# Water Use and Conservation in Manufacturing:
# Evidence from U.S. Microdata

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# Disclaimer

Any opinions and conclusions expressed here today are those of the author and do not necessarily reflect those of the U.S. Census Bureau.

All results have been reviewed to ensure that no confidential information is disclosed.

# Why Study Water?

- Water can be a scarce resource, particularly in certain places at certain times.
  - In the U.S., upwards of 66% of the population lives in areas vulnerable to water shortages (Padowski and Jawitz 2012).

- Understanding both water use and conservation efforts can help ensure that limited supplies can meet the demands of a growing population and economy.

# Why Study Water Use by Manufacturing?

- In the U.S., fourth largest water use.

    – Roughly on par with domestic/residential use.

- Unlike some other uses, recirculation is a distinct possibility.

    – Recirculation reduces the need for new water intake.

- Reducing industrial water intake by just 1% (through increased recirculation or otherwise) would leave untouched enough water to serve 2.3 million people.

# Relatively Neglected in Economics

- Industrial water use has received relatively little attention in the economics literature, relative to agricultural, residential, and recreational uses.
- Series of papers from 1992-2013 by Steven Renzetti, Joel Bruneau, and Diane Dupont that use microdata from Canada's Industrial Water Use Survey.
  - Negative own-price elasticity for water intake.
  - Water recirculation is a substitute for both water intake and water discharge.
  - Larger firms are more likely to self-supply water. Costs matter too.
  - Water intake is a substitute for water recirculation, labor, energy, and capital.
  - Water recirculation is a substitute for labor; complement to energy and capital.
  - Recirculation is more prevalent in larger plants, when water intake must be treated prior to use, in certain water-intensive industries, and in drier regions.
  - Reciruclation depends on the price of intake water and the price of water treatment prior to discharge.
- No similar studies for U.S. manufacturing because of the lack of comprehensive survey data.

# Water Use in U.S. Manufacturing

- In 2005, the U.S. manufacturing sector self-supplied 18.2 billion gallons of water per day (4.4% of total water withdrawals).
  - Additional water is supplied by 'public' suppliers.
  - About 82-89% of water is self-supplied.
- Water is used for multiple purposes:
  - Clean, cool, and convey intermediate inputs
  - Embedded in final product
  - Generate steam for electric power generation
  - Domestic purposes (drinking, sanitation)

## TABLE 1
## Percent of Water Intake and Gross Water Use, by Purpose

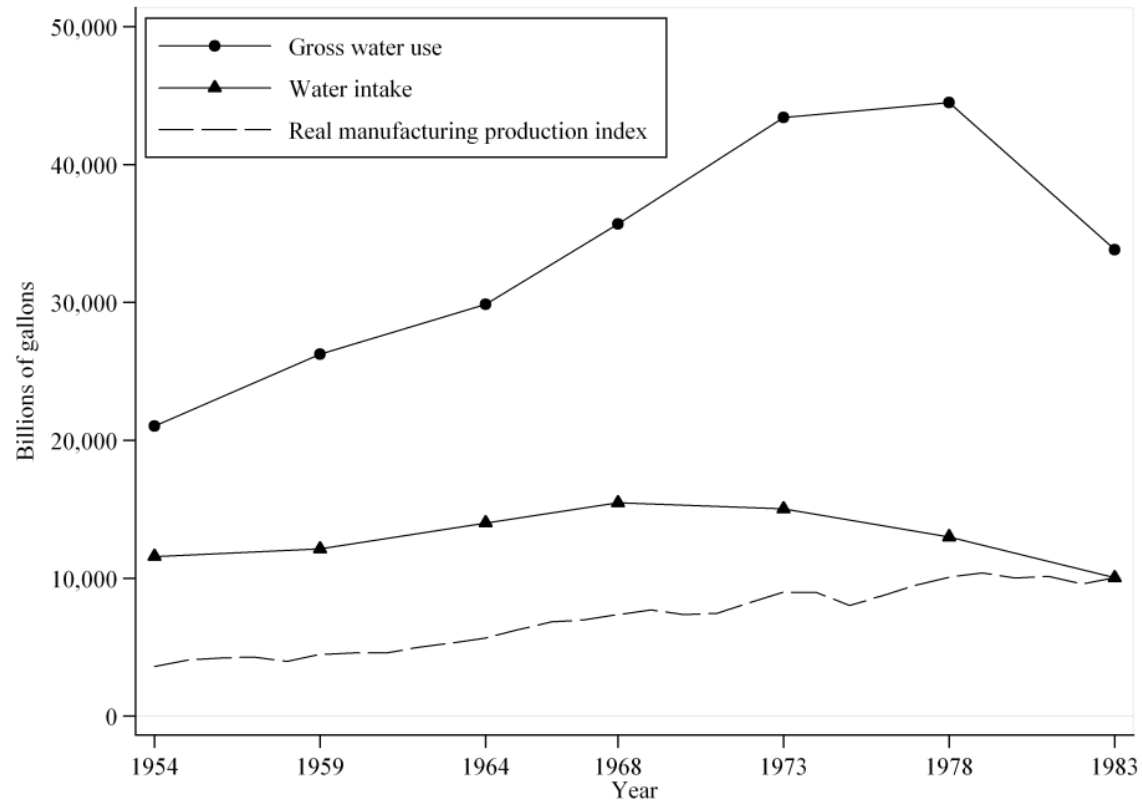|  | Water intake | | Gross water use | |
|---|---|---|---|---|
|  | 1973 | 1978 | 1973 | 1978 |
| Process | 26.3 | 28.7 | 27.1 | 33.1 |
| Steam electric power generation | 18.1 | 15.8 | 8.7 | 7.8 |
| Air conditioning | 1.9 | 1.6 | 4.8 | 4.2 |
| Other cooling and condensing | 48.1 | 44.8 | 56.2 | 49.4 |
| Sanitary services | 1.4 | 2.1 | 0.5 | 0.6 |
| Boiler feed | 4.2 | 4.2 | 2.7 | 3.6 |
| Other uses | * | 2.7 | * | 1.3 |

* Aggregated with boiler feed in 1973.

- *Process water* is all water that comes directly in contact with products and/or materials, including water which is consumed in the manufacturing of products."
- *Other cooling and condensing* includes water used "in conjunction with the operation of process equipment, but which does not come in direct contact with products or materials."

## TABLE 2
## Top Ten Water-Using Manufacturing Industries, 1978

| Industry (SIC code) | Water Intake | | | | Gross Water Use | | | |
|---|---|---|---|---|---|---|---|---|
| | Billions of gallons | (Rank) | Gallons per dollar of output | (Rank) | Billions of gallons | (Rank) | Gallons per dollar of output | (Rank) |
| Blast furnaces and steel mills (3312) | 2,782.8 | (1) | | | 4,573.5 | (4) | | |
| Industrial organic chemicals, n.e.c. (2869) | 1,909.9 | (2) | 182.3 | (10) | 5,184.1 | (3) | | |
| Petroleum refining (2911) | 1,149.4 | (3) | | | 8,151.2 | (1) | 565.1 | (10) |
| Paper mills, except building paper (2621) | 878.3 | (4) | | | 6,377.5 | (2) | 1,179.5 | (1) |
| Industrial inorganic chemicals, n.e.c. (2819) | 653.8 | (5) | | | 1,165.7 | (8) | | |
| Paperboard mills (2631) | 609.8 | (6) | 197.9 | (9) | 2,911.3 | (5) | 945.0 | (3) |
| Pulp mills (2611) | 287.3 | (7) | 317.1 | (4) | 814.1 | (9) | 898.5 | (4) |
| Cyclic crudes and intermediates (2865) | 201.2 | (8) | | | | | | |
| Primary aluminum (3334) | 200.5 | (9) | | | | | | |
| Phosphatic fertilizers (2874) | 190.7 | (10) | 233.2 | (6) | | | 658.4 | (8) |
| ... | | | | | | | | |
| Alkalies and chlorine (2812) | 175.8 | (12) | 213.7 | (7) | | | | |
| Plastics materials and resins (2821) | 150.7 | (13) | | | 794.7 | (10) | | |
| Primary nonferrous metals, n.e.c. (3339) | 125.2 | (16) | 291.5 | (5) | | | | |
| Raw cane sugar (2061) | 118.4 | (18) | 429.5 | (2) | | | 687.7 | (6) |
| Cellulosic manmade fibers (2823) | 109.0 | (21) | 333.1 | (3) | | | 571.2 | (9) |
| Building paper and board mills (2661) | 97.2 | (23) | 445.5 | (1) | | | 666.8 | (7) |
| Nitrogenous fertilizers (2873) | 87.4 | (24) | | | 1,211.7 | (7) | 1,008.1 | (2) |
| Gum and wood chemicals (2861) | 39.5 | (36) | 213.4 | (8) | | | | |
| Industrial gases (2813) | 37.3 | (37) | | | | | 833.5 | (5) |
| Motor vehicles and car bodies (3711) | 29.5 | (44) | | | 1,682.7 | (6) | | |

# Gross Water Use and Water Intake in U.S. Manufacturing, 1954-1983



- Aggregate water *use* by U.S. manufacturing rose from 1954 to a peak in 1978
- Aggregate water *intake* by U.S. manufacturing peaked in 1968 (a decade earlier)

# Water Recirculation in U.S. Manufacturing, 1954-1983
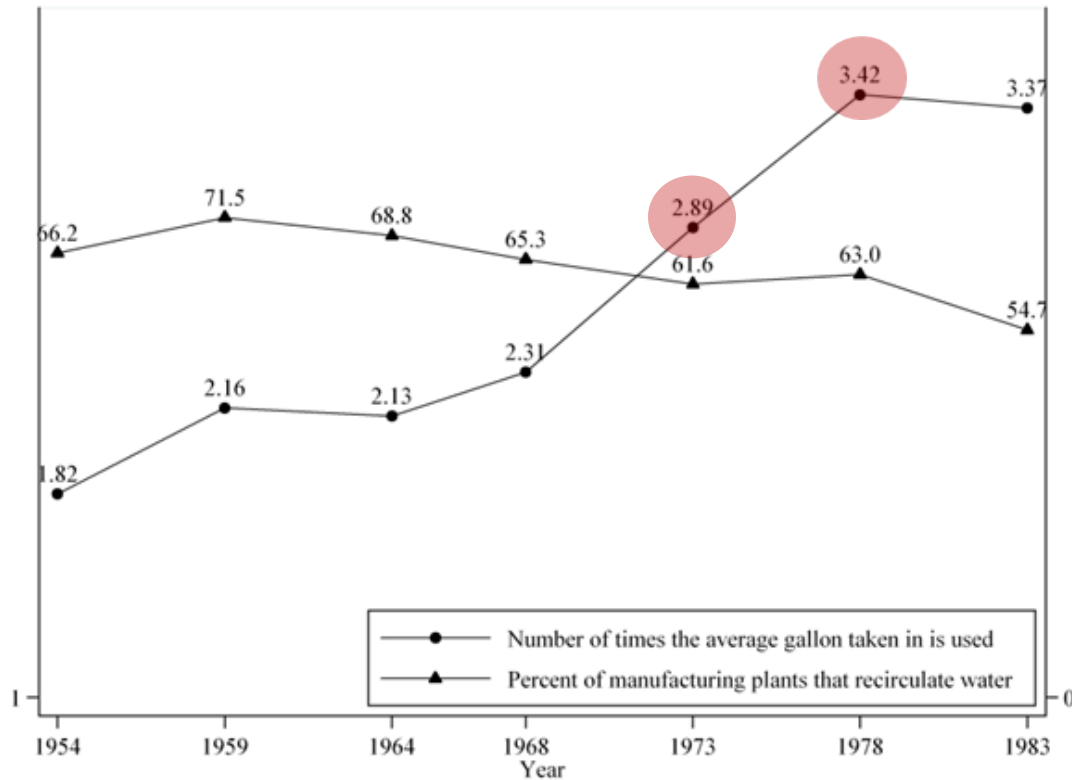


- In 1954, each gallon taken in by the manufacturing sector was used 1.82 times.
- This "circulation rate" peaked in 1978 at 3.42.
- During this time, the percent of manufacturers recirculating water more or less declined.

# The Survey of Water Use in Manufacturing (SWUM)

- Conducted on seven occasions from 1954 to 1983.
- Every 5 years, in the Census of Manufactures, every establishment was asked:



1977 CENSUS OF MANUFACTURES
SWITCHGEAR AND SWITCHBOARD APPARATUS
AND INDUSTRIAL CONTROLS – Continued

Name of establishment (Same as address box)

**Item 17A ▶ WATER USE DURING 1977** 348

1. What was the total quantity of water intake for this establishment for use in the production process and auxiliary operations (such as cooling and condensing, sanitary services, and boiler feed) during the calendar year 1977?

Mark (X) one box only
1 ☐ Under 1 million gallons   3 ☐ 10–19 million gallons   5 ☐ 50–99 million gallons
2 ☐ 1–9 million gallons   4 ☐ 20–49 million gallons   6 ☐ 100 million gallons or over

2. Did you recirculate any water during the calendar year 1977? . . . . . . . . . . . . . .   1 ☐ YES   2 ☐ NO   349

**Item 17B ▶ CONSUMPTION OF SELECTED MATERIALS DURING 1977**

*Instructions – Please read*

- Those reporting more than 20 million gallons received the SWUM the following year.
  - Upwards of 97% of the water withdrawn by the manufacturing sector is by the 3-4% of plants that use 20+ million gallons.
    - 34-43% of manufacturing employment and 47-54% of value added.

FORM MC-D-13A
(9-6-79)

U.S. DEPARTMENT OF COMMERCE
BUREAU OF THE CENSUS

Form Approved: O.M.B. No. 41-S79040

NOTICE – Response to this inquiry is required by law (title 13, U.S. Code). By the same law, your report to the Census Bureau is confidential. It may be seen only by sworn Census employees and may be used only for statistical purposes. The law also provides that copies retained in your files are immune from legal process.

(Please correct if any error in name and address including ZIP code)

Survey No.
5001

# 1978 SURVEY OF WATER USE IN MANUFACTURING

Please complete and return this form within 30 days after receipt to:

BUREAU OF THE CENSUS
1201 East Tenth Street
Jeffersonville, Indiana 47132

PLEASE RETURN THIS COPY

## GENERAL INSTRUCTIONS

Report all quantities in millions of gallons per year. Do not report in gallons per minute or gallons per day.

If the quantity used for the year is →
5,600,000,000 gallons – report as 5,600
5,600,000 gallons – report as 6
600,000 gallons – report as 1
Less than 500,000 gallons – report as 0

If no water is used, treated, or discharged, report "None." If your records on water used are in cubic feet, convert to gallons (1 cubic foot equals 7.5 gallons). Reasonably accurate estimates are acceptable.

Brackish water is defined as all water with 1,000 to 10,000 parts per million of dissolved solids.

Salt water is defined as all water with more than 10,000 parts per million of dissolved solids.

### Item 1 – WATER INTAKE BY SOURCE AND BY KIND, 1978

1 – Include water supplied by a water system (whether municipally or privately owned), the primary purpose of which is the supply of water to the general public. Include water supplied by systems, the principal function of which is the supply of water to industrial users.

2 through 5 – Include water obtained from your own water supply system, and water obtained from another company where the supplying company is not primarily a water supplier to the general public and/or industrial users. Include only your own portion of water obtained from a joint water supply system.

| Water from – | Item code (a) | Fresh (b) | Brackish (c) | Salt (d) |
|---|---|---|---|---|
| 1. Public water system | 1010 | | | |
| 2. Company surface water system, such as streams or lakes | 1020 | | | |
| 3. Company ground water systems, such as wells or deep springs | 1030 | | | |
| 4. Company tide water system from estuaries, bays, or oceans | 1040 | | | |
| 5. Other sources | 1060 | | | |
| 6. TOTAL (Sum of lines 1 through 5) → | 1099 | | | |

### Item II – WATER INTAKE BY PURPOSE AND BY KIND, 1978

1 – Process water is all water that comes directly in contact with products and/or materials, including water which is consumed in the manufacture of products.

2a, 2b, 4, and 5 – Self-explanatory.

2c – Include water which is used for cooling and condensing purposes in conjunction with the operation of process equipment, but which does not come in direct contact with products or materials.

3 – Sanitary service includes all water used for drinking, lunchrooms or cafeterias, and domestic sewage.

| | Item code |
|---|---|
| 1. Process | 2010 |
| 2. Cooling and condensing – a. For steam electric power generation | 2020 |
| b. For air conditioning | 2030 |
| c. Other cooling and condensing | 2040 |
| 3. Sanitary service | 2045 |
| 4. Boiler feed | 2055 |
| 5. Other uses | 2065 |
| 6. TOTAL (Sum of lines 1 through 5 should equal Item I, line 6) → | 2099 |

### Item III – TOTAL WATER INTAKE, WATER RECIRCULATED AND REUSED, AND GROSS WATER USED, BY PURPOSE, 1978

If no water was recirculated or reused, mark "No" box on line 1 and skip to Item IV.

If water was recirculated or reused –

In col. (b) report the sum of cols. (b) through (d) for each line in Item II above.

In col. (c) report the estimated quantity of water recirculated or reused. For example: If 100 million gallons of intake water were recirculated twice, report 200 million gallons in this column.

In col. (d) report the estimated quantity of water that would have been required if no water had been recirculated or reused. Col. (d) should equal the sum of cols. (b) and (c), less consumption and evaporation loss.

| | Item code (a) | Total intake (b) | Recirculated and reused (c) | Gross water used (d) |
|---|---|---|---|---|
| 1. Was any water recirculated or reused? (Mark "X" one box) 3002 ☐ No – SKIP to Item IV  3001 ☐ Yes – Complete columns (b) through (d) | | | | |
| 2. Process | 3010 | | | |
| 3. Cooling and condensing – a. For steam electric power generation | 3020 | | | |
| b. For air conditioning | 3030 | | | |
| c. Other cooling and condensing | 3040 | | | |
| 4. Sanitary service | 3045 | | | |
| 5. Boiler feed | 3055 | | | |
| 6. Other uses | 3065 | | | |
| 7. TOTAL (Sum of lines 2 through 6) → | 3099 | | | |

### Item IV – WATER DISCHARGED BY POINT OF DISCHARGE AND BY TREATMENT, 1978

Treated means the use of any of a wide variety of techniques used to cool, detoxify, decompose, separate-to-store, or ameliorate. Treated or untreated water applies to the status of the effluent as it reaches the discharge point.

Include all water brought to ultimate discharge point whether treated or not. Do not include water held in your ponds, lagoons or basins, for reuse or treatment, until actually discharged. Do not report water evaporated or otherwise consumed and not brought to ultimate discharge point.

1 – Report water discharged to public utility sewer systems, whether municipally or privately owned.

2 through 5 – Self-explanatory.

6 – Include seepage into ground from your holding ponds, lagoons, etc. (Note – If water is transferred to an agricultural establishment for spray irrigation, report such quantity on line 7.)

7 – Include transfers, after your own use, to another establishment of either your company or another company.

| Water used and discharged to – | Item code (a) | Untreated (b) | Treated (c) |
|---|---|---|---|
| 1. Public utility sewer | 4010 | | |
| 2. Streams and rivers | 4015 | | |
| 3. Lakes and ponds | 4025 | | |
| 4. Bays and estuaries | 4031 | | |
| 5. Ocean | 4035 | | |
| 6. Ground (wells, spray, seepage, etc.) | 4040 | | |
| 7. Transferred to other users | 4050 | | |
| 8. TOTAL (Sum of lines 1 through 7) → | 4099 | | |

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### Item V – WATER DISCHARGED BY LAST USE AND BY TREATMENT

Col. (c) – Includes process water that has come directly into contact with products and/or materials.

Cols. (d), (e), (h), and (f) – Self-explanatory.

Col. (f) – Include water which has been used for cooling and condensing purposes in conjunction with the operation of process equipment, but which has not come in direct contact with products or materials.

Col. (g) – Sanitary service water discharged is that water which has been used for drinking, lunchrooms or cafeterias, and domestic sewage.

| Item (a) | Item code (b) | Process (c) | COOLING AND CONDENSING | | | Sanitary service (g) | Boiler feed (h) | Other uses (i) | TOTAL (Should equal Item IV, line 8) (j) |
| | | | For steam electric power generation (d) | For air conditioning (e) | Other cooling and condensing (f) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **MILLIONS OF GALLONS FOR THE YEAR** | | | | | | | | | |
| 1. Untreated | 5010 | | | | | | | | |
| 2. Treated | 5020 | | | | | | | | |
| 3. Percent treated by method of treatment (When more than one method of treatment is used, the percentages may add to more than 100 percent) | | | | | | | | | |
| **REPORT TO THE NEAREST WHOLE PERCENT** | | | | | | | | | |
| a. Surface skimming (e.g., oil separation) | 5031 | % | % | % | % | % | % | % | % |
| b. Neutralization (pH control) | 5032 | % | % | % | % | % | % | % | % |
| c. Coagulation | 5033 | % | % | % | % | % | % | % | % |
| d. Flotation | 5034 | % | % | % | % | % | % | % | % |
| e. Primary settling | 5035 | % | % | % | % | % | % | % | % |
| f. Biological oxidation: trickling filters, activated sludge, digestion basins, ponds, and lagoons | 5036 | % | % | % | % | % | % | % | % |
| g. Secondary settling | 5037 | % | % | % | % | % | % | % | % |
| h. Filtration | 5038 | % | % | % | % | % | % | % | % |
| i. Chlorination | 5039 | % | % | % | % | % | % | % | % |
| j. Other – Specify | 5040 | % | % | % | % | % | % | % | % |
| | 5040 | % | % | % | % | % | % | % | % |
| | 5040 | % | % | % | % | % | % | % | % |

### Item VI – CAPITAL EXPENDITURES, ASSETS, AND ANNUAL COSTS FOR WATER TREATMENT, 1978

Instructions –

1 – Include capital expenditures for new plant and equipment acquisitions (both replacement and expansion) and expenditures for construction in progress. Capital expenditures are those chargeable to your establishment's accounts for plant and equipment that are subject to depreciation or amortization. Include expenditures for both end-of-line techniques and changes-in-production processes. NOTE – If you report on form MA-200, this line should equal Item 3, line c, on that form.

2 – Report the original cost of depreciable assets used for abatement of water pollutants such as buildings, structures, machinery, and equipment for which depreciation or amortization reserves are maintained. Include cumulative costs for both end-of-line techniques and changes-in-production processes. Exclude land. Report as of the end of 1978.

3a – Report the annual operating costs and expenses for abatement of water pollutants in 1978. Include all costs and expenses to operate and maintain plant(s) and equipment to abate water pollutants. Include leasing costs of equipment to treat water, payments to private contractors and consultants, monitoring costs, and rental costs of land. NOTE – If you report on form MA-200, this line should equal the part of the cost reported in Item 7a, on form MA-200 that is for abatement of water pollutants. Do not reduce annual costs by subtracting the estimate of costs recovered. Do not include payments to governmental units for public sewerage use.

4 – Report land that you own or rent or lease from others primarily for abatement of water pollutants. For example, land use used for settling ponds, drying beds, equalization basins, sludge lagoons, etc.

| | Item code (a) | Report in thousands of dollars (b) | | Mark (X) here if less than $500 and greater than 0 (c) |
| | | Millions ($000) | Thousands (000) | |
|---|---|---|---|---|
| 1. Capital expenditures for abatement of water pollutants | 6010 | $ | | ☐ |
| 2. Estimated gross value of assets (original cost) of your in-place plant and equipment for abatement of water pollutants | 6020 | $ | | |
| 3. Annual operating costs for abatement of water pollutants a. Report your best estimate of the annual costs of abatement of water pollutants | 6031 | $ | | ☐ |
| b. Report your best estimate of the percentage incurred by KIND OF COST (Report to the nearest whole percent) | | | | |
| (1) Depreciation | 6032 | % | | |
| (2) Labor | 6033 | % | | |
| (3) Private contractor services | 6034 | % | | |
| (4) Materials and supplies (including fuel and power) | 6035 | % | | |
| (5) Equipment leasing and other costs | 6036 | % | | |
| (6) TOTAL (Sum of lines (1) through (5) should equal 100%) → | | 100% | | |
| 4. Land used in the abatement of water pollutants a. Report your best estimate of the number of acres of land used in the abatement of water pollutants | 6041 | Acres | | |
| b. Estimate the percentage of such land that is rented and/or leased (Report to the nearest whole percent) | 6042 | % | | |

| | Item code (a) | Report in thousands of dollars (b) | | Mark (X) here if less than $500 and greater than 0 (c) |
| | | Millions ($000) | Thousands (000) | |
|---|---|---|---|---|
| c. Estimate the rental cost of such land that is rented and/or leased | 6043 | $ | | ☐ |

Remarks

### Item VII – CERTIFICATION

| Name of person to contact regarding this report | Address (Number and street, city, State) | ZIP code | Telephone | | |
| | | | Area code | Number | Extension |
|---|---|---|---|---|---|
| | | | | | |

This report is substantially accurate and covers the period from _____ to _____

| Signature of authorized person | Title | Date |
|---|---|---|
| | | |

# New Old Data

- The SWUM was among the many historic data files recovered by CES in 2009-2010.
- Numerous challenges:
  - Arcane, proprietary format (CENIO)
    - Files could not simply copied to another system.
    - Success rested on an old, faltering mainframe.
  - Data within a file were completely unstructured
    - For the 1973 SWUM, half the record layout is missing.
      - However, the position of items on the survey form and the published aggregate statistics both allow one to deduce variables
    - For the 1978 SWUM, there are two record types within the file:  establishment-wide data and item-specific data.
  - Data employed multiple, now-esoteric character codes within a record.
    - FIELDATA (1973)
    - Excess-3 (1978)
    - Binary integer (1973 & 1978)
      - Extraction yielded fields consisting of a base-64 6-character string with a combination of 26 letters, 10 numeric characters, and 28 symbols and special characters.
      - For example:     `@@^R;8`          = 1,146,616
- SWUM samples
  - 1973: 10,700 manufacturing plants (plus 1,690 in mineral industries)
  - 1978:   9,600 manufacturing plants (plus 1,060 in mineral industries)

# Results

- Controlling for industry, gross water use intensity (gross water use divided by value added) suggests that water use is largest for larger establishments.
  - At least two phenomena underlie this result
    - Number of purposes
    - Recirculation

# Water Use by Purpose

| | Number of water use purposes (OLS) | Probability water used for... (Probit) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Process | Steam electric power gener. | Air conditioning | Other cooling & condensing | Sanitary services | Boiler feed |
| 100-249 employees | +0.433*** (0.035) | +0.229*** (0.061) | +0.292*** (0.078) | +0.316*** (0.056) | +0.250*** (0.051) | +0.461*** (0.047) | +0.356*** (0.049) |
| 250-499 employees | +0.840*** (0.038) | +0.504*** (0.070) | +0.545*** (0.084) | +0.749*** (0.060) | +0.402*** (0.057) | +0.979*** (0.059) | +0.651*** (0.057) |
| 500-999 employees | +1.094*** (0.042) | +0.556*** (0.077) | +0.731*** (0.090) | +1.070*** (0.063) | +0.619*** (0.064) | +1.083*** (0.070) | +0.853*** (0.064) |
| 1000-2499 employees | +1.465*** (0.047) | +0.759*** (0.091) | +1.094*** (0.098) | +1.480*** (0.071) | +0.877*** (0.078) | +1.279*** (0.098) | +1.260*** (0.080) |
| 2500+ employees | +1.925*** (0.061) | +1.103*** (0.120) | +1.718*** (0.134) | +2.034*** (0.102) | +1.251*** (0.114) | +1.730*** (0.174) | +1.760*** (0.117) |
| Multi-unit firm | +0.206*** (0.038) | +0.225** (0.064) | −0.143* (0.076) | +0.077 (0.057) | +0.187*** (0.050) | +0.228*** (0.050) | +0.157*** (0.051) |
| Industry effects (4-digit SIC) | yes | yes | yes | yes | yes | yes | yes |
| R-squared (pseudo) | 0.3362 | 0.2009 | 0.1878 | 0.2781 | 0.1918 | 0.1692 | 0.2108 |
| Number of observations | 9,859 | 9,859 | 9,859 | 9,859 | 9,859 | 9,859 | 9,859 |

- Controlling for industry, the very largest establishments (with 2500+ employees) use water for 1.92 more purposes than the smallest establishments.
- For all 6 purposes, the probability that water is used for particular purpose increases monotonically with establishment size.
- The *share* of water used for different purposes:
  - Increases with establishment size: steam electric power generation, air conditioning, and other cooling and condensing
  - Decreases with establishment size: process, sanitation, and boiler feed

# Water Circulation Rate

Log (gross water use / water intake)

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| 100-249 employees | +0.099*** | +0.114*** | +0.107*** | +0.099*** | +0.099** | +0.100*** |
| | (0.029) | (0.028) | (0.029) | (0.028) | (0.028) | (0.028) |
| 250-499 employees | +0.222*** | +0.256*** | +0.236*** | +0.221*** | +0.221*** | +0.222*** |
| | (0.032) | (0.032) | (0.032) | (0.032) | (0.032) | (0.032) |
| 500-999 employees | +0.245*** | +0.291*** | +0.274*** | +0.256*** | +0.256*** | +0.257*** |
| | (0.037) | (0.036) | (0.036) | (0.035) | (0.035) | (0.035) |
| 1000-2499 employees | +0.362*** | +0.438*** | +0.414*** | +0.399*** | +0.401*** | +0.401*** |
| | (0.044) | (0.044) | (0.043) | (0.043) | (0.043) | (0.043) |
| 2500+ employees | +0.635*** | +0.755*** | +0.706*** | +0.710*** | +0.712*** | +0.711*** |
| | (0.069) | (0.067) | (0.067) | (0.066) | (0.066) | (0.066) |
| Multi-unit firm | +0.144*** | +0.142*** | +0.122*** | +0.125*** | +0.125*** | +0.125*** |
| | (0.026) | (0.026) | (0.026) | (0.026) | (0.026) | (0.026) |
| Primary source: Surface | | −0.422*** | −0.435*** | −0.402*** | −0.402*** | −0.403*** |
| | | (0.034) | (0.033) | (0.033) | (0.033) | (0.033) |
| Primary source: Ground | | −0.054** | −0.084*** | −0.087*** | −0.085*** | −0.087*** |
| | | (0.024) | (0.024) | (0.024) | (0.024) | (0.024) |
| Primary source: Tidewater | | −0.633*** | −0.620*** | −0.610*** | −0.618*** | −0.617*** |
| | | (0.070) | (0.069) | (0.071) | (0.071) | (0.071) |
| Percent of water discharged that is treated | | | +0.327*** | +0.296*** | +0.295*** | +0.296*** |
| | | | (0.025) | (0.025) | (0.025) | (0.025) |
| County average daily precipitation | | | | | | −0.014 |
| | | | | | | (0.023) |
| Industry effects (4-digit SIC) | yes | yes | yes | yes | yes | yes |
| State effects | no | no | no | yes | yes | yes |
| Water use region effects | no | no | no | no | yes | yes |
| R-squared | 0.2477 | 0.2657 | 0.2796 | 0.2977 | 0.2988 | 0.2989 |
| Number of observations | 9,859 | 9,859 | 9,859 | 9,859 | 9,859 | 9,859 |

- Larger establishments are also found to recirculate water more, implying greater *use* without necessarily greater *intake*.
  - Controlling for only industry, water circulation rate increases monotonically with establishment size.
  - The largest establishments (with 2500+ employees) use each gallon of water 89% more than the smallest establishments.
  - Result is robust to the addition of other explanatory variables....

# Water Circulation Rate

Log (gross water use / water intake)

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| 100-249 employees | +0.099*** | +0.114*** | +0.107*** | +0.099*** | +0.099** | +0.100*** |
| | (0.029) | (0.028) | (0.029) | (0.028) | (0.028) | (0.028) |
| 250-499 employees | +0.222*** | +0.256*** | +0.236*** | +0.221*** | +0.221*** | +0.222*** |
| | (0.032) | (0.032) | (0.032) | (0.032) | (0.032) | (0.032) |
| 500-999 employees | +0.245*** | +0.291*** | +0.274*** | +0.256*** | +0.256*** | +0.257*** |
| | (0.037) | (0.036) | (0.036) | (0.035) | (0.035) | (0.035) |
| 1000-2499 employees | +0.362*** | +0.438*** | +0.414*** | +0.399*** | +0.401*** | +0.401*** |
| | (0.044) | (0.044) | (0.043) | (0.043) | (0.043) | (0.043) |
| 2500+ employees | +0.635*** | +0.755*** | +0.706*** | +0.710*** | +0.712*** | +0.711*** |
| | (0.069) | (0.067) | (0.067) | (0.066) | (0.066) | (0.066) |
| Multi-unit firm | +0.144*** | +0.142*** | +0.122*** | +0.125*** | +0.125*** | +0.125*** |
| | (0.026) | (0.026) | (0.026) | (0.026) | (0.026) | (0.026) |
| Primary source: Surface | | −0.422*** | −0.435*** | −0.402*** | −0.402*** | −0.403*** |
| | | (0.034) | (0.033) | (0.033) | (0.033) | (0.033) |
| Primary source: Ground | | −0.054** | −0.084*** | −0.087*** | −0.085*** | −0.087*** |
| | | (0.024) | (0.024) | (0.024) | (0.024) | (0.024) |
| Primary source: Tidewater | | −0.633*** | −0.620*** | −0.610*** | −0.618*** | −0.617*** |
| | | (0.070) | (0.069) | (0.071) | (0.071) | (0.071) |
| Percent of water discharged that is treated | | | | +0.327*** | +0.296*** | +0.295*** | +0.296*** |
| | | | | (0.025) | (0.025) | (0.025) | (0.025) |
| County average daily precipitation | | | | | | −0.014 |
| | | | | | | (0.023) |
| Industry effects (4-digit SIC) | yes | yes | yes | yes | yes | yes |
| State effects | no | no | no | yes | yes | yes |
| Water use region effects | no | no | no | no | yes | yes |
| R-squared | 0.2477 | 0.2657 | 0.2796 | 0.2977 | 0.2988 | 0.2989 |
| Number of observations | 9,859 | 9,859 | 9,859 | 9,859 | 9,859 | 9,859 |

- Primary source of water
  - Results suggest that when *self-supplied* water is the primary source of an establishment's water – whether surface water, groundwater, or tidewater – the water circulation rate is <u>lower</u> than when water is from public systems (the omitted category).
    - Recirculation is particularly low among establishments in which tidewater and surface water are primary sources.
    - This suggest that, for some manufacturing plants, the cost of pumping (and treating) their own water is so low that
      - (i) they choose to self-supply water in the first place, and
      - (ii) there is less incentive to invest in recirculation.

# Water Circulation Rate

Log (gross water use / water intake)

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| 100-249 employees | +0.099*** | +0.114*** | +0.107*** | +0.099*** | +0.099** | +0.100*** |
| | (0.029) | (0.028) | (0.029) | (0.028) | (0.028) | (0.028) |
| 250-499 employees | +0.222*** | +0.256*** | +0.236*** | +0.221*** | +0.221*** | +0.222*** |
| | (0.032) | (0.032) | (0.032) | (0.032) | (0.032) | (0.032) |
| 500-999 employees | +0.245*** | +0.291*** | +0.274*** | +0.256*** | +0.256*** | +0.257*** |
| | (0.037) | (0.036) | (0.036) | (0.035) | (0.035) | (0.035) |
| 1000-2499 employees | +0.362*** | +0.438*** | +0.414*** | +0.399*** | +0.401*** | +0.401*** |
| | (0.044) | (0.044) | (0.043) | (0.043) | (0.043) | (0.043) |
| 2500+ employees | +0.635*** | +0.755*** | +0.706*** | +0.710*** | +0.712*** | +0.711*** |
| | (0.069) | (0.067) | (0.067) | (0.066) | (0.066) | (0.066) |
| Multi-unit firm | +0.144*** | +0.142*** | +0.122*** | +0.125*** | +0.125*** | +0.125*** |
| | (0.026) | (0.026) | (0.026) | (0.026) | (0.026) | (0.026) |
| Primary source: Surface | | −0.422*** | −0.435*** | −0.402*** | −0.402*** | −0.403*** |
| | | (0.034) | (0.033) | (0.033) | (0.033) | (0.033) |
| Primary source: Ground | | −0.054** | −0.084*** | −0.087*** | −0.085*** | −0.087*** |
| | | (0.024) | (0.024) | (0.024) | (0.024) | (0.024) |
| Primary source: Tidewater | | −0.633*** | −0.620*** | −0.610*** | −0.618*** | −0.617*** |
| | | (0.070) | (0.069) | (0.071) | (0.071) | (0.071) |
| Percent of water discharged that is treated | | | | +0.327*** | +0.296*** | +0.295*** | +0.296*** |
| | | | | (0.025) | (0.025) | (0.025) | (0.025) |
| County average daily precipitation | | | | | | −0.014 |
| | | | | | | (0.023) |
| Industry effects (4-digit SIC) | yes | yes | yes | yes | yes | yes |
| State effects | no | no | no | yes | yes | yes |
| Water use region effects | no | no | no | no | yes | yes |
| R-squared | 0.2477 | 0.2657 | 0.2796 | 0.2977 | 0.2988 | 0.2989 |
| Number of observations | 9,859 | 9,859 | 9,859 | 9,859 | 9,859 | 9,859 |

- Environmental regulation
  - The more heavily regulated a facility's water pollution discharges are, the more it may recirculate water (as a substitute for discharge).
  - Proxy:  The percent of an establishment's water discharge that was treated.
    - *No* discharged water was treated: about 50% of cases
    - *All* discharged water was treated:  about 14% of cases
  - Results suggest that regulation indeed has a statistically significant positive effect on the water circulation rate.

# Water Circulation Rate

Log (gross water use / water intake)

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| 100-249 employees | +0.099*** | +0.114*** | +0.107*** | +0.099*** | +0.099** | +0.100*** |
| | (0.029) | (0.028) | (0.029) | (0.028) | (0.028) | (0.028) |
| 250-499 employees | +0.222*** | +0.256*** | +0.236*** | +0.221*** | +0.221*** | +0.222*** |
| | (0.032) | (0.032) | (0.032) | (0.032) | (0.032) | (0.032) |
| 500-999 employees | +0.245*** | +0.291*** | +0.274*** | +0.256*** | +0.256*** | +0.257*** |
| | (0.037) | (0.036) | (0.036) | (0.035) | (0.035) | (0.035) |
| 1000-2499 employees | +0.362*** | +0.438*** | +0.414*** | +0.399*** | +0.401*** | +0.401*** |
| | (0.044) | (0.044) | (0.043) | (0.043) | (0.043) | (0.043) |
| 2500+ employees | +0.635*** | +0.755*** | +0.706*** | +0.710*** | +0.712*** | +0.711*** |
| | (0.069) | (0.067) | (0.067) | (0.066) | (0.066) | (0.066) |
| Multi-unit firm | +0.144*** | +0.142*** | +0.122*** | +0.125*** | +0.125*** | +0.125*** |
| | (0.026) | (0.026) | (0.026) | (0.026) | (0.026) | (0.026) |
| Primary source: Surface | | −0.422*** | −0.435*** | −0.402*** | −0.402*** | −0.403*** |
| | | (0.034) | (0.033) | (0.033) | (0.033) | (0.033) |
| Primary source: Ground | | −0.054** | −0.084*** | −0.087*** | −0.085*** | −0.087*** |
| | | (0.024) | (0.024) | (0.024) | (0.024) | (0.024) |
| Primary source: Tidewater | | −0.633*** | −0.620*** | −0.610*** | −0.618*** | −0.617*** |
| | | (0.070) | (0.069) | (0.071) | (0.071) | (0.071) |
| Percent of water discharged that is treated | | | +0.327*** | +0.296*** | +0.295*** | +0.296*** |
| | | | (0.025) | (0.025) | (0.025) | (0.025) |
| County average daily precipitation | | | | | | −0.014 |
| | | | | | | (0.023) |
| Industry effects (4-digit SIC) | yes | yes | yes | yes | yes | yes |
| State effects | no | no | no | yes | yes | yes |
| Water use region effects | no | no | no | no | yes | yes |
| R-squared | 0.2477 | 0.2657 | 0.2796 | 0.2977 | 0.2988 | 0.2989 |
| Number of observations | 9,859 | 9,859 | 9,859 | 9,859 | 9,859 | 9,859 |

- Geography (additional regulatory effects, water scarcity, and other impacts)
  - Inclusion of dummy variables for the *50 states* and for *20 industrial water use regions* has relatively effect on findings.
  - County average daily precipitation:
    - Negative, as might be expected, but not statistically significant .
      - This suggests that the aridity of a manufacturing plant's locale does not impact its water circulation rate, at least not above and beyond any effect captured by the controls for state and river basin.
      - Padowski and Jawitz (2012) have noted that there can be a disconnect between local conditions and water availability, due to the presence of rivers and manmade water infrastructure.

# Water Circulation Rate
# by Establishment Size

- With this full set of explanatory variables:
  - Positive, monotonic relationship between establishment size and water circulation rate
  - The largest establishments (with 2500+ employees) use each gallon of water 104% more than their smallest counterparts (with 1-99 employees).
  - The circulation rate among these largest establishments is 36% greater than the next category of plants (1000-2499)...
  - Which is 15% than the next category (500-999 employees)...
  - Which is 4% greater than the next category (250-499)...
  - Which is 13% greater than the next category (100-249)...
  - Which is 10% greater than the smallest category.
  - Establishments belonging to multi-unit firms are found to use water 13% more times.

# Water Circulation Rate by Purpose

Log (gross water use / water intake)

| | All purposes | Process | Steam electric power gener. | Air conditioning | Other cooling & condensing | Sanitary services | Boiler feed |
|---|---|---|---|---|---|---|---|
| 100-249 employees | +0.100*** | +0.078*** | +0.315 | +0.147 | +0.201*** | +0.006 | −0.076*** |
| | (0.028) | (0.026) | (0.197) | (0.105) | (0.050) | (0.007) | (0.028) |
| 250-499 employees | +0.222*** | +0.126*** | +0.470** | +0.386*** | +0.390*** | +0.009 | −0.016 |
| | (0.032) | (0.031) | (0.223) | (0.112) | (0.057) | (0.007) | (0.033) |
| 500-999 employees | +0.257*** | +0.117** | +0.578** | +0.385*** | +0.461*** | +0.004 | −0.000 |
| | (0.035) | (0.032) | (0.269) | (0.117) | (0.061) | (0.006) | (0.036) |
| 1000-2499 employees | +0.401*** | +0.169*** | +0.589** | +0.777*** | +0.637*** | +0.008 | +0.086** |
| | (0.043) | (0.041) | (0.255) | (0.127) | (0.071) | (0.008) | (0.043) |
| 2500+ employees | +0.711*** | +0.241*** | +0.559 | +1.142*** | +1.092*** | −0.009 | +0.182*** |
| | (0.066) | (0.065) | (0.382) | (0.161) | (0.102) | (0.010) | (0.061) |
| Multi-unit firm | +0.125*** | +0.024 | +0.276* | +0.167 | +0.236*** | −0.012 | +0.084*** |
| | (0.026) | (0.022) | (0.167) | (0.103) | (0.047) | (0.013) | (0.028) |
| Primary source: Surface | −0.403*** | −0.102*** | −0.513** | −0.400*** | −0.593*** | −0.012 | −0.059* |
| | (0.033) | (0.033) | (0.242) | (0.096) | (0.051) | (0.007) | (0.031) |
| Primary source: Ground | −0.087*** | +0.022 | −0.199 | −0.278*** | −0.186*** | +0.000 | −0.048** |
| | (0.024) | (0.023) | (0.221) | (0.082) | (0.042) | (0.006) | (0.021) |
| Primary source: Tidewater | −0.617*** | −0.055 | −1.270*** | −0.823*** | −0.813*** | +0.002 | −0.095* |
| | (0.071) | (0.074) | (0.343) | (0.190) | (0.114) | (0.015) | (0.052) |
| Percent of water discharged that is treated | +0.296*** | +0.075*** | +0.580*** | +0.480*** | +0.557*** | +0.007 | +0.051** |
| | (0.025) | (0.024) | (0.180) | (0.086) | (0.046) | (0.005) | (0.024) |
| County average daily precipitation | −0.014 | −0.037 | +0.111 | +0.226*** | −0.079* | −0.002 | −0.009 |
| | (0.023) | (0.026) | (0.124) | (0.103) | (0.045) | (0.004) | (0.023) |
| Industry effects (4-digit SIC) | yes | yes | yes | yes | yes | yes | yes |
| State effects | yes | yes | yes | yes | yes | yes | yes |
| Water use region effects | yes | yes | yes | yes | yes | yes | yes |
| R-squared | 0.2989 | 0.2729 | 0.4080 | 0.2487 | 0.2571 | 0.0416 | 0.1260 |
| Number of observations | 9,859 | 8,572 | 775 | 3,381 | 7,651 | 8,330 | 7,367 |

- No effects:  *Sanitary services*
- Increases with establishment size (mostly):
  - *Process*
  - *Air conditioning*
  - *Other cooling & condensing*
- Highest for largest:  *Boiler feed*
- Increases to a point:  *Steam electric power generation*  (max at 1000-2499)

# (Preliminary) Conclusions

- Water use per unit of output is largest for the largest establishments.
  - Larger establishments use water for more purposes.
  - Larger establishments recirculated water more — implying greater *use* without necessarily greater *intake*.
- Water circulation is also found to be:
  - Lower when water is self-supplied.
  - Higher when treatment of discharged water is high.
  - Unaffected by the aridity of a locale.
- Certain purposes dominate both overall water use as well as recirculation.

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22

# Future Work

- Explore other items collected on the SWUM.
- Use data from the 1978 SWUM.
- Link data from the 1973 and 1978 SWUM
  - Who adopts (or abandons) certain water uses and recirculating technologies?
- Examine relationship with:
  - Productivity
  - Capital intensity
  - Energy use
  - Plant age