta_0) + \gamma_1 + \gamma_2 + \gamma_3 \end{aligned}$$

N.B.: $\widetilde{U}_D$ rescales U_D so $P_{\widetilde{U}_D} \sim U[0,1]$.

LIV/MTE estimation

	(1)	(2)	(3)	(4)
χ^2	220	235	243	251
H0: $\delta_1 - \delta_0, \gamma_1, \gamma_2, \gamma_3 = 0$	0	0	.005	0.000
H0: $\delta_1 - \delta_0 = 0$	.108	.141	.298	0.0002
H0: $\gamma_2, \gamma_3 = 0$	.002	.002	.656	.056
H0: $\delta_1 - \delta_0, \gamma_2, \gamma_3 = 0$	.001	.001	.15	0.000
ATE	1.04^{***}	1.00^{***}	1.31^{*}	1.41^{**}
	(.40)	(.36)	(.69)	(.70)
ATE*	1.04^{***}	1.10^{***}	1.05^{**}	1.04^{**}
	(.31)	(.40)	(.46)	(.47)
Carr & Kitagawa	0.286	0.252	0.866	0.374
Year FE & ln(Area)	Y	Y	Y	Y
ln(mi. CBD)	Y	Y	Y	Y
H.car & Maj. St.& Corner		Y		Y
Sample	Q.E.	Q.E.	E.Q.E.	E.Q.E.
Observations	351	351	533	533

$$p = F(X, Z)$$

$$Y = X'\delta_0 + \widehat{p}X'(\delta_1 - \delta_0) + \gamma_1\widehat{p} + \gamma_2\widehat{p}^2 + \gamma_3\widehat{p}^3 + \varepsilon$$

$$MTE(X, \widetilde{U}_D) = X'(\delta_1 - \delta_0) + \gamma_1 + 2\gamma_2\widetilde{U}_D + 3\gamma_3\widetilde{U}_D^2$$

$$ATE = E(X)'(\delta_1 - \delta_0) + \gamma_1 + \gamma_2 + \gamma_3$$

Model Validity

- [Vytlacil, 2002] shows that the LIV/MTE model implies

$$
\begin{aligned}
&Pr(Y_{D,Z=1} = Y_{D,Z=0}) = 1\,(\text{Exogeneity})\\
&Pr(D_{Z=1} \geq D_{Z=0}) = 1\,(\text{Monotonicity})\\
&Z \perp (Y_{11}, Y_{10}, Y_{01}, Y_{00}, D_1, D_0 | X)\,(\text{Randomness})
\end{aligned}
$$

- Balke and Pearl [1997] show that Exogeneity, Monotonicity and Randomness $\implies$ for any subset of the support of Y, $D = 1$ is more likely if an only if $Z = 1$. This is testable!
- Carr and Kitagawa [2021] proposes a test based on this intuition. We usually pass this test. The controls are important. We often fail a test that assumes unconditional exogeneity (Mourifié and Wan [2017].

Proposition: Extrapolation of MTE estimates

$$Y_1^* = X^*\beta_1 + U_1^*$$
$$Y_0^* = X'\beta_0 + U_0^*$$
$$D^* = \mathbb{1}[v(X^*, Z^*) - U_D^* \geq 0]$$
$$\cancel{(X, Z) \perp (U_1, U_0, U_D)}$$
$$P^*_{U_1,U_0,U_D} = P_{U_1,U_0,U_D}$$

Then we can extrapolate MTE to Relevant sample to get

$$ATE^* = E(X^*)'(\delta_1 - \delta_0) + \gamma_1 + \gamma_2 + \gamma_3$$

For comparison sake,

$$ATE = E(X)'(\delta_1 - \delta_0) + \gamma_1 + \gamma_2 + \gamma_3$$

Validity of Extrapolation

Extrapolating our estimations from Quasi-experimental to Relevant sample requires

- No heterogeneous treatment effects (so $MTE = ATE$).

Or,

- That the structural equations and joint distribution of residuals is the same in both samples.
- We do not have a test for this condition.
- We can show that patterns in the two data sets are broadly similar.

MTE estimation (repeat)

	(1)	(2)	(3)	(4)
χ^2	220	235	243	251
H0: $\delta_1 - \delta_0, \gamma_1, \gamma_2, \gamma_3 = 0$	0	0	.005	0.000
H0: $\delta_1 - \delta_0 = 0$	.108	.141	.298	0.0002
H0: $\gamma_2, \gamma_3 = 0$	.002	.002	.656	.056
H0: $\delta_1 - \delta_0, \gamma_2, \gamma_3 = 0$	.001	.001	.15	0.000
ATE	1.04***	1.00***	1.31*	1.41**
	(.40)	(.36)	(.69)	(.70)
ATE*	1.04***	1.10***	1.05**	1.04**
	(.31)	(.40)	(.46)	(.47)
Carr & Kitagawa	0.286	0.252	0.866	0.374
Year FE & ln(Area)	Y	Y	Y	Y
ln(mi. CBD)	Y	Y	Y	Y
H.car & Maj. St.& Corner		Y		Y
Sample	Q.E.	Q.E.	E.Q.E.	E.Q.E.
Observations	351	351	533	533

$$p = F(X, Z)$$

$$Y = X'\delta_0 + \widehat{p}X'(\delta_1 - \delta_0) + \gamma_1\widehat{p} + \gamma_2\widehat{p}^2 + \gamma_3\widehat{p}^3 + \varepsilon$$

$$MTE(X, U_D) = X'(\delta_1 - \delta_0) + \gamma_1 + 2\gamma_2 U_D + 3\gamma_3 U_D^2$$

$$ATE = E(X)'(\delta_1 - \delta_0) + \gamma_1 + \gamma_2 + \gamma_3$$

The value of water and sewer service

Apply our estimate of ATE^* to Relevant sample.

- Average parcel is 125' deep. Treated area is: (installed sewer length 1874-80) $\times 250' \approx 138 \times 10^6$ ft^2.
- Area of untreated parcels transacted in relevant sample 1874-1880 $\approx 1.8 \times 10^6$ ft^2. Total price $\approx 0.81 \times 10^6$\$ (1880 dollars) $\Longrightarrow 0.45$\$ ft^2.
- Value of sewers and piped water

$$\begin{aligned} V^* &\approx 0.45 \times (e^{ATE^*} - 1) \times (138 \times 10^6) \\ &\approx 113 \times 10^6 \$ \end{aligned}$$

  for $ATE^* = 1.04$ (one of our smallest).
- Note that $0.45 \times (e^{ATE^*} - 1)$ is about .82\$ ft^2, which means piped water and sewer increases the value of land by about 180%.

Flows vs Stocks

- An average unsewered parcel in our Quasi-experimental receives sewer service 3 years after we observe it.
- Interest rates were about 8% during this period (Hoyt).
  - $r = 0.08 \Longrightarrow \delta = \frac{1}{1+r} \approx 0.93$.
  - V^* is PV of three years of flow.
  - Full asset price is

$$V^{*\infty} = \sum_{t=0}^{\infty} (\delta^3)^t V^* \approx 4.9 V^*$$

    That is, we should scale up by about a factor of 5 for asset value.
  - $4.9 \times 113m \approx 554m\$$.
- To the extent that the taxes used to pay back sewer bonds are capitalized into land prices, our estimates of the value of plumbing and piped water is understated.

Expenditure on water and sewer

- We digitized expenditures on water and sewer for the entire period [Chicago Board of Public Works, 1873].
- Water system had large pumping stations while sewer system was mainly just pipes.
- Financed primarily by bonds paid by property taxes, not special assessments as for roads.
- Expenditures 1874-1880:
  - Sewer Construction: \$1.5 M
  - Maintenance: \$0.4 M per year $\sim\approx$ \$5 M present value
  - Waterworks construction: \$2.4 M
  - Total: \$8.9 M (1880 dollars)
- $\frac{\text{Increased land value}}{\text{Total cost}} = \frac{554\times10^6\$1880}{8.9\times10^6\$1880} \approx 60$

Land value vs. health effects

- Anderson et al. [2018] estimate that all water related public health interventions (water, sewer, and water treatment) were jointly responsible for a reduction in infant mortality of 43 log points, or about a 35% reduction.
- Alsan and Goldin [2019] estimate that infant mortality in Boston between 1880 and 1915 was about 163/1000.
- From the 1880 census, there were 3014 infants living in the Relevant sample area in 1880.
- Multiplying, water and sewer access prevent 172 infant deaths/year, or 516 for a three year period.
- Costa and Kahn [2004] estimates that the 1900 value of statistical life was 516,000 USD2011 $\approx$ 23,200 USD1880.
- Multiplying $516 \times 23,300 = 12$m USD1880. This about one tenth of the 113m three year value of water and sewer access.

Conclusions

- Water and sewer infrastructure is understudied relative to its likely importance for two reasons,
  - Data availability
  - Credible research designs

  We resolve these problems with purpose collected data and a new research design.
- We also develop a methodology for extrapolating MTE estimates from samples with quasi-experimental variation to economically relevant samples.
- Both our research design and and the extrapolation methodology should find wider application.
- Sewer and water infrastructure constructed in Chicago from 1874-1880 at least doubled the transaction price of treated parcels on average. This leads to an increase in land value of about 60 times the cost of construction.

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