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

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UEA London, April 2022

Our question(s)

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

- Urban economists: 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 effects 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 60.

Why is this important?

- As of 2015, 15% of world urban population w/o safe drinking water. 40% w/o safe sanitation (World Bank). Should policy makers expand access? Developing world cities have many other problems.
- Spatially-detailed water and sewer data are scarce. Transportation and power infrastructure are better studied.
- Methodological contributions: (1) A new cross-sectional research design; (2) new method to extrapolate from local natural experiments to economically relevant areas.

Literature

- Most existing evidence suggests huge benefits of better water and sewers in 19th century U.S. and Europe (e.g., Cutler and Miller [2005], Ferrie and Troesken [2008], Alsan and Goldin [2019], Kesztenbaum and Rosenthal [2017]). Anderson et al. [2019] finds smaller effects.
- Literature in developing countries considers health impacts of particular policies (e.g. water company privatization [Galiani et al., 2005], subsidy for household water connections [Devoto et al., 2012]). Only Gamper-Rabindran et al. [2010] analyze water/sewer construction. No evidence on land values.

Background: Chicago after the Civil War

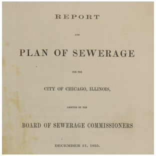
- Chicago had 300,000 people in 1870 and 1.7 million by 1900. Land markets experienced successive waves of booms, panics, and busts (Hoyt 1933).
- Public health environment is disastrous. Flat and swampy terrain complicates efforts to keep sewage and water separate. In 1860:

  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).
- 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.

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 Tyler 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 (using water hauled in horse-drawn carts) to allow them to function at a grade of 1:2500. This still required a massive program of regrading streets.

Sewer construction II



REPORT

PLAN OF SEWERAGE

CITY OF CHICAGO, ILLINOIS,

BOARD OF SEWERAGE COMMISSIONERS

DECEMBER 31, 1855.

- 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 grades.
- Water mains and sewers were typically installed at the same time.

The Southwest Triangle

From the 1855 sewer plan:

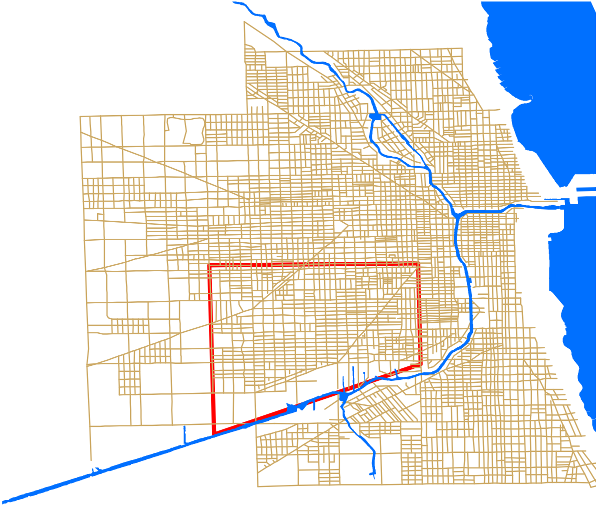
- "It will be necessary to raise the grades of streets an **average of eighteen inches** per 2500 feet going west."
- "Extreme south-west part of city too low..." to provide sewers, the "depth of filling required to raise streets over it, would **average two feet**" (p. 16).
- This area was defined as 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.

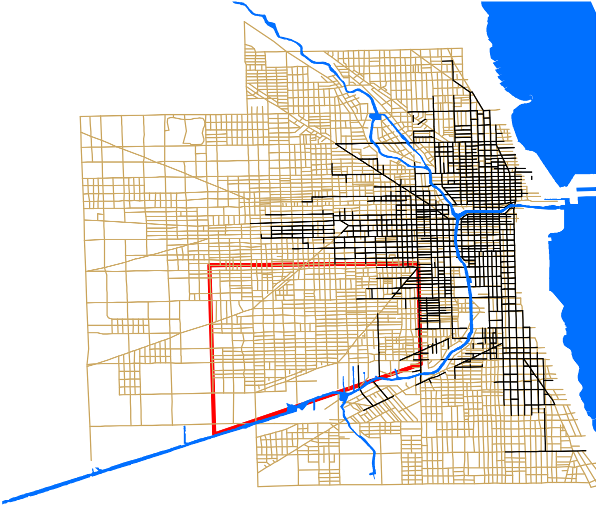
Data: Sewer networks by year

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

1880 Street Map and SW Triangle

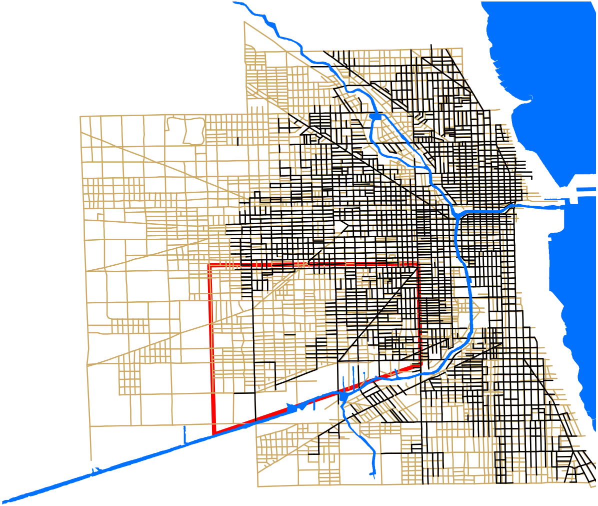


1870 Sewer Network



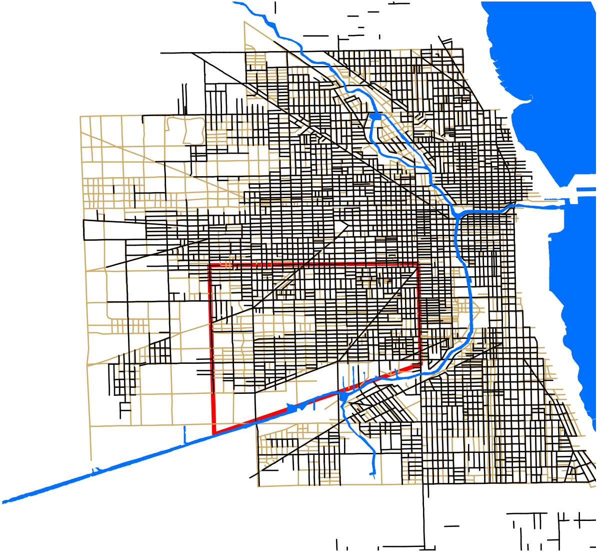
Sewer service is delayed south of Tyler street

1880 Sewer Network



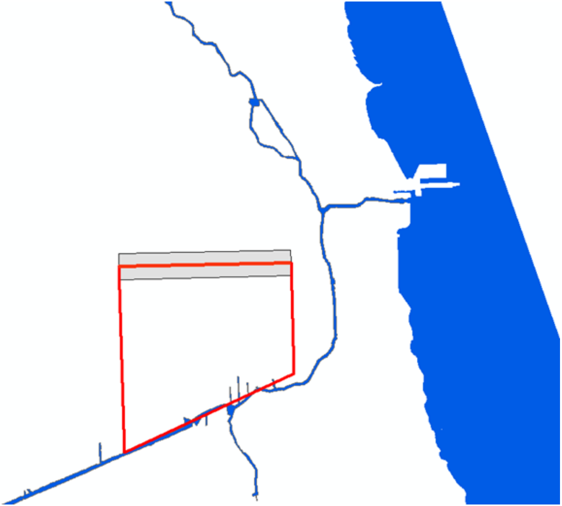
Sewer service is delayed south of Tyler street

1890 Sewer Network



Sewer access is nearly universal by 1990

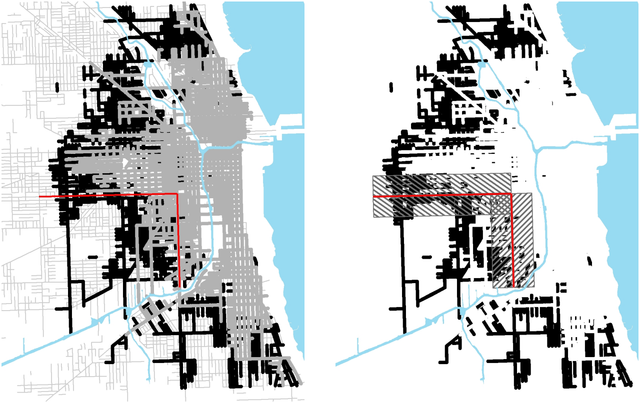
SW Triangle and 2000' buffer around EW leg



Data: Real Estate Transactions

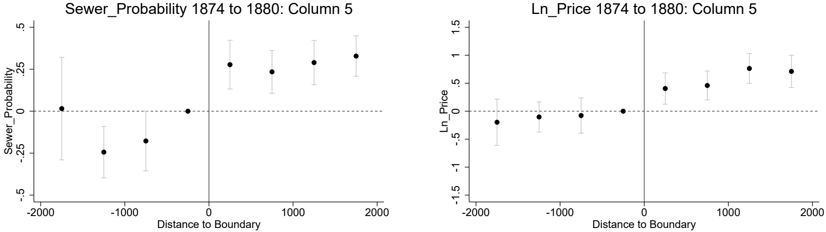
- The Chicago Tribune regularly published a record of every parcel sale that was filed at the courthouse the previous day, including price, dimensions, date of sale, and an indicator for "improvement," and nearest intersection.
- We collect the parcel transactions for every Sunday paper from 1874 to 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.

Study areas



Left: Sewers < 1874, $1874 - 1880$, > 1880, and boundaries of SW$\triangle$. *Right*: 'Relevant' sample area (1874-1880 expansion) and 'Quasi-experimental' sample areas.

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).

LATE $\approx$ 1.3 log points $\approx$ 3.7. *s.e.* $\approx$ 0.2. TSLS Table

MTE Framework,Carneiro et al. [2010]

$$\text{Treated units: } Y_1 = X'\beta_1 + U_1$$
$$\text{Untreated units: } Y_0 = X'\beta_0 + U_0$$
$$\text{Selection into treatment: } D = \mathbb{1}[v(X,Z) - U_D \geq 0]$$
$$(X,Z) \perp (U_1, U_0, U_D)$$

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

$$\text{First stage: } p = F(X,Z)$$
$$\text{Second stage: } Y = X'\delta_0 + \widehat{p}X'(\delta_1 - \delta_0) + \gamma_1 \widehat{p} + \gamma_2 \widehat{p}^2 + \gamma_3 \widehat{p}^3 + \varepsilon$$

$$\Longrightarrow ATE = E(X)'(\delta_1 - \delta_0) + \gamma_1 + \gamma_2 + \gamma_3$$
$$\approx 0.8 \text{ log points}$$

MTE Table

Proposition: Extrapolation of MTE estimates

$$\text{Treated units: } Y_1^* = X^{*\prime}\beta_1 + U_1$$
$$\text{Untreated units: } Y_0^* = X^{*\prime}\beta_0 + U_0$$
$$\text{Selection into treatment: } D^* = \mathbb{1}[v(X^*, Z^*) - U_D^* \geq 0]$$
$$\cancel{(X, Z) \perp (U_1, U_0, U_D)}$$
$$\text{Common error distribution: } P^*_{U_1,U_0,U_D} = P_{U_1,U_0,U_D}$$

Then we can extrapolate MTE to Relevant sample to get

$$\begin{aligned} ATE^* &= E(X^*)'(\delta_1 - \delta_0) + \gamma_1 + \gamma_2 + \gamma_3 \\ &\approx 0.8 \text{ log points} \end{aligned}$$

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 $LATE = ATE$).

Or,

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

Tests for heterogeneous treatment effects are sensitive to technique, and so the data do not allow us to distinguish between the two possibilities. We do everything and rely on a conservative (small) estimate of LATE.

Model Validity (1)

[Vytlacil, 2002] shows that the MTE model implies

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

Balke and Pearl [1997] show that for any subset A of the support of $Y \implies$

$$Pr(Y \in A, D = 1 | Z = 1, X) \geq Pr(Y \in A, D = 1 | Z = 0, X)$$

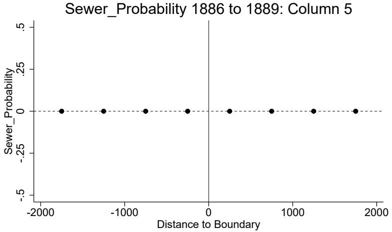
and

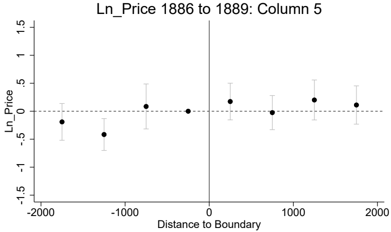
$$Pr(Y \in A, D = 0 | Z = 0, X) \geq Pr(Y \in A, D = 0 | Z = 1, X)$$

Carr and Kitagawa [2021] proposes a test based on this intuition. We usually pass this test (the controls are important).

Model Validity (2)

Sewer incidence and land price by distance to boundary, 1886-9





Left: Share of parcels sewered 1886-9 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).

Cross border price difference almost disappears with universal water and sewer access (in spite of path dependence).

The Value of Water and Sewer Access

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

$$\begin{aligned} V^* &\approx 0.45 \times (e^{ATE^*} - 1) \times (138 \times 10^6) \\ &\approx 69 \times 10^6 \$ \end{aligned}$$

for $ATE^* = 0.75$ (one of our smallest).

Flows vs Stocks

- An average unsewered parcel in our Quasi-experimental receives sewer service in 4 years after we observe it.
- Interest rates were about 8% during this period (Hoyt).
  - $r = 0.08 \implies \delta = \frac{1}{1+r} \approx 0.93$.
  - V^* is PV of four years of flow.
  - Full asset price is

$$V^{*\infty} = \sum_{t=0}^{\infty} (\delta^4)^t V^* \approx 3.8 V^*$$

    That is, we should scale up by about a factor of 4 for asset value.
  - $3.8 \times 69m \approx 262m\$$.
- 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
  - Waterworks construction: \$2.4 M
  - Total: \$4.3 M (1880 dollars)
- $\frac{\text{Increased land value}}{\text{Total cost}} = \frac{262 \times 10^6 \$1880}{4.3 \times 10^6 \$1880} \approx 60$

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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TSLS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
A: OLS								
Sewer=1	.413***	.39***	.4***	.328***	-.018	.194***	.276***	.239***
	(.086)	(.082)	(.084)	(.139)	(.101)	(.08)	(.081)	(.078)
R-squared	0.386	0.502	0.504	0.567	0.598	0.505	0.376	0.439
B: Red. Form								
SW Triangle=0	.657***	.568***	.714***	.439***	.292*	.3***	.336***	.332***
	(.072)	(.069)	(.073)	(.093)	(.151)	(.068)	(.063)	(.059)
R-squared	0.486	0.568	0.591	0.606	0.602	0.527	0.397	0.462
C. 1st Stage								
SW Triangle=0	.432***	.443***	.451***	.323***	.194**	.443***	.259***	.259***
	(.039)	(.04)	(.043)	(.057)	(.097)	(.04)	(.031)	(.031)
R-squared	0.451	0.455	0.455	0.456	0.474	0.455	0.333	0.335
F-stat	119.729	125.018	110.664	32.311	3.992	125.018	71.711	71.283
D. IV								
Sewer=1	1.522***	1.283***	1.582***	1.36***	1.501	.678***	1.296***	1.283***
	(.22)	(.191)	(.209)	(.352)	(1.067)	(.164)	(.277)	(.266)
Mouriffe Wan 95%	1	1	1	1	1	1	0	0
Year FE & ln(Area)	Y	Y	Y	Y	Y	Y	Y	Y
ln(mi. CBD)	Y	Y	Y	Y	Y	Y	Y	Y
Imp. & Corner		Y	Y	Y	Y	Y		Y
H.car & Maj. St.			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

back

MTE estimation

χ^2	220	221	237	243	245
H0: $\delta_1 - \delta_0$, γ_1, γ_2, $\gamma_3 = 0$	0	0	0	.005	.002
H0: $\delta_1 - \delta_0 = 0$	.108	.07	.074	.298	.205
H0: γ_2, $\gamma_3 = 0$	.002	0	.001	.656	.498
H0: $\delta_1 - \delta_0$, γ_2, $\gamma_3 = 0$	.001	.001	.001	.15	.076
ATE	1.04***	.72**	.8***	1.31*	1.31**
	(.4)	(.35)	(.32)	(.69)	(.65)
*ATE**	1.04***	.75***	.89***	1.05**	.87**
	(.31)	(.27)	(.36)	(.46)	(.41)
Carr & Kitagawa	0.156	0.154	0.434	0.792	0.916
Year FE & ln(Area)	Y	Y	Y	Y	Y
ln(mi. CBD)	Y	Y	Y	Y	Y
Improved and Corner		Y	Y		Y
Horsecar and Major Street			Y		
Sample	Q.E.	Q.E.	Q.E.	E.Q.E.	E.Q.E.
Observations	351	351	351	533	533

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

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

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

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

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