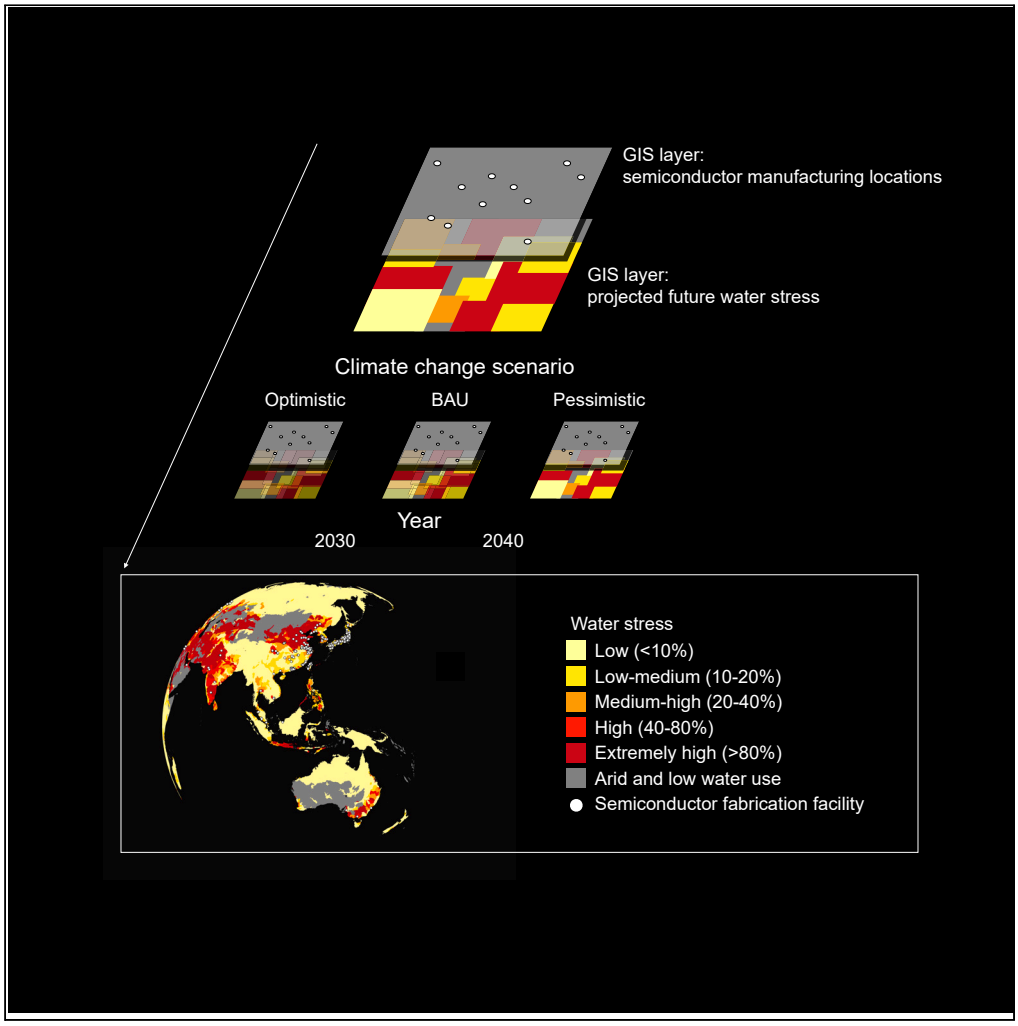
iScience

CellPress
OPEN ACCESS

Article

Climate change induced water stress and future semiconductor supply chain risk



Josh Lepawsky

jlepawsky@mun.ca

Highlights

Semiconductor manufacturing is projected to face significant future water stress risk

40% of facilities will be located in high- or extremely high risk in 2030 and 2040

24–40% of facilities under construction will be high- or extremely high risk

>40% of facilities announced since 2021 will be in high- or extremely high risk

Lepawsky, iScience 27, 108791
February 16, 2024
https://doi.org/10.1016/j.isci.2024.108791

iScience

CellPress
OPEN ACCESS

Article

Climate change induced water stress and future semiconductor supply chain risk

Josh Lepawsky[1,2,*]

SUMMARY

Climate change is a driver of water stress risk globally. Semiconductor manufacturing requires large volumes of water. Existing research at the intersection of water stress risk and semiconductor manufacturing offers snapshots of current conditions but has not investigated how future climate scenarios may impact semiconductor supply chain security. This study combines location data for semiconductor manufacturing facilities with data on specific customer-supplier networks and with data for global water stress risk under three climate scenarios for the years 2030 and 2040. Results suggest that 40 percent of existing facilities, 24–40 percent of facilities under construction, and 40–49 percent of facilities announced since early 2021 are in basins of high- or extremely high water stress risks in 2030 and 2040. Network dynamics mean that water stress risks could cascade from individual firms or regions of concern to systemically throughout the network, thus negatively impacting semiconductor supply chain security globally.

INTRODUCTION

Climate change is a driver of water stress risk. Semiconductor manufacturing is a water intensive process.[1] Semiconductors are an essential intermediate commodity for information and communication technology (ICT) products and concerns about semiconductor supply chains are expressed by governments around the world.[2,3] As such, semiconductors are a critical link within and between global production networks (GPNs) for many classes of finished goods that contain ICT components yet are not themselves typically understood as electronic devices (e.g., automobiles).[4–6] Consequently, climate change-induced water stress risks that inhere in semiconductor manufacturing infrastructure have the potential to propagate through interconnected GPNs for other commodities.

There have long been concerns about the environmental footprint and impacts arising from the broader electronics manufacturing sector.[7–12] Similarly, decades of public health research has documented the occupational health harms to workers from chemicals used to manufacture electronics in the US[13,14] and beyond as electronics manufacturing increasingly globalized.[15–18] As the global production networks of electronics have been extended,[3,19–22] so too have their environmental consequences.[18,23,24]

Meanwhile, there is less attention devoted to how changing environmental conditions, especially those relating to climate, may impact global electronics manufacturing. Indeed, only a small amount of previous research has quantified water stress risks for the semiconductor sector globally. Moreover, the extant literature is devoted to providing a snapshot of existing conditions at a sector[25,26] or individual firm level[27] rather than potential future conditions induced under climate change scenarios.

This study maps geographies of projected future water stress risks under three climate change scenarios (optimistic, business as usual, pessimistic) for the years 2030 and 2040 and their overlap with the global distribution of semiconductor manufacturing facilities. Results suggest that at least 40 percent of all existing semiconductor facilities will be in basins experiencing high- or extremely high water stress risks under climate scenarios for 2030 and 2040. Results also suggest that, depending on the climate scenario considered, 24–40 percent of all such facilities currently under construction and 40–49 percent of facilities announced since March 3, 2021, are located in basins projected to be at high- or extremely high water stress risk in 2030 and 2040. Two regions of concern are identified: Taiwan and the US desert southwest. The analysis suggests that aggregate results coupled with network dynamics of semiconductor global production networks may cascade from individual firms or regions of concern to systemically throughout the network.

RESULTS AND DISCUSSION

Global water stress risk and semiconductor manufacturing

Figure 1 depicts projected water stress risks at a basin level overlain by semiconductor facility locations under a business as usual (BAU) scenario for 2030. Five such water stress categories are depicted: "Low (<10%)," "Low-medium (10–20%)," "Medium-high (20–40%)," "High (40–80%)," and "Extremely high (>80%)". These water stress categories encapsulate a composite index of water availability and use (e.g., irrigation, industrial use, domestic use) in each basin.[28] Thus, semiconductor manufacturing facilities located in low risk basins mean

[1]Department of Geography, Memorial University of Newfoundland and Labrador, St. John's, NL A1B-3X9, Canada
[2]Lead contact
*Correspondence: jlepawsky@mun.ca
https://doi.org/10.1016/j.isci.2024.108791

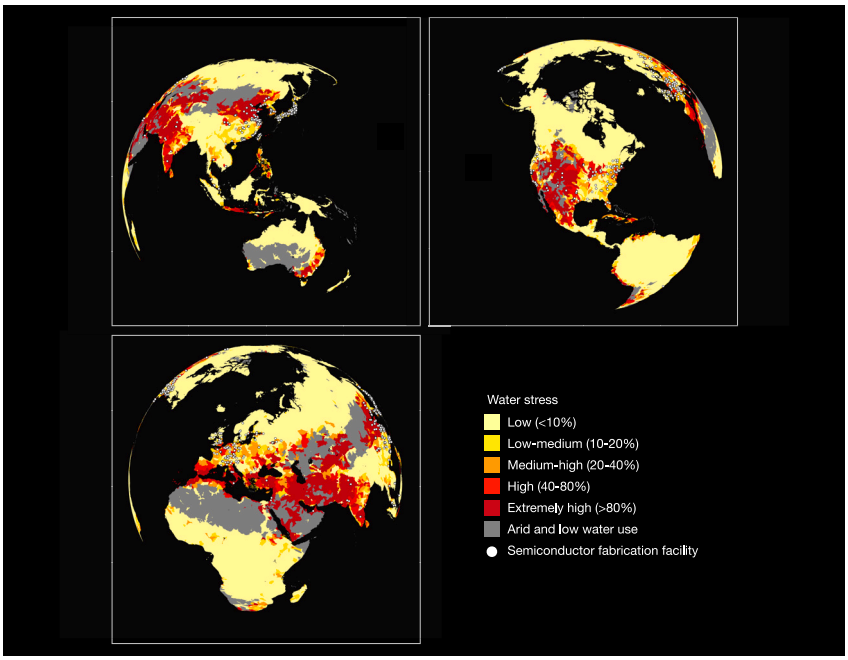


Figure 1. Global water stress risk and semiconductor manufacturing locations

Global semiconductor fabrication locations and projected water stress risk at a basin level under a business as usual (BAU) scenario for 2030.

those facilities operate in basins where total water withdrawals are less than 10% of available renewable surface and ground water supplies in a given basin. In contrast, semiconductor manufacturing facilities located in extremely high risk basins means those facilities operate in basins where total water withdrawals are greater than 80% of available renewable surface and groundwater supplies. The water stress risk categories (low, low-medium, medium-high, high, and extremely high) are based on a synthesis of physical quantity and quality factors as well as regulatory and reputational factors for hydrological basins globally as specified by the Aqueduct 3.0 dataset.[28] The water stress risk factors of the Aqueduct 3.0 dataset specifically cover semiconductor manufacturing and this same dataset is used by Intel and the world's largest contract semiconductor manufacturer, TSMC, for their own corporate water stress risk assessments.[29,30]

Table 1 offers a quantitative summary of water stress risks projected for 2030 and 2040 under all three climate emergency scenarios (optimistic, BAU, and pessimistic). These results suggest that there is a high likelihood of water stress risks arising for semiconductor production infrastructure in the next two decades.

Several aspects of Table 1 are notable. First, while there are differences in the projected water stress risks between each decade and each climate scenario, those differences are not dramatic. The most near term and optimistic scenario of 2030 is similar to the most far term and pessimistic scenario of 2040. Meanwhile, not less than 40 percent of all existing semiconductor facilities are projected to be in basins experiencing high- or extremely high water stress risks under the climate scenarios for 2030 and 2040. The 40 percent figure expands to over 64 percent of facilities if locations projected to experience at least medium-high water stress risk are included.

Results indicate that for years 2030 and 2040 across all climate scenarios approximately 24–40 percent of the facilities under construction are located in basins categorized as high- or extremely high risk. Results indicate that approximately 40–49 percent of facilities announced since March 3, 2021 (i.e., site selections have been made, but construction has not yet begun) are located in basins categorized as high- or extremely high risk. Both of these aggregate measures are concerning. They mean, for example, that a minimum of 1/4 of all semiconductor facilities currently being built are sited in areas with the highest risks of future water stress. In this regard, the sector is locking in a substantial potential of high risk water scenarios over the next two decades. Perhaps more concerning is that in the recent flurry of announcements of new facilities to be built (e.g., since the passage of the US CHIPS Act in 2022), decisions are being made that will increase water stress risks for the sector even further. In the case of facilities categorized as "announced", final sites have been selected but construction has not yet begun. This means there may be the potential to still avert some of the riskiest aggregate scenarios for the sector if siting decisions are revised.

Network dynamics and geographies of water stress risks to semiconductor production

The aggregate results for facilities classified as under construction or as announced are indicative of the magnitudes of water stress risks that may be being built into semiconductor manufacturing infrastructure. At the same time, such aggregate measures do not necessarily tell us much in terms of how such risks may or may not propagate through semiconductor GPNs or the other GPNs to which semiconductors are crucial intermediate inputs. Risks arising from water stress are unlikely to be evenly divided among all facilities in semiconductor GPNs. To

Table 1. Count of semiconductor manufacturing facilities per water stress risk category under climate scenarios for 2030 and 2040

	2030						2040					
	Optimistic		BAU		Pessimistic		Optimistic		BAU		Pessimistic	
Water Stress Risk	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent
Arid and low water use	3	<1	3	<1	3	<1	3	<1	3	<1	3	<1
Extremely high	374	27	386	28	382	27	311	22	379	27	355	25
High	238	17	228	16	201	14	301	22	238	17	204	15
Medium-high	295	21	286	21	313	22	294	21	282	20	336	24
Low-medium	271	19	282	20	286	21	189	14	191	14	191	14
Low	212	15	208	15	208	15	295	21	300	22	304	22

the extent that specific semiconductor facilities that are either under construction or have been announced have not yet established contracts to supply particular customers, the water stress risks that inhere to those specific facilities are at this point an open question.

Network dynamics refer to how individual firms are connected or disconnected from other firms in the same GPN. These relationships condition risks to overall network resiliency as well as to individual firms within the network.[3] A topological approach to networks can help identify key points, nodes, or "hotspots" of potential network fragility, or failure, both for individual firms and for the network as a whole.[31,32] Figure 2 thus helps understand how water stress risk may cascade through semiconductor GPNs under unfolding climate emergency scenarios.

Figure 2 covers a subset of known semiconductor manufacturing facilities (i.e., "suppliers") and their linkages with known customers. Similar patterns appear here with respect to future projected water stress risk as those summarized in Table 1. Only one semiconductor supplier is projected to be in a low water stress risk scenario in 2030 under a BAU scenario. Meanwhile, greater than 50 percent of these semiconductor suppliers are projected to face high- or extremely high water stress risk. Those risks inhering to suppliers can cascade to customers. Figure 2 makes clear that the topological situation (or network dynamics) of water stress, semiconductor supplier locations, and their downstream customers are unevenly distributed. Customers with more suppliers located in higher water stress basins will be more at risk of disruptions in their semiconductor supply chains. Thus, Figure 2 suggests important implications for how water stress risks may propagate through semiconductor GPNs.

Region of concern: Taiwan

Much attention is focused on Taiwan as a key region in global semiconductor supply chains since better than 90 percent of global production of the most advanced semiconductor manufacturing occurs in facilities located on the island.[33–35] Risks to semiconductor manufacturing arising from water stress in Taiwan have also gained attention from media[36,37] and financial ratings agencies.[38]

The causes of increasing water stress risk in Taiwan arise from a combination of ecological and political-economic factors. Ecological factors include multiple facets of the unfolding climate emergency while political-economic factors span a range of drivers from underpriced water supplies, decaying water delivery infrastructure, and an export-oriented economy for agricultural and semiconductor products, both of which are water intensive sectors.[36]

Water stress risks are not evenly distributed across Taiwan and, therefore, differentially impact semiconductor manufacturing facilities depending on where they are located on the island. The data analyzed here identifies 159 individual facilities on the island of Taiwan. Not less than 19 of those facilities are located in watersheds categorized as at extremely high risk of water stress under the climate scenarios for 2030 and 2040. Although 19 of 159 facilities represent not quite 12 percent of all facilities on the island of Taiwan, seven of those 19 facilities (i.e., more than a third) are all part of a single manufacturing location known as Fab 15, phases 1–7 operated by TSMC. Total water consumption at TSMC's Taiwan-based sites increased from 58 million metric tons per year in 2019 to 76.1 million metric tons in 2021,[29] even as the firm has worked hard to reduce consumption of municipal water sources on a per unit of product basis. TSMC is investing in water reclamation facilities, but even when complete the firm's own reports suggest those facilities will be able to provide no more than two-thirds of daily water supplies for the firm's plants in Taiwan.[29,39]

TSMC is one of only three companies in the world currently able to manufacture semiconductors at the state-of-the-art 10 nm or less.[35] Fab 15, phases 1–7 is known to supply semiconductors as intermediate products to key component manufacturers (e.g., Hisilicon; Mediatek) and lead firms (e.g., Apple) for several classes of end market electronic devices: smartphones, tablets, notebooks, and desktops.

In the smartphone sector, TSMC became Apple's sole supplier of central processing units (CPUs) for iPhones in 2016 and Fab 15 specifically was supplying the CPUs for all iPhones released as of late 2018.[40] On average, Apple depends for over 50 percent of its total revenue on iPhone sales.[41] Meanwhile, Apple is TSMC's largest single customer and accounts for about 1/4 of TSMC's total annual revenues.[42,43] By these measures, TSMC and Apple exist in a strong co-dependent relationship with one another that may exacerbate acute and chronic future water stress risk induced by the unfolding climate emergency. So while the absolute number of TSMC facilities located in extremely high-risk watersheds in Taiwan may appear small (n = 7), the relative importance of those facilities within broader semiconductor GPNs is more significant and may propagate water stress risk far beyond Fab 15.

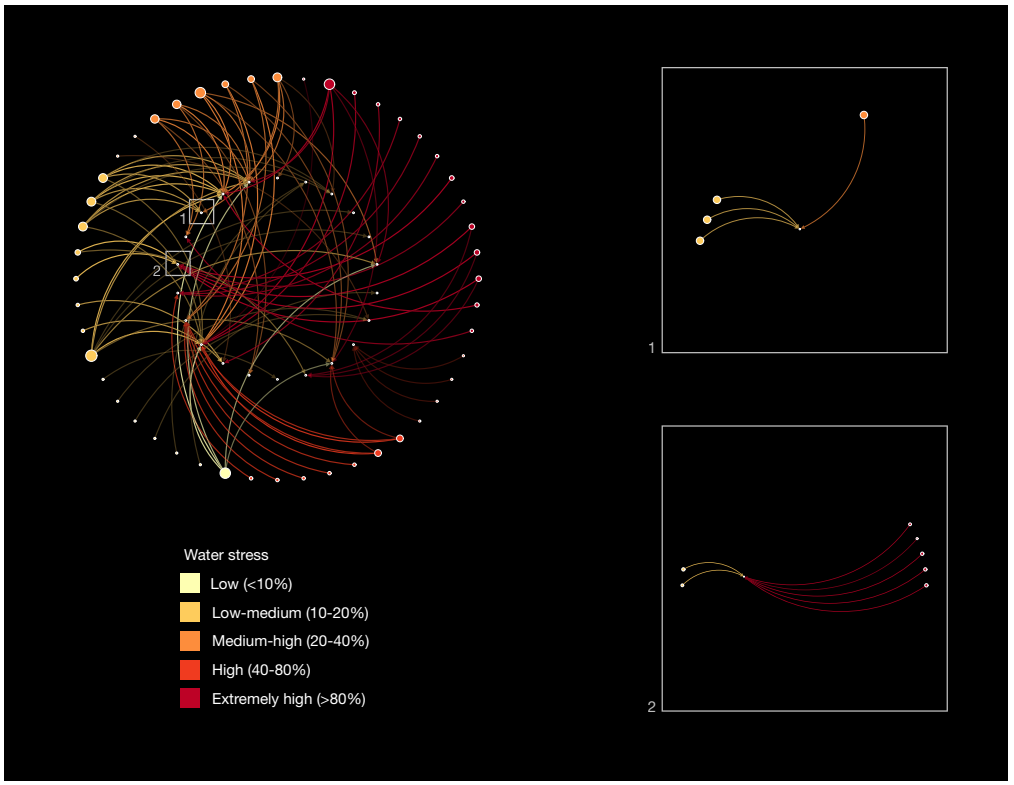


Figure 2. Network of known customer-supplier linkages

Known customer-supplier linkages in the global semiconductor manufacturing sector (see STAR Methods) categorized by their water stress risk under a BAU scenario for the year 2030. The outer ring of nodes are existing semiconductor manufacturing facilities (i.e., "suppliers") classified by the water stress category of the basin in which they are actually located. The inner ring of nodes are actual customers of the semiconductor manufacturing facilities depicted in the outer ring. Arrows depict the flow of semiconductors from suppliers (outer ring) to customers (inner ring). The color of each arrow corresponds to the water stress risk category of the semiconductor manufacturing facility from which each arrow originates. The size of semiconductor manufacturing facility node of the outer ring is proportional to the number of customers it supplies. 25 of 48 (>52 percent) semiconductor facilities depicted in Figure 2 are located either in high- or extremely high risk watersheds in the 2030 BAU scenario. Topological analysis helps show how different customers supplied by semiconductor facilities are differently positioned with respect to the distribution of water stress risks. For example, Panel 1 shows three of four semiconductor manufacturing facilities supplying a customer are at low-medium risk for water stress while the fourth is at medium-high risk. Meanwhile, Panel 2 shows that five of seven semiconductor manufacturing facilities supplying a customer are located in basins projected to be of extremely high water stress risk under the 2030 BAU scenario.

Both TSMC and Apple are firms with multibillion dollar revenues. As such, they can both currently afford to devote resources to overcoming water stress issues through inter-basin transfers of water in the short term in Taiwan.[37,44,45] However, as climate change continues to unfold, and water stress risks increase systemically, the two firms may find that, along with others in semiconductor GPNs, doing so is more challenging and more expensive.[46]

Due to the technical difficulties of manufacturing the most advanced semiconductors, the know-how and infrastructure for doing so are highly concentrated in a small number of firms and locations, largely in Taiwan. This situation means lead firms in the electronics sector do not necessarily have the capacity to simply switch suppliers, at least not quickly, for key components if and when suppliers' facilities experience production difficulties. Consequently, operational disruptions at key nodes in semiconductor GPNs, such as TSMC's Fab 15, may cascade through supply chains, both those of individual firms and systemically throughout the network.

Taiwan is already faced with making choices between allocating water between the two thirstiest sectors of its economy: semiconductors and agriculture. Total cereal exports from Taiwan have declined precipitously since the onset of drought in 2020–2021 (Figure 3). Consequently, the chronic risk of water stress induced by the climate emergency has implications for other GPNs heavily dependent on water. Semiconductors are a lucrative and strategic export. Yet, so too is food security crucial to Taiwan's sovereignty and, depending on one's point of view, risks to it may not be sensibly measured through agriculture's value as a percentage of Taiwan's GDP. The semiconductor sector and the agricultural sector are both strategically important to Taiwan's sovereignty but in quite different ways. In other words, government and policy makers in Taiwan may be confronted with decisions about how to allocate water to sectors with incommensurable values attached to them and, as such, may not be able to rely purely on economic calculations to make those decisions. Thus, decisions about how to allocate water between the two sectors will be inherently political with potentially far-reaching social consequences.

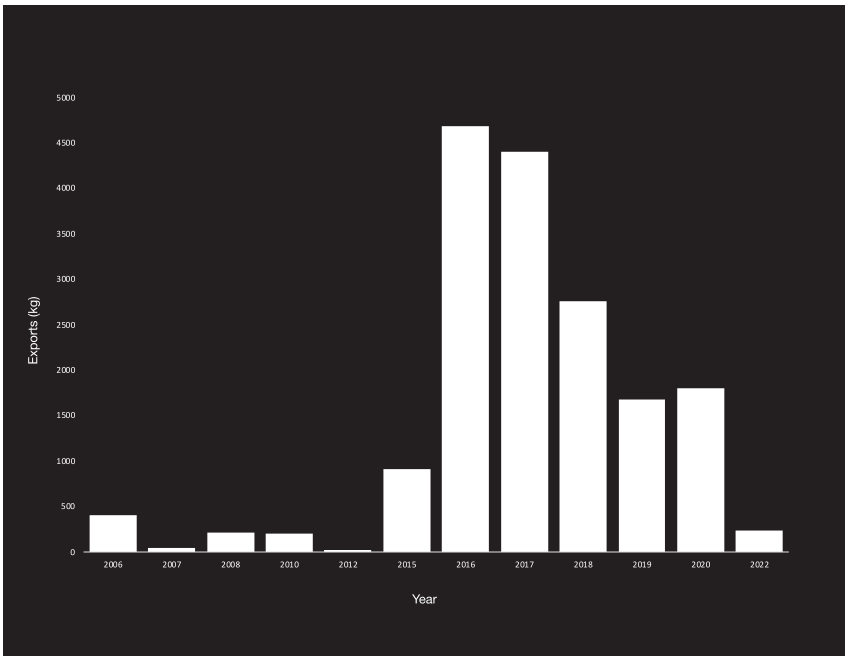


Figure 3. Taiwan cereal exports, 2006-2022

Total cereal exports from Taiwan, 2006–2022. Data source: Taiwan Statistics Office: https://portal.sw.nat.gov.tw/APGA/GA30E.

Region of concern: US

Meanwhile, in the US the Creating Helpful Incentives to Produce Semiconductors (CHIPS) Act appropriates nearly $300 billion toward reinvigorating domestic US capacity in semiconductor research and manufacturing.[47–49] An important explicit goal of the act is to support the re-shoring of semiconductor manufacturing to the continental United States. In this respect, CHIPS is a future-oriented piece of legislation. The re-shoring of semiconductor manufacturing infrastructure is a process that will unfold over a number of years. To date, in the wake of this renewed industrial policy major semiconductor manufacturers are constructing new facilities in several US states: Arizona (Intel, 2 facilities and TSMC, 1 facility), Idaho (Micron, 1 facility), Ohio (Intel, 1 facility), and Texas (Samsung, 1 facility). All but one of these six facilities (Intel's Ohio facility) are sited in watersheds classified as at high- or extremely high risk of water stress under any future climate scenario considered in this analysis.

Although water stress risks classified as high- or extremely high are distributed unevenly throughout the continental United States (Figure 1), the unfolding situation in the US desert southwest region is of particular concern. For example, on December 20, 2022, Arizona's Water Infrastructure Finance Authority (WIFA)[50] passed a resolution to enter into a non-binding term agreement with IDE Technologies for the construction and operation of a desalination plant and water distribution system originating at the Sea of Cortez to supply the state of Arizona with up to 1,000,000 acre feet of water per year at an estimated cost of $5 billion and an operational contract life of 100 years.[51] Dubbed the Arizona water project solution (AWPS), it proposes a public-private partnership in which private investors will own and operate the infrastructure that will bring water sourced from the Sea of Cortez along an approximately 300 km long pipeline through the Sonora desert, across the Mexico-US border, and delivered to the Phoenix region under a contract with a 100 year amortization period.

Drought conditions have persisted in Arizona since 1994.[52] Regional hydrological conditions continue to decline. In 2021 the US Bureau of Reclamation announced its first ever "shortage declaration" for the Colorado River basin.[53] Historically, Intel and other semiconductor manufacturers saw Arizona's low risk of other environmental hazards (e.g., earthquakes, hurricanes, tornadoes) as outweighing the risks associated with water stress.[54] Intel's extant facilities in Arizona will use 1.1 percent of the total water promised by the IDE project. Meanwhile, Intel has announced two new facilities to be located in Chandler, Arizona which will further increase its water use. If all of TSMC's newly announced facilities for Arizona are eventually built, they are estimated to require up to 40,000 acre-feet of water per year[55] or about 4 percent of the total water promised by the IDE project. Eight other semiconductor fabrication companies currently operate 10 additional facilities in the state, but not all of them publicly report water use figures, making it difficult to put a precise figure on total water use by the semiconductor manufacturing sector in the state.

Water stress risks affecting organizational strategy

There is some evidence of organizational change underway at Intel in response to water stress issues, despite the firm's decision to build new fabrication facilities in Arizona under these worsening long-term drought conditions. In its sustainability report for 2019–2020, Intel announced

for the first time a goal of achieving "net positive water use" by 2030.[56] The firm is attempting to meet this goal through multiple strategies, including changes to facility-level processes that help to conserve water use but also by financially supporting water conservation and restoration efforts in several regions around the world where Intel facilities are located.[57] These strategies mean that some amount of Intel's resources are being devoted to the issue of water stress and, in that respect, point to material changes within the firm arising from this issue throughout its operations globally.

At the same time, Intel's claims to be reaching its goal of net positive water raise important questions about how genuine those water conservation strategies actually are. So far, it appears that the company's claims to have reached net positive water already are based on calculations that balance negative values for water extraction at some facilities and locations with positive values at other locations or regions where water restoration projects have been funded by the company. Thus, for example, Intel funded water restoration projects in India lead to a measure of net positive water use in the country of 346 percent. That surplus is then used to balance water deficits at the firm's facilities in other locations such as those in China or Israel.[58] This approach to calculating net positive water raises important questions about reconciling a firm's commitment to responsible water management within its operations with the uneven geographies of climate change impacts on water stress and its unequal climate justice implications.[59,60]

There are efforts underway industry-wide to enhance the recycling of water for use in semiconductor manufacturing.[1] These emerging systems and processes can achieve impressive recovery rates, some claiming as high as 98 percent. However, these new water reclamation systems are not evenly deployed throughout the industry and can be expensive to implement. Meanwhile, even major semiconductor manufacturers such as TSMC which are beginning to deploy such water reclamation systems still anticipate being unable to meet their water needs as their own corporate reports disclose.

Conclusions

There are no electronics without semiconductors[3] and no semiconductors without secure access to large volumes of water for manufacturing them.[2] At least 40 percent of all existing semiconductor facilities are located in basins projected to experience high- or extremely high water stress risks under any climate scenario analyzed here for 2030 and 2040. Between 24 and 40 percent of facilities currently under construction and 40–49 percent of facilities announced are in basins anticipated to be at high- or extremely high water stress risk in 2030 and 2040 depending on the climate scenario considered.

Major semiconductor manufacturing firms, such as Intel and TSMC, take water stewardship concerns seriously. Firms in the sector are making impressive progress in water use reduction techniques. Yet, no matter how dramatic those reductions are, they cannot create a situation in which the water needed for semiconductor manufacturing is simultaneously accessible to other water users (e.g., farmers; municipal drinking water). Struggles between competing interests over access to water are likely to increase under such a situation. Moreover, the network dynamics of semiconductor GPNs mean the water stress risk as it pertains to any one company is only part of the issue. Network dynamics also mean that disruptions to production at individual key nodes in the network could lead to a cascading propagation of water stress risks from regions of particularly high risk of water stress to broader portions of overall GPNs for electronics.

Much of the policy attention focused on systemic risks to global semiconductor supply chains is framed in terms of classical concerns over the geopolitics of interstate rivalry.[33–35] This analysis shows that future climate change induced water stress risks to semiconductor supply chains must also be taken seriously, both at the level of individual firms but also, and especially, systemically throughout global semiconductor manufacturing networks and the ecological, political, economic, and social contexts in which they operate.

Water stress issues as they relate to semiconductor manufacturing are likely to be compounded in the future as various stressors combine both in the aggregate and variably over Earth's surface. The water demands of semiconductor manufacturing already compete with demands from other water intensive sectors such as agriculture and domestic/municipal use. The relative severity of these compounding stressors is conditioned by place-based ecological, political, economic, and social factors. This study has laid some important groundwork for future analyses that may examine how these compounding stressors vary geographically at a systemic level globally.

Limitations of the study

There are several caveats to note about this study. First, the water stress projections of the Aqueduct 3.0 dataset are derived from water availability simulations of representative concentration pathways (RCPs) from the Coupled Model Intercomparison Project phase 5 (CMIP5) climate models built, analyzed, and assessed in other research.[61] This study assumes that those RCPs provide accurate projections for the years 2030 and 2040 under the three climate change scenarios (optimistic, business as usual, and pessimistic) modeled in the Aqueduct 3.0 dataset.[28] Another important limitation of the Aqueduct 3.0 dataset is that it does not account for inter-basin transfers of water via technological means (e.g., aqueducts or trucking). As Hoste et al.,[28] note for example, "[m]any major metropolitan areas source their water from adjacent subbasins". For this reason, the results described in this analysis should be understood as indicative rather than absolute values. As such, Aqueduct 3.0 is "primarily a prioritization tool and should be augmented by local and regional deep dives".[28] An additional study limitation relates to the GPN@NUS data which are limited to the top 10 lead firms (measured in terms of revenue or shipments and market share) in semiconductors, personal computers, mobile handsets, and televisions for snapshot years (2015 and 2018).[3] As such, these data can only offer a partial picture of interconnected customer-supplier relationships in the overall global production of electronics.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
  - Lead contact
  - Materials availability
  - Data and code availability
- METHOD DETAILS
  - Water stress data
  - Semiconductor fabrication plant location data from SEMI
  - Semiconductor fabrication plant location data from GPN@NUS
- QUANTIFICATION AND STATISTICAL ANALYSIS

ACKNOWLEDGMENTS

I gratefully acknowledge four anonymous reviewers for providing insightful comments. My sincere thanks to Professor Henry Yeung, co-director of the Global Production Networks Center at the National University of Singapore (GPN@NUS) for sharing data on customer-supplier relationships of semiconductor manufacturers. Funding for this work was provided by the Social Sciences and Humanities Research Council of Canada 435-2018-0846.

AUTHOR CONTRIBUTIONS

JL; Conceptualization, formal analysis, investigation, resources, data curation, writing – original draft, writing – reviewing and editing, visualization, project administration, and funding acquisition.

DECLARATION OF INTERESTS

The author declares no competing interests.

Received: September 25, 2023
Revised: December 7, 2023
Accepted: January 2, 2024
Published: January 5, 2024

REFERENCES

1. Johnson, D. (2022). Scarcity Drives Fabs to Wastewater Recycling - IEEE Spectrum.
2. United States Goverment, The White House (2021). Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth | 100-Day Reviews under Executive Order 14017 (The White House).
3. Yeung, H.W.-C. (2022). Interconnected Worlds: Global Electronics and Production Networks in East Asia (Stanford University Press).
4. Leonard, M. (2021). Why the Automotive Supply Chain is in a Semiconductor Jam (Supply Chain Dive).
5. King, I., and Wu, D. (2021). Your Wait for a New Car May Get Longer as the Chip Crisis Worsens.
6. Moore, S.K. (2023). How and When the Chip Shortage Will End (in 4 Charts - IEEE Spectrum).
7. Bernstein, A., DeGrasse, B., Grossman, R., Paine, C., and Siegal, L. (1977). Silicon Valley: Paradise Or Paradox?: The Impact of High Technology Industry on Santa Clara County (Pacific Studies Center).
8. Harris, M. (2023). Palo Alto: A History of California, Capitalism, and the World, 1st ed. (Little, Brown and Company).
9. Siegel, L. (1982). Background Report on Silicon Valley (Pacific Studies Center).
10. Williams, E.D., Ayres, R.U., and Heller, M. (2002). The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices. Environ. Sci. Technol. *36*, 5504–5510.
11. Smith, T., Cole, L.W., and Wilmsen, C. (2003). Pioneer Activist for Environmental Justice in Silicon Valley, 1967-2000: Oral History Transcript (University of California Libraries).
12. Spencer, K.A. (2018). A People's History of Silicon Valley: How the Tech Industry Exploits Workers, Erodes Privacy and Undermines Democracy (Eyewear Publishing).
13. LaDou, J. (1984). The Not-So-Clean Business of Making Chips. Technology Review *87*, 22–36.
14. LaDou, J. (1986). Health Issues in the Microelectronics Industry. Occup. Med. *1*, 1–11.
15. LaDou, J. (1991). Deadly migration: hazardous industries' flight to the Third World. Technology Review *94*, 46–53.
16. LaDou, J. (1992). 1st World Exports to the Third-World - Capital, Technology, Hazardous-Waste, and Working-Conditions - Who Wins. West. J. Med. *156*, 553–554.
17. Ong, A. (1987). Spirits of Resistance and Capitalist Discourse: Factory Women in Malaysia (State University of New York Press).
18. Smith, T., Sonnenfeld, D.A., and Pellow, D.N. (2006). Challenging the Chip: Labor Rights and Environmental Justice in the Global Electronics Industry (Temple University Press).
19. Lee, J., Kim, J.-C., and Lim, J. (2016). Globalization and Divergent Paths of Industrial Development: Mobile Phone Manufacturing in China, Japan, South Korea and Taiwan. J. Contemp. Asia *46*, 222–246.
20. Lüthje, B. (2002). Electronics Contract Manufacturing: Global Production and the International Division of Labor in the Age of the Internet. Ind. Innov. *9*, 227–247.
21. Lüthje, B., and Butollo, F. (2017). Why the Foxconn Model Does Not Die: Production Networks and Labour Relations in the IT Industry in South China. Globalizations *14*, 216–231.
22. Sun, Y., and Grimes, S. (2016). China's increasing participation in ICT's global value chain: A firm level analysis. Telecommun. Pol. *40*, 210–224.
23. Chiu, H.-M. (2011). The Dark Side of Silicon Island: High-Tech Pollution and the Environmental Movement in Taiwan. Appl. Econ. Lett. *22*, 40–57.
24. Lepawsky, J. (2022). Mapping chemical discardscapes of electronics production. Geoforum *132*, 113–124.
25. Frost, K., and Hua, I. (2018). A Spatially Explicit Assessment of Water Use by the

Global Semiconductor Industry, pp. 1–5. In, pp.
26. Frost, K., and Hua, I. (2019). Quantifying spatiotemporal impacts of the interaction of water scarcity and water use by the global semiconductor manufacturing industry. Water Resour. Ind. *22*, 100115.
27. Lee, D., and Raby Amadori, F. (2020). Water Risk Assessment & Strategy for (Lenovo Group Ltd).
28. Hofste, R., Kuzma, S., Walker, S., Sutanudjaja, E., Bierkens, M., Kuijper, M., Faneca Sanchez, M., Van Beek, R., Wada, Y., Galvis Rodríguez, S., and Reig, P. (2019). Aqueduct 3.0: Updated Decision-Relevant Global Water Risk Indicators. WRIPUB *53*.
29. TSMC (2021). TSMC 2021 Sustainability Report.
30. Corporation, I. (2023). Intel Sustainability 2022-23 Corporate Responsibility Report | Water Stewardship (Custom Report).
31. Freeman, L.C. (2008). Social Network Analysis (SAGE).
32. Scott, J. (1991). Social Network Analysis: A Handbook (SAGE Publications).
33. Miller, C. (2022). Chip War: The Fight for the World's Most Critical Technology (Simon & Schuster).
34. Wasser, B., Rasser, M., and Kelley, H. (2022). When the Chips Are Down | Gaming the Global Semiconductor Competition (Center for a New American Security).
35. Varas, A., Varadarajan, R., Goodrich, J., and Yinug, F. (2021). Strengthening the Global Semiconductor Supply Chain in an Uncertain Era (Boston Consulting Group | Semiconductor Industry Association)).
36. Narvaez, L., Janzen, S., Eberle, C., and Sebesvari, Z. (2021). Taiwan Drought (United Nations University).
37. Zhong, R., and Chien, A.C. (2021). Drought in Taiwan Pits Chip Makers against Farmers.
38. Ratings, F. (2021). Taiwan Drought Highlights Water Stress as Growing Environmental Risk.
39. TSMC (2019). TSMC 2019 Corporate Sustainability Report.
40. Ihara, K., and Sato, H. (2018). Taiwan's TSMC wields souped-up iPhone chips to overpower rivals (Nikkei Asia).
41. Statista. (2023). Apple iPhone Revenue Share 2023. Statista.
42. Lovejoy, B. (2021). TSMC Client List Shows Apple Makes up a Quarter of its Revenue (9to5Mac).
43. Taipei Times. (2022). TSMC's Largest Customer Makes up 26% of Revenue - Taipei Times.
44. Reuters. (2021). Chipmakers in Drought-Hit Taiwan Order Water Trucks to Prepare for "The worst." (Reuters).
45. Li, L. (2023). Taiwan Braced for Further Water Shortages in its Chipmaking Hubs (Financial Times).
46. Goldstein, A., Turner, W.R., Gladstone, J., and Hole, D.G. (2019). The private sector's climate change risk and adaptation blind spots. Nat. Clim. Chang. *9*, 18–25.
47. Brown, P. (2021). Congress Asks Biden Administration to Fund CHIPS Act | Electronics360.
48. Haldane, M. (2023). How Rising Industrial Policy Gave Arizona the Economic Heft to Land TSMC Deal. South China Morning Post.
49. (2022). Promises to keep. Nat. Clim. Chang. *12*, 769.
50. Water Infrastructure Finance Authority of Arizona (2022). WIFA Resolution 2023-027 – IDE Technologies' Proposal.
51. Rose, J.R. (2022). The Arizona Water Project Solution Proposal.
52. Arizona Department of Water Resources Drought Frequently Asked Questions | Arizona Department of Water Resources.
53. Bureau of Reclamation. (2021). Reclamation Announces 2022 Operating Conditions for Lake Powell and Lake Mead | Historic Drought Impacting Entire Colorado River Basin (Newsroom).
54. Salter, J. (2021). Here's why TSMC and Intel keep building foundries in the Arizona desert (Ars Technica).
55. Chien-chung, C., and Huang, F. (2023). TSMC attempts to assuage fears over Arizona fabs' water demands - Focus Taiwan (Focus Taiwan - CNA English News).
56. Corporation, I. (2020). Corporate Responsiblity at Intel | 2019-2020 Report.
57. Corporation, I. (2021). Corporate Responsibility Report | 2020-2021.
58. Corporation, I. (2023). Intel 2022-23 Corporate Responsibility Report.
59. Armarego-Marriott, T. (2023). Factoring in racial justice. Nat. Clim. Chang. *13*, 602.
60. Vigliarolo, B. (2022). Intel's Net Positive Water Use Only Tells Part of the Story (The Register).
61. Luck, M., Landis, M., and Gassert, F. (2015). Aqueduct Water Stress Projections: Decadal Projections of Water Supply and Demand Using CMIP5 GCMs | Technical Note (World Resources Institute).
62. Bastian, M., Heymann, S., and Jacomy, M. (2009). Gephi: An Open Source Software for Exploring and Manipulating Networks. ICWSM *3*, 361–362.
63. GPN@NUS Global Production Networks Centre – NUS Faculty of Arts and Social Sciences.
64. Hofste, R., Kuzma, S., Walker, S., Sutanudjaja, E.H., Bierkens, M.F.P., Kuijper, M.J.M., Sanchez, M.F., Beek, R.V., Wada, Y., Rodríguez, S.G., et al. (2021). Aqueduct 3.0: Updated Decision-Relevant Global Water Risk Indicators (World Resources Institute).
65. Reig, P., Shiao, T., and Gassert, F. (2013). Aqueduct Water Risk Framework (World Resources Institute).

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
ARC GIS	ESRI	https://www.arcgis.com/index.html
Aqueduct 3.0	Hofste et al.[28]	https://github.com/wri/aqueduct30_data_download/blob/8ec9d11ef3aec36bb58b9750cbdb55ee0200e537/metadata.md
Gephi 0.10.1 20230117201	Bastian et al.[62]	https://gephi.org/users/publications/
QGIS 3.28.2-Firenze	QGIS Association	https://www.qgis.org/en/site/

RESOURCE AVAILABILITY

Lead contact

Further information and requests for datasets should be directed to and will be fulfilled by the lead contact, Josh Lepawsky (jlepawsky@mun.ca).

Materials availability

This study did not generate new unique materials.

Data and code availability

- All data reported in this paper will be shared by the lead contact upon request.
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

Data used in this paper come from three main sources: SEMI, a trade organization that publishes market research on semiconductor manufacturing facilities globally; a custom proprietary dataset assembled by the Global Production Networks Center at the National University of Singapore[63] ultimately derived from market research firms IHS Markit and Informa Tech and provided courtesy of Professor Henry Yeung, Co-Director of GPN@NUS; and the Aqueduct 3.0 model produced by the World Resources Institute (WRI). Each dataset is discussed in more detail below with reference to specific sources, relevant context of the data, as well as their potential and limitations for answering questions posed in this study.

The procedure to obtain the results described in the study involves four steps. First, the Aqueduct 3.0 dataset is available as a QGIS file format and this dataset was downloaded and imported as a layer into QGIS. Next, location data for semiconductor manufacturing facilities from the SEMI dataset and the GPN@NUS dataset were geocoded using ESRI ARC GIS software. This latter step created latitude and longitude coordinates for each individual semiconductor manufacturing facility based on their known street addresses. Next, the geocoded semiconductor facility data were imported as layers into QGIS with one layer for the SEMI data and one layer for the GPN@NUS data. The geocoded locations of the semiconductor manufacturing locations were then joined (i.e., 'overlayed') with the Aqueduct 3.0 dataset in QGIS. Joining these datasets enabled the classification of all semiconductor manufacturing facility locations with the water stress category of the basin (i.e., watershed) in which a given facility is located. The latter step permitted the calculation of counts and percentages of semiconductor manufacturing facilities located in watersheds categorized by the water stress categories as defined by the Aqueduct 3.0 dataset and lead to the results depicted in Figure 1 and Table 1. Next, the QGIS layer for the GPN@NUS data classified by water stress category were imported into Gephi, a network analysis software. As described in more detail below, the GPN@NUS data contain information about actually existing customer-supplier relationships between individual semiconductor manufacturing facilities (i.e., 'suppliers') and their customers. This information meant that a network of customer-supplier relationships could be constructed that also contained information about the water stress category of each semiconductor manufacturing facility (i.e., supplier). The latter step lead to the results depicted in Figure 2.

Combining the geocoded data for semiconductor manufacturing facilities with the Aqueduct 3.0 dataset of global water stress at the basin (i.e., watershed) level allows for the identification of 'hotspots' or regions of concern defined by their particular importance to global distributions of semiconductor manufacturing facilities.

Water stress data

Water stress data are sourced from the World Resources Institute (WRI) Aqueduct 3.0 dataset.[64] Notably, the WRI data are also used by Intel and the world's largest contract semiconductor manufacturer, TSMC, for their own corporate water stress risk assessments.[29,30]

Aqueduct offers weighted water stress risks based on a synthesis of physical quantity and quality factors as well as regulatory and reputational factors for hydrological basins globally.[28] These weighted risk factors are provided for several indicative economic sectors, including semiconductor manufacturing, under three climate breakdown scenarios derived from publicly available global circulation models.[65] Future climate projections of the model include an optimistic scenario, a business as usual (BAU) scenario, and a pessimistic scenario.[61] The water stress risk categories are expressed in terms of percentage of total water withdrawals relative to the available renewable surface and groundwater supplies.[28] Five such water stress categories are included in the Aqueduct data: "Low (<10%)", "Low-Medium (10–20%)", "Medium-high (20–40%)", "High (40–80%)", and "Extremely high (>80%)". Thus, for example, the "Low (<10%)" category means that total water withdrawals are less than 10% of available renewable surface and ground water supplies in a given basin; meanwhile, "Extremely high (>80%)" means that total water withdrawals are greater than 80% of available renewable surface and ground water supplies in a given basin.

The Aqueduct 3.0 dataset uses the PCRaster Global Water Balance (PCR-GLOBWB 2) model which was chosen by Aqueduct's modelers because it meets WRI's open data commitment.[28] PCR-GLOBWB 2 has a spatial resolution of 5x5 arc minutes which equates to approximately 10 × 10 km pixels, with variations resulting from latitude. The Aqueduct 3.0 database also combines with a second model (HydroBASINS level 6) to derive the geography of the hydrological basins mapped in the Aqueduct dataset. Essentially, the Aqueduct 3.0 model is a synthesis of expert judgment. As Hofste et al. note their goal in creating the Aqueduct 3.0 model was, "to select a [spatial] level large enough to minimize the nonnatural effect of transfers of water ('inter-basin transfer') and small enough to capture meaningful local variations".[28] Understanding the combination of hydrological models in the Aqueduct dataset is important because of their aggregate effects on the spatial resolution of the underlying dataset.[28] The geocoded location data for individual semiconductor manufacturers in the SEMI and GPN@NUS data provide latitude and longitude precision equivalent to the street address level. However, such a granular level of location precision is irrelevant given the spatial resolution of the Aqueduct 3.0 model in which individual basins cover areas of approximately 10 × 10 km pixels (i.e., 100 km^2). Essentially, the Aqueduct basin areas are spatial 'containers' inside of which latitude/longitude coordinates of semiconductor facilities are data points.

Semiconductor fabrication plant location data from SEMI

Data on semiconductor facilities were purchased from SEMI, a trade organization for the global semiconductor industry. SEMI's 'World Fab Watch' database provides data updated quarterly on semiconductor fabrication facilities located around the world. At the time of purchase the data covered up to March 3, 2021 and contained 1371 facility records attributed to 569 unique company names. SEMI data include information on a wide range of factors such as the location by street address of each facility, the production status of a facility, its year of first production, the size of wafer it can produce, and the facility's production capacity (e.g., wafers produced per month). The SEMI data include records for both extant facilities and those that are categorized as announced, under construction, and planned. As of March 3, 2021 the database included 21 facilities attributed to 12 unique companies that were either announced, under construction, or planned. A search of trade literature and business news was used to add records to the SEMI data on facilities announced, under construction, or planned after March 3, 2021. This search added 23 additional records to the SEMI data.

Semiconductor fabrication plant location data from GPN@NUS

Yeung procured a proprietary dataset from IHS Markit and Informa Tech for his analysis of electronics GPNs.[3] These custom data are similar to those available from SEMI but include additional information for two snapshot years, 2015 and 2018, on specific customer and supplier relationships between the world's top 10 lead firms (measured in terms of revenue or shipments and market share) in semiconductors, personal computers, mobile handsets, and televisions.[3]

The GPN@NUS dataset on semiconductor manufacturing facilities provides location data at the city level of specific, named facilities. This information enabled the GPN@NUS data to be cross referenced with the SEMI data on facility location. This cross referencing enabled specific semiconductor manufacturing facility locations to be connected to information on their customers i.e., who those semiconductor foundries supply. As noted, the GPN@NUS data are limited to the top 10 lead firms in several categories of end use electronics for snapshot years (2015 and 2018).

Semiconductor foundries represent significant capital investments and thus new facilities are built relatively infrequently. SEMI data include information on each facility about when construction was complete and when the facility actually went into production. This makes it possible to cross-reference the operations of specific facilities in the SEMI dataset with the two snapshot years in the GPN@NUS dataset. Taken together, then, cross-referencing the GPN@NUS data with the SEMI data offers a partial, albeit incomplete, map of interconnected global networks of semiconductor GPNs. Notwithstanding those limits, it is possible to identify areas of particular concern (or 'hotspot' nodes in the semiconductor global production network). Network visualization was conducted using Gephi.[62]

QUANTIFICATION AND STATISTICAL ANALYSIS

This study reports counts and percentages of semiconductor manufacturing facilities located in watersheds categorized by water stress as defined by the Aqueduct 3.0 dataset. No statistical tests were required or used to quantify these data.