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Abstract

This report provides an estimate of the hydrologic footprint for the Caterpillar Corporation facility in Montgomery, IL. The hydrologic footprint includes conventional water use at the facility, evaporated water associated with electricity use, on-site stormwater, and conventional and evaporative water uses associated with the Caterpillar supply chain. At this facility, the total hydrologic footprint is about 86×10^6 m^3/y (33×10^{10} gal/y), and water withdrawal by industries in the supply chain dominates the hydrologic footprint (Figure 1).

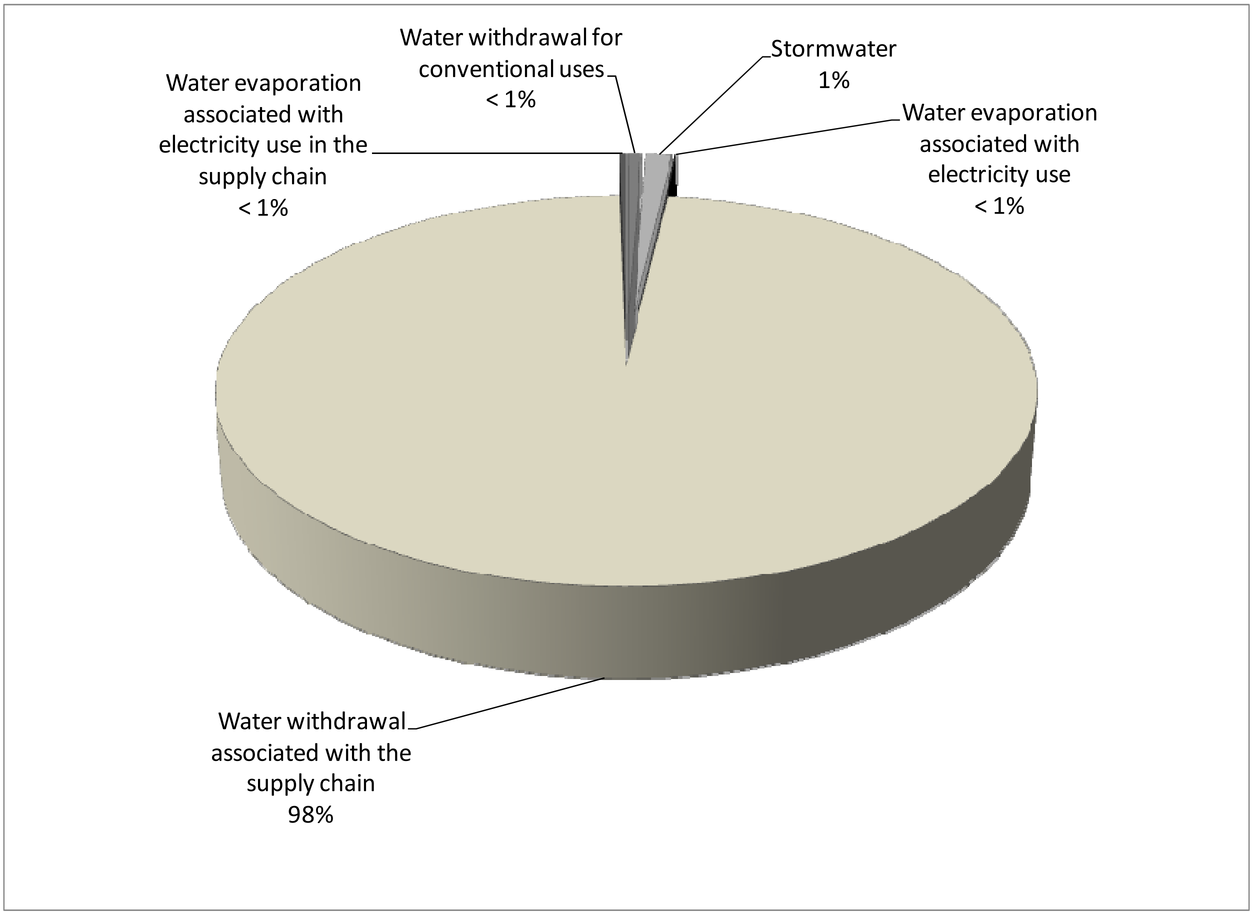

Figure 1. Distribution of water use in the estimated hydrologic footprint for the Caterpillar facility in Montgomery, IL. Results summarized in this figure represent an average from the range of estimated values.

Introduction

This report is part of a continuing study to evaluate the role of industry in the hydrologic cycle. The hydrologic footprint can contribute to that understanding because it provides a comprehensive measurement of how much water is used by an industry. In this study, the hydrologic footprint is defined as the total amount of water involved in the following activities:

- **Direct water use associated with industrial activity.** This category includes process, product, washing, maintenance, and irrigation water. Water used by employees for drinking, cooking, showers, and toilets is also included.
- **Indirect water use associated with consumption of electricity.** A substantial amount of water withdrawal in the United States is for cooling water in thermoelectric plants. As a result, the amount of electricity used by an industry adds to the hydrologic footprint.
- **Stormwater runoff.** The volume of stormwater generated from a plant site depends on the precipitation rate, the characteristics of the surfaces where the precipitation falls, and the on-site stormwater management plan.
- **Indirect water use associated with the supply chain for that industry.** Economic activity in any single industry drives related economic activity through a supply chain of many other industries. These kinds of relationships can be captured in economic input-output models. Each industry in the supply chain also has direct and indirect water uses. Assuming that the water withdrawal is proportional to the level of economic activity, it is possible to estimate the amount of water used in the supply chain and relate that amount to the economic activity of the original single industry.

One of the objectives of this study was to focus on industry near Aurora, IL. Reasons for that focus include: Aurora is the second largest city in Illinois; Aurora is in the rapidly developing Fox River watershed; the municipal water supply includes both groundwater and surface water sources; and there are growing concerns that regional demand for water will exceed the supply. The specific industry evaluated in this study is the Caterpillar facility in Montgomery, IL (Montgomery is adjacent to and west of Aurora).

Immediately following this introduction is a description of the methods and sources of information used to estimate the hydrologic footprint. The subsequent section describes results based on data specific to the Caterpillar facility, as well as publicly available data on precipitation and land use. Estimates of the supply chain contributions to the hydrologic footprint come from a public domain software program designed as a life-cycle assessment tool. The report concludes with a discussion of the results, conclusions, recommendations for further study, and a list of references.

Methods and Sources of Information

The Caterpillar facility in Montgomery, IL is located just west of IL State Route 31 in the northeast corner of Kendall County. According to the 1987 Standard Industrial Classification (SIC), Caterpillar Incorporated is a "Construction Machinery and Equipment" industry (SIC = 3531). In the 1997 North American Industrial Classification System (NAICS = 333120), the sector is "Construction Machinery Manufacturing". Caterpillar Incorporated manufactures construction and mining equipment, diesel and natural gas engines, and industrial gas turbines, but not all of these products are manufactured at the Montgomery facility. A brief description of the hydrologic footprint components and the data that define that footprint follows.

Direct water use associated with industrial activity

This category includes all conventional water use such as process water, water used for cleaning equipment, and water used by employees. Caterpillar personnel (Hastert, 2005) provided data on water withdrawal. Water at this Caterpillar facility is pumped from three wells on the property. Most of the water comes from the Galesville Sandstone aquifer, but the St. Peter Sandstone aquifer is also tapped. The average depth of the wells is about 427 m (1400 ft).

Indirect water use associated with consumption of electricity

According to the United States Geological Survey, nearly half of the total water withdrawn in the United States in 2000 was used as cooling water in thermoelectric plants (Hutson et al., 2005). Although most of that water was returned to surface waters (it is not a consumptive use), the water was returned at a higher temperature, which enhances evaporation. Torcellini et al. (2003) estimated evaporative water loss rates for power plants throughout the United States. For Illinois, the estimated evaporation rate was 3.97×10^{-3} m^3 (1.05 gal) of water for every 1 kWh generated. The weighted evaporation rate throughout the United States was 1.78×10^{-3} m^3 (0.47 gal) of water evaporated for every 1 kWh generated.

Caterpillar also provided data on electricity consumption (Hastert, 2005). Prior to 2002 this Caterpillar facility purchased all of the electricity used on site. In 2002, they began operating a co-generation system and in 2003 and 2004 that system produced most of the electricity they used.

Stormwater runoff

Stormwater runoff depends on precipitation, area, land use, slope, and stormwater management practices. Precipitation data near Montgomery, IL are available from monitoring stations maintained by the United States Geological Survey (USGS, 2005) and the Illinois State Water Survey (ISWS, 2007). These gage stations are located about 4.7 km (2.9 mi) and 10.1 km (6.3 mi) from the Caterpillar facility, respectively. Data used to estimate this part of the hydrologic footprint were average values weighted according to the inverse distance from these gages. Area, land use, and slope were estimated from USGS maps available through TerraServer (2005). The annual volume of stormwater is the product of the average precipitation and the site area. The estimate used here is based on total stormwater potential; there are no adjustments for stormwater management practices at the Caterpillar facility.

Indirect water use associated with the supply chain

Industrial supply chains typically include an array of industries that interact with each other through interconnected networks and feedback loops. It would be very difficult for any single industrial facility to have an accurate description of all the interactions in its own supply chain.

One way to investigate supply chain interactions for industrial sectors is to use the economic input-output, life cycle assessment (eiolca) software program developed at Carnegie Mellon University. The eiolca.net program (Carnegie Mellon University Green Design Institute, 2005) is based on an input-output (IO) model of the U.S. economy developed by the U.S. Department of Commerce. Because it incorporates information from other public databases, the eiolca.net program can be used to estimate the effects, relative to resource use or emissions, of individual industry sectors throughout the United States. Furthermore, the program captures the economic interactions so it is possible to examine links between an industry sector and that sector's supply chain. Using eiolca.net it is possible, for example, to estimate the total amount of water withdrawn as a result of economic activity in the Construction Machinery Manufacturing sector. Output from the program includes not only an estimate of demands specific to that sector; it also provides estimates of demands for other sectors of the economy representing suppliers that deal with the Construction Machinery Manufacturing sector.

Several versions of the software are available at the eiolca.net web site, and data sources for these models are described by Hendrickson et al. (2006). Results presented here are from the eiolca.net model for 2002, which represents the U.S. economy with a 428 × 428 matrix of interacting industrial sectors. This version also includes information for water withdrawal across the U.S. economy, based on water use data from 2000 published by the United States Geological Survey (Hutson et al., 2004). Blackhurst et al. (2010) recently described how they allocated water withdrawal estimates across industrial sectors.

Some other important points about the eiolca.net program are:

- Data are limited to U.S. industries. If the supply chain includes international partners, those interactions are not captured directly in this model.
- The model is linear. For example, the resource demands associated with $2 million of economic activity are two times the demands associated with $1 million dollars of activity. There is no economy of scale factor.
- The model is based on average performance across each industrial sector. Data for the Construction Machinery Manufacturing sector used in this study represent a range of facilities with a variety of products such as construction machinery, logging equipment, and surface mining machinery. Water withdrawal and electricity demand are likely to vary from one facility to another even in the same sector.

Absent from the supply chain analysis is any assessment of the stormwater component of the supply chain hydrologic footprint. The significance of this lack of information will be revisited in the discussion section.

Results

Data and calculations for each of the four components of the hydrologic footprint are presented in this section. The section concludes with a table summarizing the overall hydrologic footprint. It is important to recognize that the eiolca.net program and the included Department of Commerce information represent entire sectors of the economy. These data are not specific to the Caterpillar facility in Montgomery; they are used here to explore the concept of a hydrologic footprint.

Direct water use associated with industrial activity

Average annual water withdrawal from 2001 through 2004 was 4.69×10^5 m^3 (1.24×10^8 gal) (Table 1). Some of this water was used for steam generation and cooling of the co-generation plant. The data suggest that water withdrawal generally decreased over the four years, at a rate of about 3.78×10^4 m^3 (10^7 gal) per year.

Indirect water use associated with electricity

Data from 1990 and 2000 – 2004 (Figure 2) reveal how beginning in 2002 the amount of purchased electricity dropped dramatically as the co-generation facility came on-line. The evaporation rate estimates from Torcellini et al. (2003) apply only to the purchased electricity (in a co-generation facility the production of steam provides cooling). Prior to co-generation the average annual amount of purchased electricity was 1.33×10^8 kWh, so the amount of water lost each year through evaporation ranged from 2.4×10^5 m^3 to 5.3×10^5 m^3 (6.3×10^7 to 1.4×10^8 gal). In 2003 and 2004, the average annual amount of purchased electricity was only 1.77×10^7 kWh, so the amount of water lost each year through evaporation ranged from 3.1×10^4 m^3 to 7.0×10^4 m^3 (8.2×10^6 to 1.8×10^7 gal). These more recent values will be used in the hydrologic footprint assessment.

Table 1. Annual water withdrawal for the Caterpillar facility in Montgomery, IL, 2001 - 2004 (Hastert, 2005).

	Annual water withdrawal				
	2001	2002	2003	2004	Mean
10^3 m^3	526	545	416	394	470
10^6 gallons	139	144	110	104	124

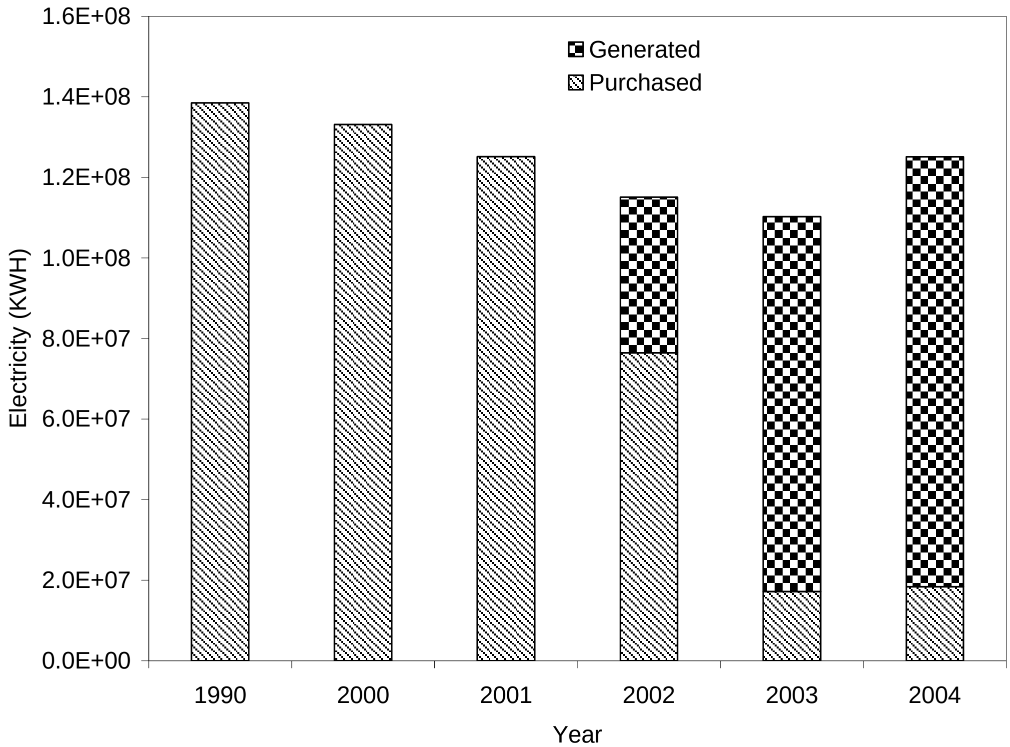

Figure 2. Electricity consumption at the Caterpillar, Inc. facility in Montgomery, IL in 1990 and from 2001 through 2004 (Hastert, 2005). The co-generation facility began operating in 2002.

Stormwater runoff

The estimated mean annual precipitation (Table 2) from 2000 through 2004 is 0.77 m (30.3 in).

Table 2. Annual total precipitation data near the Caterpillar facility from USGS (2005) and ISWS (2007) gage data. The average is weighted according to the inverse distance.

	Gage data (in/y)		Weighted average	
Water year	USGS	ISWS	in/y	m/y
2000	30.85	36.67	32.7	0.83
2001	32.67	38.10	34.4	0.87
2002	31.91	29.96	31.3	0.79
2003	25.25	39.33	29.7	0.75
2004	20.41	34.45	24.9	0.63
Average	28.22	35.7	30.6	0.77

The site is roughly rectangular except where the southeast corner is cut off by a railroad track (Figure 3), and the total area is approximately 1.24×10^6 m^2 (0.48 mi^2). Most of the area appears to be impermeable surfaces (buildings, parking lots, and work yards). Four roughly rectangular areas in the photograph are turf-dominated (northeast corner, northwest corner, and just south of a parking lot), but they account for only about 7% (9.4×10^4 m^2) of the total area.

A topographic map of the site (Figure 4) shows an average elevation of about 201 m (660 ft) above sea level. The natural gradient is slight. There is about a 0.1% slope from the northwest toward the southeast.

Based on the total facility area (1.24×10^6 m^2), the volume of total stormwater ranges from 7.8×10^5 to 1.08×10^6 m^3/y with an average of 9.5×10^5 m^3/y (2.52×10^8 gal/y). In the absence of information about on-site stormwater management practices, there is no attempt to distinguish between infiltration and runoff.

Figure 3. Aerial photograph (dated 1999) of the Caterpillar, Inc. facility in Montgomery, IL and surroundings. The location is approximately longitude 88.4° west and latitude 41.7°N. The photograph is a product of the United States Geological Survey, obtained from TerraServer (2005). The solid white line was added to the photograph to help identify the property.

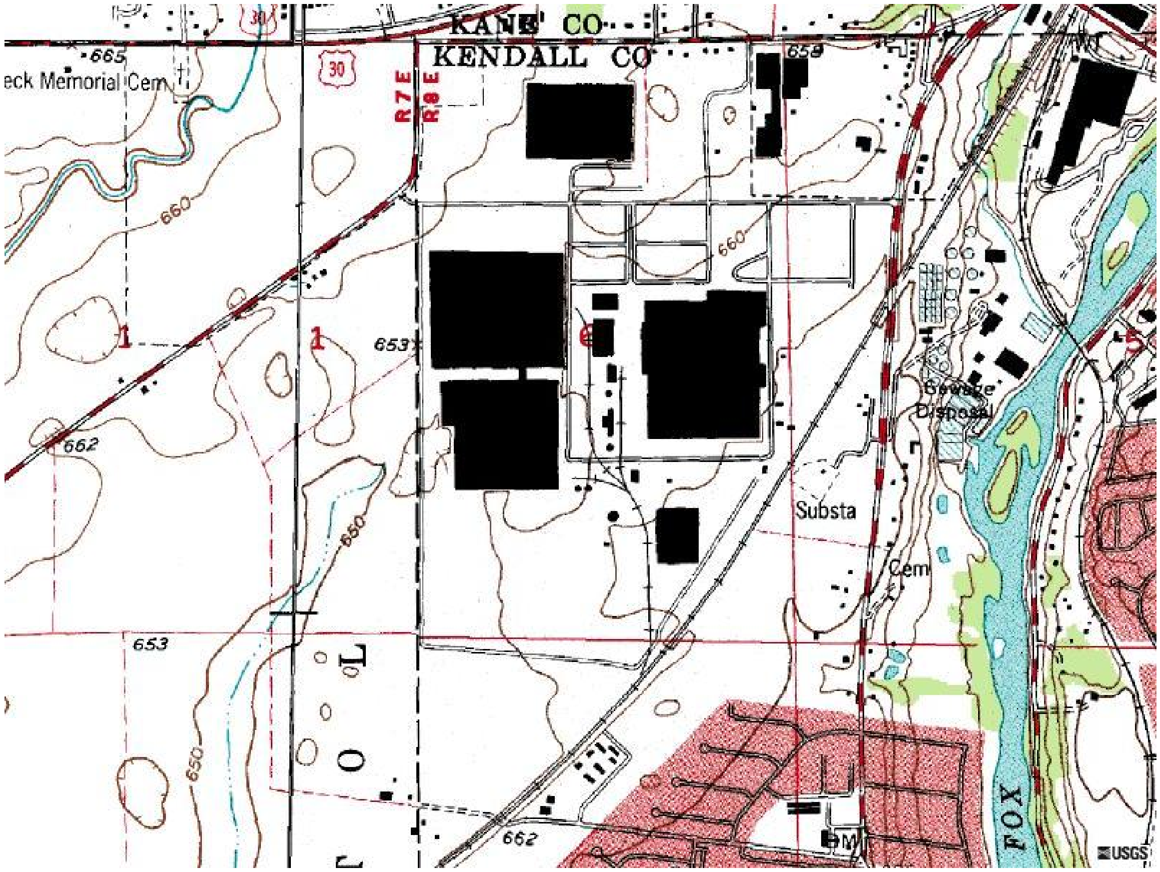

Figure 4. 1983 topographic map of the Caterpillar, Inc. facility in Montgomery, IL and surroundings. The location is approximately longitude 88.4° west and latitude 41.7°N. The map is a product of the United States Geological Survey, obtained from TerraServer (2005).

Indirect water use associated with the hydrologic footprint of suppliers

This section describes estimates of supply chain water use associated with the Construction Machinery and Equipment sector. Values presented here (Table 3) have been scaled to water and electricity use at the Caterpillar facility. The estimated average annual water withdrawal for the supply chain is 79.3×10^6 m^3 (2.1×10^{10} gal). The estimated average annual water evaporation due to supply chain electricity use is 0.22×10^6 m^3 (5.8×10^7 gal).

Total hydrologic footprint

Based on the data presented in this study, the total hydrologic footprint for the Caterpillar facility (Table 4) ranges from about 72×10^6 to 99×10^6 m^3/ y. The average value is 86×10^6 m^3/y (2.3×10^{10} gal/y).

Table 3. Water withdrawal and electricity use for the Construction Machinery and Equipment sector and its supply chain. The table also includes an estimate of the amount of water evaporation associated with the electricity use.

Resource demand	Minimum	Maximum	Average
Water withdrawal (10^6 m^3/y)			
Total of all sectors	66.9	92.5	79.7
Construction Machinery and Equipment	0.4	0.5	0.5
Other sectors (supply chain)	66.5	92.0	79.2
Electricity consumed (10^7 kWh/y)			
Total of all sectors	9.1	9.6	9.4
Construction Machinery and Equipment	1.7	1.8	1.8
Other sectors (supply chain)	7.4	7.8	7.6
Water evaporated (10^6 m^3/y)			
Total of all sectors	0.2	0.4	0.3
Construction Machinery and Equipment	< 0.1	0.1	0.1
Other sectors (supply chain)	0.1	0.3	0.2

Table 4. Estimated hydrologic footprint for the Caterpillar facility in Montgomery, IL.

	10^6 m^3/y		
Direct or indirect water use	Minimum	Maximum	Average
Water withdrawal for conventional uses	0.4	0.5	0.5
Stormwater	0.8	1.1	0.9
Water evaporation associated with electricity use	< 0.1	0.1	0.1
Water withdrawal associated with the supply chain	66.5	91.9	79.3
Water evaporation associated with electricity use in the supply chain	0.1	0.3	0.2
Total hydrologic footprint	67.8	93.9	81.0

Discussion and Conclusions

Conventional water use within the facility contributes only about 1% of the overall hydrologic footprint. As a result, increasing the water use efficiency at this Caterpillar facility would have only a small effect on the hydrologic footprint. The largest contribution to the hydrologic footprint comes from water withdrawal throughout the supply chain, which contributes about 98% of the total. When an industrial facility has a small, direct hydrologic footprint, one of the most effective ways to further reduce that footprint could be to work with their suppliers to encourage increased water use efficiency throughout the supply chain.

Dominance of the supply chain is apparently not unusual. Blackhurst et al. (2010) reported that for 96% of the sectors water withdrawal in the supply chain exceeded direct water withdrawal by that sector. The ratio of direct-to-indirect (supply chain) water withdrawal has an approximately log normal distribution with a mean value near 0.01; the Caterpillar facility is roughly average in this sense.

Given the importance of the supply chain, it makes sense to look at the major sectors that make up the supply chain. Interestingly, although over 400 sectors could contribute to the supply chain, only ten sectors contribute over 90% of the hydrologic footprint (Table 5). Power generation is by far the largest contributor, which is consistent with Hutson et al. (2005) who reported that power generation accounted for most of the water withdrawal in the United States. Because there is a relatively small number of significant contributors in the supply chain, at least for the Construction Machinery and Equipment Sector, the task of working with the supply chain to reduce the hydrologic footprint appears feasible.

Although stormwater contributes only about 1% of the overall hydrologic footprint for this Caterpillar facility, results from this project suggest that stormwater deserves additional study. There was no information about stormwater for the supply chain in this study. Stormwater at the Caterpillar facility itself, however, accounts for over 50% of the direct (non-supply chain) footprint. It is possible that stormwater accounts for a similar fraction of the hydrologic footprint of a substantial number of industries in the supply chain. If so, it would be worthwhile to estimate the supply chain stormwater contribution to the total hydrologic footprint.

Table 5. The top ten sectors, their NAICS codes, and the fraction they contribute to water withdrawal in the Caterpillar supply chain.

NAICS	Sector	Fraction
221100	Power generation and supply	0.67
325510	Paint and coating manufacturing	0.10
1111B0	Grain farming	0.05
331110	Iron and steel mills	0.03
111920	Cotton farming	0.02
322130	Paperboard Mills	0.01
212210	Iron ore mining	0.01
325190	Other basic organic chemical manufacturing	0.01
325130	Synthetic dye and pigment manufacturing	0.01
2122A0	Gold, silver, and other metal ore mining	0.01

Hydrologic footprints could become a useful way to assess the relative effect of industrial facilities on hydrologic budgets. Industries could use the information to compare the performance at different facilities; planners could use hydrologic footprints to provide guidance about what relatively water-efficient industries should be encouraged to develop in arid regions.

Finally, the information presented here only addresses the hydrologic footprint in terms of volume. The footprint, however, could be a two-dimensional concept that also addresses water quality issues. For example, data from this study could be presented as shown in Figure 5. The semi-quantitative relationships depicted here are based on several subjective judgments:

- Evaporation probably removes water from the watershed, but it generates high quality water.
- Stormwater quality varies widely, but it is probably dominated by conventional contaminants such as suspended solids, oil & grease, and nutrients.
- Water withdrawn for plant use will be discharged to wastewater treatment plants prior to discharge to surface waters.

Water quality is becoming a growing concern because many microcontaminants can survive conventional wastewater treatment processes (Sedlak et al., 2000). Furthermore, recent studies demonstrate that pharmaceutical compounds are distributed throughout water supply sources in the United States (Kolpin et al., 2002). With these concepts in mind, water quality issues, as well as water volume used, will be important in future evaluations of hydrologic footprints and developing more efficient use of water supplies.

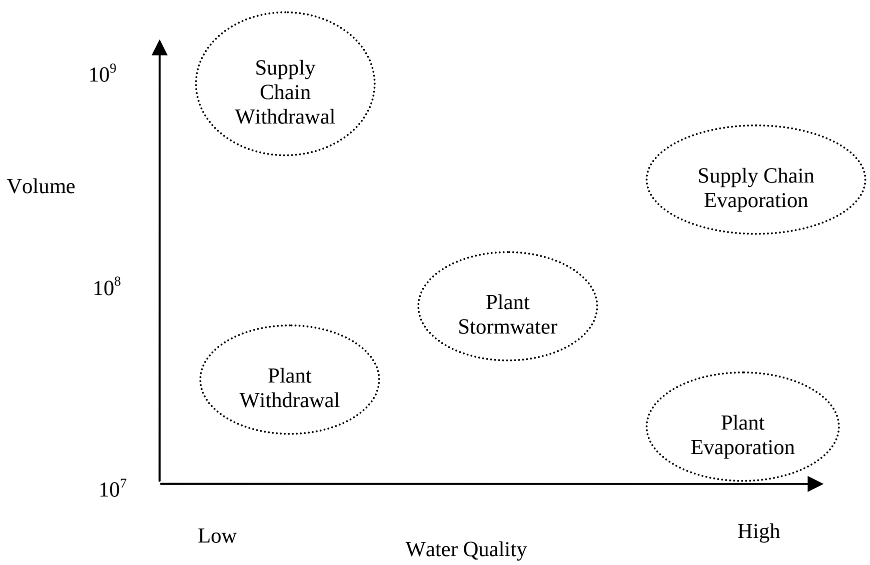

Figure 5. Schematic diagram showing relative contributions for five components of the volume+water quality hydrologic footprint for the Caterpillar facility in Montgomery, IL.

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