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Navigating Environmental Concerns Confronting U.S. Data Centers Related to Water Quantity and Quality

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Abstract

The rapid growth of data centers across the United States reflects the increasing demand for computing power in our society related to services such as cloud computing and artificial intelligence (AI). Along with the technological capability being supplied, data centers utilize a significant quantity of environmental resources. While power consumption typically receives primary focus, the utilization and impacts to water quality and quantity also deserve attention. More recently, concerns over water quality and quantity have created resistance and barriers to data center development. This review and analysis of the growth, status, and future trends related to water utilization by data centers provides the framework for recommendations that allow data center developers and operators to more smoothly and predictably navigate stakeholder concerns.

Keywords

Cooling, Consumption, Siting, Recycling, Regulation, Sustainability

1. Introduction

It is now well-recognized that modern data centers utilize a significant quantity of environmental resources during operation, including high power and water consumption, and that these demands are only increasing [1]. Over the past decade, the United States (U.S.) has experienced rapid growth in data-center construction driven by the expansion of cloud computing, digital services, and, more recently, artificial intelligence (AI). Early research emphasized that data-center water consumption is coupled to electricity demand and cooling requirements, while also identifying gaps in how water use is measured and publicly reported across the sector [2]. National assessments conducted for the U.S. Department of Energy show that data-center electricity demand has increased substantially since 2014 and is projected to continue rising through at least 2028, reinforcing concerns that associated environmental impacts—particularly increased water use—are accelerating in parallel [3] [4]. As these facilities proliferate, their resource consumption, particularly water usage and wastewater discharge, has emerged as a critical concern for communities, regulators, and environmental advocates. Yet, despite the scale and impact of these operations, reliable and publicly available data on data centers' water use and wastewater practices remain conspicuously scarce.

This expansion of data centers is geographically uneven. Data centers are heavily clustered in a limited number of high-connectivity, power-rich regions, including Northern Virginia and emerging secondary hyperscale hubs such as Atlanta and Phoenix, as well as network-critical metropolitan regions such as the New York-New Jersey corridor that support financial services and latency-sensitive operations, as shown in **Figure 1**. Market analyses indicate that these regions host a disproportionate share of new construction due to fiber density, access to scalable power, and favorable policy incentives [5]. Concentrated growth magnifies cumulative water withdrawals and wastewater discharges within specific watersheds and utility systems, often outpacing the planning horizons of local water infrastructure.

As such, current trends demonstrate that the continued growth of data centers is expected to require navigation of an increasing number of siting requirements, regulatory limitations, and community restrictions. This literature review and analysis outline the most prominent environmental elements for consideration related to water quantity and quality when assessing data center growth and identifies a spectrum of possible approaches that can help ensure such growth addresses stakeholder concerns and avoids disruptions to adjacent communities.

Analysis Boundary and Water Terminology

For clarity and consistency, this review distinguishes among key categories of water use within a defined analysis boundary. Water withdrawal refers to the total volume of water removed from surface water, groundwater, or municipal sources for data center operations or electricity generation. Water consumption denotes the portion of withdrawn water not returned to the local watershed, primarily due to evaporative cooling losses, while water discharge refers to wastewater returned to the local environment or conveyed to publicly owned treatment works (POTWs), including cooling tower blowdowns.

The review considers both on-site cooling water use and indirect water use associated with electricity generation, treating indirect water use separately because it typically occurs outside the facility boundary and may affect different watersheds. The analysis boundary includes operational-phase cooling water use, power-sector water use, and associated wastewater discharges relevant to permitting and regulatory oversight; water embedded in construction, non-electricity supply chains, and non-cooling domestic uses is outside the scope of this review.

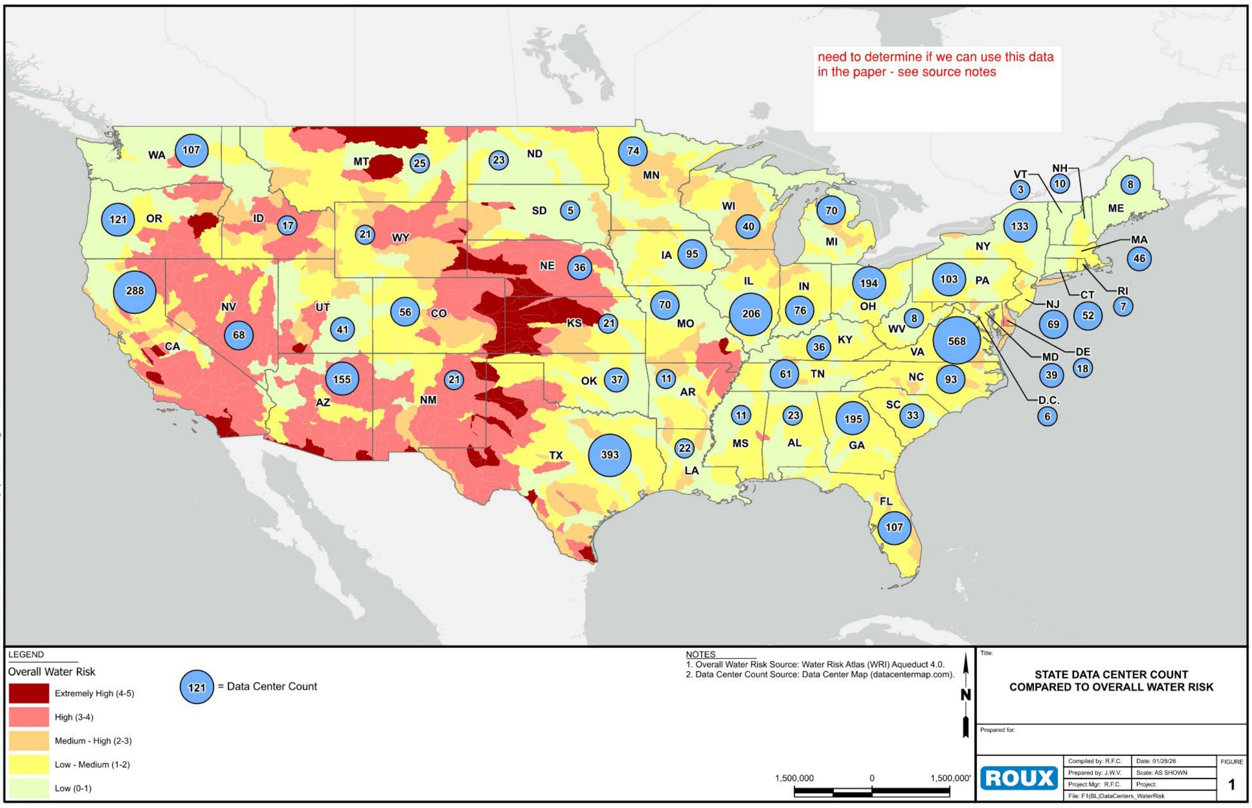

Figure 1. Spatial distribution of data centers across the United States overlaid with regions experiencing varying levels of water stress [6] (The map source is Data Center Map, https://www.datacentermap.com/usa/).

2. Background Literature Review

An understanding of the evolution and growth of data center water use, and potential associated impacts can be viewed through the differing lenses of power consumption, data center cooling technology innovation, legislative attention, and corporate sustainability disclosures. The literature highlights the need for closer integration between research institutions, industry practitioners, and policy/regulatory agencies to develop evidence-based guidelines that support sustainable data center growth while safeguarding water resources [4].

As such, each of these lenses demonstrates the trends and trajectories in water infrastructure needs that will continue to expand into the future.

2.1. Growing Power Consumption

Water usage for power generation has been stated to require 11,857 gallons of water per megawatt-hour (MWh) of electricity produced [7]. This number is based on the: 1) total water withdrawal from US power plants; and 2) the total energy produced. However, only thermoelectric power (*i.e.*, fossil fuel, nuclear, and geothermal) requires water withdrawals from either groundwater or surface water to support power generation through steam driven turbine generators [8], non-thermoelectric power (e.g., hydroelectric, solar, wind) does not require water withdrawals. Additionally, thermoelectric power plants vary based on technology with water usage rates significantly lower for power plants utilizing recirculating cooling loop systems when compared to once-through systems which withdrawal water, utilize that water for cooling and discharge it back to the source [8]. Lastly, the volume of water each power plant consumes vary based how much is consumed versus how much water is returned to the source. Therefore, determining the water footprints of a data center requires individualized analysis as there are many variables which change by location Small and medium data centers can require approximately one to five megawatts (MW) of power while large and hyperscale data centers can use anywhere between 20 and 100 MWs or more. Large hyperscale AI data centers can use significantly more power. For example, Meta is currently building a 4-million square foot data center in Louisiana with an estimated power demand of 1,500 MW to 2,262 MW [9]. Note that in the data center industry, the size of data centers is often presented in terms of power usage as shown above (e.g., 10 megawatt [MW]). However, in technical terms a 10 MW data center is actually a 10-MWh data center consuming 10 MWs per hour or 87,600 MWs per year (if operating 24 hours per day for 365 days). For consistency with the industry, data centers referred to herein will omit the hours from the size and it should be assumed that any reference to a data center of a given size refers to the number of megawatts which are consumed per hour unless otherwise stated.

Extrapolating the water requirement figure above suggests a 20 MW data center could use as much as 2-billion gallons of water per year where a 2,262 MW data center could use as much as 233-billion gallons of water per year for energy production.

Such indirect water use linked to power generation is often unrecognized but can greatly exceed on-site consumption in magnitude. For example, water usage on site for data center cooling was estimated in 2023 to be about 17 billion gallons of water nationally—with hyperscale and colocation facilities using the lion's share (84%) [4]. According to the Lawrence Berkeley National Laboratory's United States Data Center Energy Usage Report (Berkeley Report), U.S. data centers consumed approximately 1.9% of total national electricity demand in 2018, prior to the rapid acceleration associated with AI-driven workloads. Even still, the proliferation of AI marks a new era for data centers' power demands and the Berkeley Report estimated they could grow to utilize as much as 12% of projected annual U.S. electricity consumption in 2028, corresponding to an annual data-center electricity demand on the order of 580 terawatt (TWh) under the upper-bound scenario. Using the Berkeley Report's estimated indirect water consumption intensity for electricity used by data centers, power-sector water requirements associated with data-center electricity demand are on the order of hundreds of billions of gallons per year nationally (for example, the report estimates nearly 211 billion gallons of indirect water use in 2023), and they increase further under higher 2028 electricity-demand scenarios [4] [10].

2.2. Path of Cooling Technology Innovation

Cooling has long been recognized as one of the operational challenges in data centers due to the high rate that electrical energy is converted into heat during computation.

Early data centers (*i.e.*, computer rooms) had raised floors that were originally designed as a cable management solution but were utilized as a cold air plenum that created a more targeted approach to cool the information technology equipment (ITE). Cold air was blown into the raised floor, and perforated floor tiles would allow cold air to discharge proximate to the ITE [11]. This design was satisfactory for low-density equipment ranging in size from approximately 6 kilowatt (kW) to 9 kW per rack [12]. During that time conventional air-based cooling systems accounted for a substantial fraction of total facility energy consumption, often approaching or exceeding 40%, prompting sustained research into alternative cooling strategies as computing density increased [13].

Efficiency improvements were made to the equipment rooms by dividing them into hot and cold aisles using different physical containment barriers such as curtains [14]. This design reduced energy consumption on the chiller plant as much as 35% because the cold air was managed more efficiently [15].

As data centers' power demand and server density increased, dedicated computer room air conditioners (CRAC) were built. CRACs were supplied with cold water using a chiller and that cold air was directed at the ITE. These systems were typically designed to keep the entire room housing the ITE cool.

In the early 2000s, as processing speeds increased, microprocessor size decreased, and data centers became denser (*i.e.*, more microprocessors per square foot) the energy demand increased to 10 kW to 50 kW per rack (*i.e.*, high-density) [12] [14] [15], cooling technologies were forced to improve again.

Data center developers implemented "free cooling" where economizers (air-side or water-side) were implemented [16]:

1) Air-side economizer brings in outside air when ambient temperatures are within the data center's cooling setpoints reducing operation of the Computer Room Air Handlers (CRAH).

2) Water-side economizers utilize a separate condenser loop allowing ambient conditions to do the same work as the chiller plant, thereby reducing energy demands.

The most recent developments in cooling technology include direct liquid cooling where the heat generated from the ITE is transferred directly to a liquid [16]—which will likely become standard for the highest density racks requiring the most energy. With the increasing focus on AI which utilized high-performance computing (HPC) and advanced storage architecture [17], the power per rack could increase to 100+ kW or more requiring significantly more cooling demand.

Thus, the range of ITE cooling technologies implemented at data centers can include:

1) *Standard refrigerated air systems*: these systems use the same technology as a residential window air conditioner based on the principles of gas expansion and contraction using a compressor.

2) *Industrial Open Loop Chiller Plant*: These systems convey hot water to the top of a chiller tower where the water flows down, releasing heat through evaporation. These systems require make-up water to replenish the loss through evaporation and water exchanges when the mineral content increases to a point where equipment scaling can occur, reducing the effectiveness of the chiller.

3) *Air Cooled Evaporative Chillers*: These systems operate as a closed loop where the heat from the data center is transferred to a second closed loop system which is then passed over an air-cooled heat exchanger. The closed loop system results in reduced water demand as water is not lost to evaporation.

4) *Immersion Cooling Technologies*: These systems place microprocessors directly in contact with the cooling liquid. These systems are more complicated than air cooled systems; however, with a heat transfer rate approximately 25 times faster than air, this technology will likely be implemented on larger and AI data centers as technology continues to advance.

5) *In-chip microfluidic cooling*: This (currently experimental) system utilizes a series of tiny channels etched onto the back of a silicon chip. The channels allow liquid to flow directly onto the chip and can remove heat up to three times better than cold plates [18].

Foundational work from the early 2010s emphasized that the thermal limits of air cooling were being approached as processor heat fluxes rose, particularly in high-density and blade server configurations [13]. These early investigations framed cooling not only as an energy-efficiency issue but also as a system-level constraint affecting future data center scalability. By the early 2010s, research expanded to examine hybrid and economizer-based cooling systems that leveraged ambient conditions to reduce reliance on mechanical refrigeration. Studies demonstrated that both air-side and water-side economizers could reduce cooling energy demand in temperate and subtropical climates, provided that appropriate humidity and temperature control strategies were maintained [19]. Subsequent reviews consolidated this body of work, highlighting free cooling as a transitional strategy while also noting its sensitivity to climate, air quality, and operational constraints [20].

As server power densities continued to rise, research increasingly focused on liquid-based cooling technologies capable of removing higher heat fluxes with lower energy penalties. Direct-to-chip liquid cooling and two-phase cooling systems were shown to outperform air cooling in both thermal efficiency and energy recovery potential, particularly for high-performance computing and emerging accelerator-based workloads [1]. These studies emphasized that liquid cooling enables higher coolant temperatures, which in turn improves opportunities for waste heat recovery and reduces overall system energy intensity. Parallel work explored the integration of natural and engineered water bodies as heat sinks, including lakes, mine pools, and other low-temperature water sources [21]. These approaches demonstrated reductions in cooling energy demand while introducing new considerations related to thermal discharge and site-specific water quality [22]. Collectively, this literature identified the need for careful assessment of environmental impacts beyond energy metrics alone.

While energy efficiency dominated early discussions of data center sustainability, research beginning in the mid-2010s highlighted that water use had received comparatively little systematic attention. Initial assessments of data center water footprints demonstrated that both direct cooling water use and indirect water consumption associated with electricity generation contributed significantly to overall environmental impact [23]. These early analyses underscored large uncertainties in water footprint estimates due to variability in energy sources, cooling technologies, and reporting practices. Subsequent studies refined this perspective by linking water use to workload characteristics, cooling system selection, and grid-specific water intensity factors. Research showed that water consumption per unit of computational output can vary by orders of magnitude depending on server efficiency, utilization, cooling technology, and geographic location [24]. This reframing of water uses as a system-level outcome rather than a simple facility input was an important shift in thinking, reinforcing the importance of integrating water metrics into data center design.

Environmental footprint analyses of AI-focused infrastructure show that direct water use for cooling now represents a substantial share of total water demand, alongside significant indirect water consumption embedded in electricity generation (**Figure 2**) [25]. Scenario-based modeling identifies that without coordinated efficiency improvements and regional planning, AI-driven data center growth has the potential to exacerbate water stress in already constrained watersheds [26].

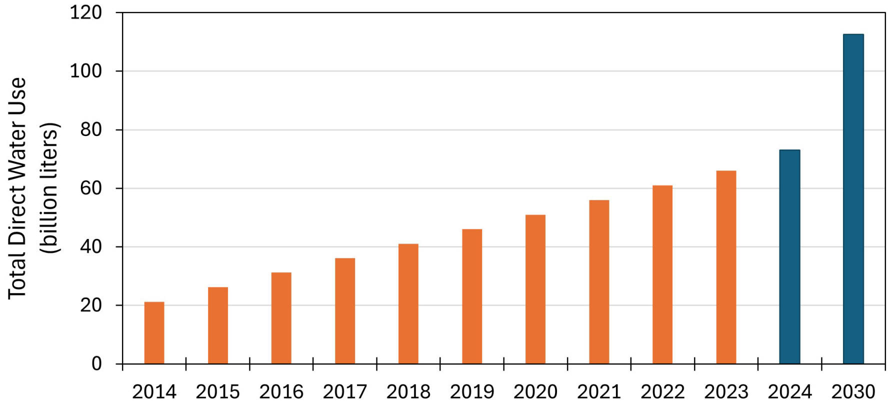

Figure 2. Data for 2014-3014 are from [4] (published in 2024). Values for 2024 and 2030 are projected estimates based on [26].

Despite increasing attention to data center water use, there is a gap in the literature documenting how source water is prepared prior to its use in data center cooling systems. While many studies quantify total water withdrawals and consumption, few provide detailed accounts of the pretreatment processes applied to condition source water for operational use. Specifically, there is limited discussion of filtration, softening, corrosion control, scaling mitigation, biological growth suppression, or the chemical additives introduced to ensure compatibility with cooling infrastructure and reliable system performance. This lack of documentation prevents clarity regarding a critical stage of the data center water lifecycle and limits stakeholder understanding of the pretreatment requirements that directly influence cooling efficiency, infrastructure durability, and downstream environmental outcomes.

Similarly, the literature also does not document the water quality characteristics of wastewater generated by data center cooling systems. Most studies treat cooling blowdown and discharge streams in aggregate terms, focusing on volume rather than composition. While thermal impacts of discharged water have been previously covered, particularly in the context of surface water cooling, less is known about the potential presence and fate of chemical additives, corrosion inhibitors, biocides, and concentrated dissolved solids in cooling system effluents [23]. Existing assessments generally assume that wastewater is managed through discharges to a conventional municipal treatment systems, yet there are limited evaluations of whether these systems are designed to handle the specific chemical and thermal profiles associated with large-scale data center operations [22].

2.3. Survey of Legislative Attention

While the Federal government often leads on industry regulatory requirements, for data centers we have seen no specific Federal legislative or regulatory action that is specific to data centers. Instead, regional governments—particularly those in areas with high energy demand or limited water resources—are currently taking the lead in managing proposed infrastructure growth. American Water Works Association (AWWA) notes that data centers are governed through multiple regulatory channels—including local land-use and building approvals, utility requirements, and water-withdrawal frameworks—rather than a single unified regulatory program [27]. A review of state-level legislative activity using the BillTrack50 database [28] identified bills that reference data centers and evaluate the extent to which environmental considerations, particularly water use and water management, appear in legislative language across states.

Extraction of available bills from the BillTrack50 platform and applying a targeted keyword filter for the term "data center" yielded a total of 28 bills introduced across various U.S. states. Based on a review, 17 of the 28 bills addressed the management of data centers—but only 6 included water-related provisions. While this review focuses on state-level legislation that explicitly references data centers to assess the emergence of water-related policy language, it is important to recognize that utility guidance identifies additional regulatory pathways that can impact data centers, such as local permitting and water-allocation requirements, that operate alongside formal legislation [27] (**Figure 3**).

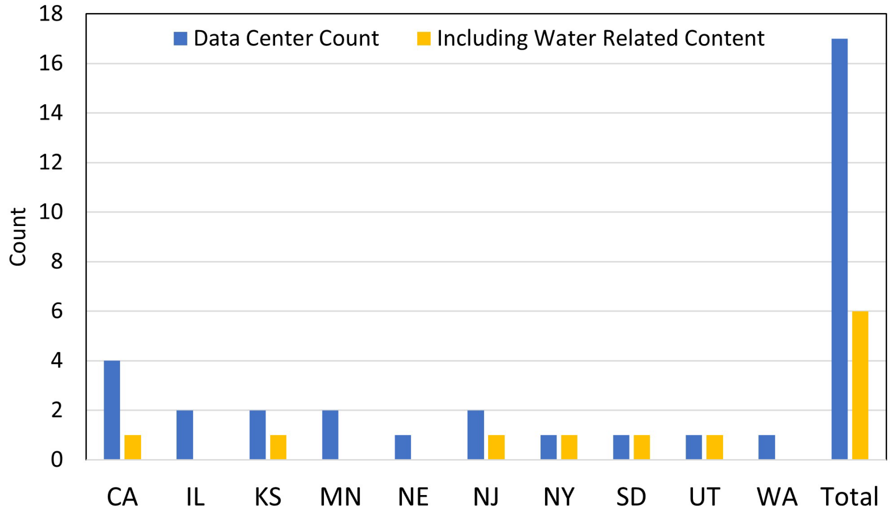

Figure 3. Count of data-center-related bills per state (Total = 17 bills).

Across the 17 bills identified as addressing the management of data centers, the current U.S. policy landscape shows a sparse mixture of environmental oversight, resource-management requirements, and economic incentive structures. As summarized in the attached table, these bills span multiple stages of the legislative process. Of the 17 bills, two are still in the introduction stage (introduced), six bills are in committee to be further studied (in committee), three bills have crossed over from one chamber (state house or senate) to the other chamber, three bills have been vetoed and four bills have been signed/enacted or adopted as shown in **Table 1**.

Substantively, the bills differ in environmental emphasis: several are directly focused on water management, such as California's AB93 and Utah's HB0076, which require water-use reporting, conservation practices, or disclosure of anticipated withdrawals; others concentrate on energy governance and grid-impact oversight, including California's AB222 and SB57, Illinois's SB0094, and Minnesota's HF28. Several states, including Kansas, South Dakota, and Nebraska, primarily advance investment- or tax-incentive legislation, with only limited or no environmental provisions. Bills in New Jersey and New York take a more comprehensive approach, pairing energy and water reporting mandates with sustainability criteria and community-impact considerations.

Overall, the reviewed legislation indicates that while some states are beginning to incorporate environmental considerations into data center policy, especially around energy use, only a small subset explicitly addresses water consumption, and those that do vary widely in depth and enforcement mechanisms of their requirements.

Table 1. U.S. state-level data-center bills and their legislative status.

State	Bill Number	Introduced	In Committee	Crossed Over	Vetoed	Signed/Enacted/Adopted
CA	AB222			X		
CA	AB93				X	
CA	SB327		X			
CA	SB57					X
IL	SB0094		X			
IL	SB0227		X			
KS	SB51			X		
KS	SB98					X
MN	HF28		X			
MN	SF769		X			
NE	LB468			X		
NJ	S3432					X
NJ	S4293				X	
NY	S06394		X			
SD	HB1005	X				
UT	HB0076	X				
WA	SB5431					X
Grand Total	17	2	6	3	2	4

For the six bills containing water-related provisions, the legislative activity is currently limited primarily to those states facing water-scarcity pressures (e.g., CA, KS) or those with stronger environmental oversight frameworks (e.g., NJ, CA, NY). These states are beginning to incorporate elements of water disclosure, conservation, or reporting into data-center policy, but these elements vary considerably in depth and enforcement. As reflected in Table 2, the recent legislative activity has been distributed across several legislative stages—one in committee (NY), two introduced (SD, UT), one signed/enacted (KS), and two vetoed (CA, NJ), demonstrating that while momentum exists, regulatory consensus has not yet solidified.

Substantively, the bills in California (AB93) and New Jersey (S4293) take the strongest stance, requiring detailed reporting of water usage and connecting water disclosures to broader environmental oversight, though both ultimately were subject to vetoes. Utah (HB0076) and South Dakota (HB1005) emphasize water-use transparency during siting and operation, with Utah mandating projected and actual water-use reporting and South Dakota requiring notification to local water providers. New York (S06394) incorporates water considerations within a broader environmental review and sustainability framework, requiring pre-construction disclosures of projected water use. Kansas (SB98) stands out as the only enacted bill among the water-focused group, requiring adherence to water conservation, reuse, and replacement practices as part of qualifying for a long-term tax exemption. Together, these bills demonstrate an overall uneasiness toward imposing strict, enforceable limits on the water footprints of data centers, with most measures instead emphasizing reporting, transparency, and conservation-aligned practices. Importantly, this pattern is reinforced by the absence of data-center-specific water legislation in the majority of U.S. states, suggesting that policy responses to data-center water use remain fragmented and largely reactive, lagging behind the rapid pace of data-center construction and expansion. Furthermore, the majority of the states have no bills relating to data centers indicating that policy initiatives are lagging behind the fast growth of data center construction.

Table 2. Summary of U.S. state-level data-center legislation and legislative status.

	Introduced	In Committee	Vetoed	Signed/ Enacted/Adopted	Grand Total
CA			1		1
AB93			1		1
This bill sought to establish statewide oversight of data-center water use in California by requiring facilities to submit water-use estimates before obtaining a business license and annual water-use reports for renewals. It also empowered the Department of Water Resources to develop future water-efficiency standards. The bill aimed to create a regulatory framework for monitoring and eventually managing water consumption as data-center development expands in water-stressed regions. Governor Newsom ultimately vetoed the bill, arguing that imposing strict reporting requirements on a fast-growing, economically important industry was premature without a better understanding of operational and economic impacts. The bill is environmental focused specifically on water requirement.			1		1
KS				1	1
SB98				1	1
This bill promotes data center investment in Kansas by granting a 20-year sales tax exemption for firms investing at least $250 million and creating 20 new jobs within two years. To qualify, firms must: Purchase electricity for 10 years from the local public utility providing retail electric service Adhere to practices that conserve, reuse, and replace water Undergo periodic reviews by the Secretary of Commerce General specifics on the local utility usage and adherence to water conservation, reuse, and replace water.				1	1

Continued

NJ			1	1
S4293			1	1
This bill requires New Jersey data centers to submit quarterly reports to the Board of Public Utilities detailing energy consumption, water usage, power sources, and sustainability metrics. Reports must include data such as kilowatt-hour energy use, water input in cubic meters, renewable energy factors, and waste heat reuse. The BPU will publish these reports and coordinate with the Department of Environmental Protection. Bill has an environmental focus on both energy consumption and water usage criteria.			1	1
NY		1		1
S06394		1		1
This bill establishes strict regulations for data centers in New York, emphasizing energy consumption, environmental impact, and community engagement. Key provisions include: 1) Pre-construction disclosures on projected energy and water usage, emissions, and community impacts. 2) Public hearings in host communities and annual sustainability updates. 3) Renewable energy transition: a) 33% by 2030. b) 66% by 2035. c) 100% by 2040. 4) Prohibition of incentives for fossil fuel power agreements. 5) Surcharge on data centers to fund energy affordability programs. 6) Penalties for non-compliance with reporting or efficiency goals. 7) Community discount plan to offset energy costs for host communities. The bill is environmental focused, including energy and water usage specifics.		1		1
SD	1			1
HB1005	1			1

Continued

This bill provides long-term sales and use tax exemptions (up to 50 years) for qualifying data centers in South Dakota to incentivize technology infrastructure investment. To be eligible, a data center must: 1) Be located in South Dakota and subject to real property taxation. 2) Be established between July 1, 2026, and June 30, 2036. 3) Include fire suppression systems. 4) Submit documentary evidence to the Department of Revenue. 5) Ensure electric utility agreements do not shift costs to other customers. 6) Notify local water providers about water consumption. 7) File annual affidavits confirming qualification. Environmental consideration including energy and water for eligibility compliance.	1				1
UT	1				1
HB0076	1				1
This bill requires large data centers (10,000 sq. ft. or more) in Utah to report water usage and discharge details to the Division of Water Rights. Operators must provide projected water diversion, usage, discharge types, and reuse/replacement plans before construction and annually after operations begin, comparing projected versus actual use and outlining conservation efforts. The division will publish aggregated data online, and failure to report will result in penalties. Bill is specifically environmental focused on water.	1				1
Grand Total	**2**	**1**	**2**	**1**	**6**

Accordingly, the six water-related bills identified here should be interpreted as a measure of emerging legislative activity, while many binding project conditions may still arise through local permitting, utility coordination, and water-resource compliance pathways [27]. This introduction of the potential for water-related regulatory requirements encourages data center developers to adopt more innovative and flexible approaches to facility design, particularly in cooling technologies, water-efficiency planning, and conservation strategies. As states begin to require advance disclosure, reporting, conservation practices, and coordination with local water providers, developers must integrate technical solutions that not only meet operational needs but also align with evolving oversight expectations. As with other types of industrial development, the data center industry is expected to get increasing regulatory attention under which future data-center projects are planned, permitted, and sustained.

2.4. Highlighting Corporate Sustainability Disclosures

Prior research on corporate water disclosure highlights that transparency around water use and risk management reflects proactive corporate engagement with sustainability, stakeholder communication, and long-term resource stewardship. Drawing on legitimacy and stakeholder perspectives, Yu *et al.* (2020) show that firms use water-related disclosures to demonstrate responsible management practices, build trust with stakeholders, and strengthen corporate credibility . Understanding the environmental profile of hyperscale data-center operations depends on the availability of consistent and transparent sustainability disclosures. Several major technology companies—including Google, Meta, Microsoft, and Apple—now publish annual reports that provide insight into electricity use and water withdrawal associated with facility operations. These disclosures represent an important window into high-level trend analysis across the sector. As public awareness of data-center water use has increased through mainstream media coverage, sustainability disclosures have also become an important tool for communicating operational context, regional variability, and water-management strategies to a broader audience beyond regulators and investors [30].

Sustainability disclosure data was compared across the 2019-2024 period for Apple, Meta, and Google, and from 2020-2024 for Microsoft [31]-[37].

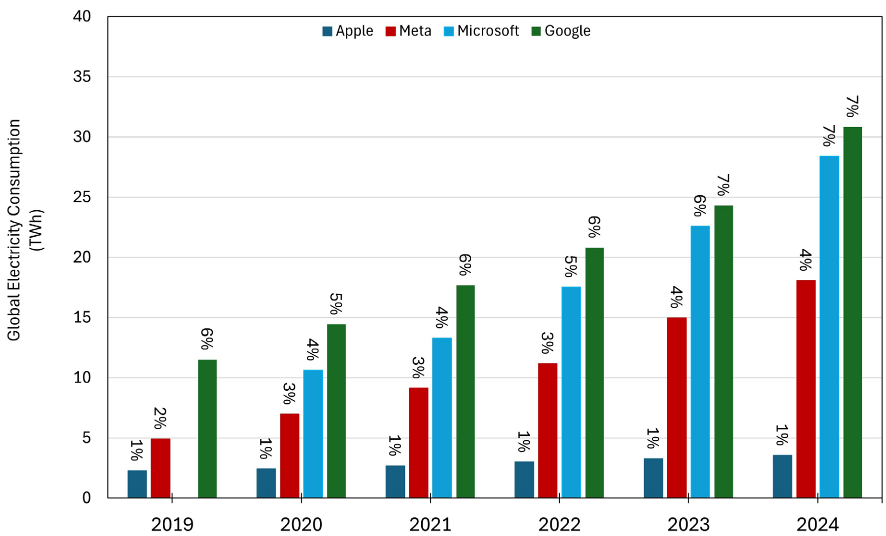

Figure 4. Annual electricity consumption attributable to data-center operations for Apple, Meta, Microsoft, and Google. The numeric labels on each bar represent the percentage of total global data center electricity demand accounted for by each company's data center operations in the given year [38].

Figure 4 presents estimated annual electricity demand attributable to data-center operations for Apple, Meta, Microsoft, and Google from 2019 through 2024.

For Google and Meta, the values shown correspond to directly reported data-center electricity consumption, while estimates for Apple and Microsoft are derived using a harmonized approach that applies an empirically observed data-center electricity share to total facility electricity consumption. This method supports a consistent, high-level comparison across companies while acknowledging differences in disclosure practices. The figure illustrates steady growth in electricity demand across all four organizations over the period, reflecting continued expansion of digital infrastructure and increasing computing intensity. Microsoft's trajectory shows particularly rapid growth after 2021, consistent with the scaling of AI-enabled workloads, while Meta and Google exhibit sustained multi-year increases aligned with global platform growth. Apple's data-center electricity demand remains comparatively lower in absolute terms but follows a similar upward trend. Collectively, these patterns highlight the scale at which leading technology companies are investing in data-center capacity and underscore the importance of integrated energy planning as part of broader sustainability strategies.

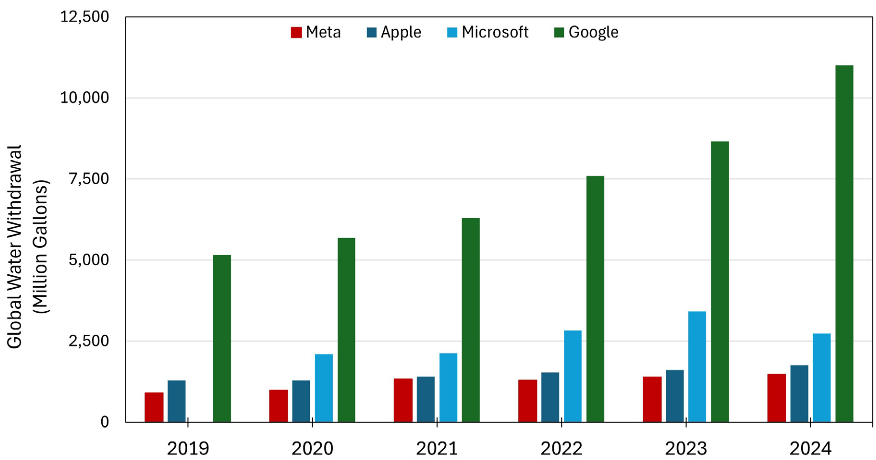

Figure 5. Annual water withdrawal associated with facility operations for Meta, Apple, Microsoft, and Google from 2019-2024.

Figure 5 compares reported facility-level water withdrawal for Apple, Meta, Microsoft, and Google from 2019 to 2024, illustrating how water demand has evolved alongside the expansion and increasing technical sophistication of data-center operations. Across all four companies, the upward trajectories reflect growth in data-center capacity, higher equipment density, and the broader adoption of advanced cooling systems required to support modern computing workloads. Microsoft reports a reduction in total water withdrawals between 2023 and 2024; however, the company notes that FY24 values reflect an updated estimation methodology for datacenter locations where site-specific data are unavailable, and prior years were not recalculated under this approach. As a result, the observed year-to-year change should be interpreted as a combination of methodological refinement and operational factors, rather than as a standalone indicator of performance improvement. Google's higher absolute withdrawal volumes highlight the scale at which large hyperscale platforms operate, underscoring the importance of integrated water-system planning, alternative sourcing strategies, and cooling-technology selection at scale. Meta and Apple exhibit steady, incremental increases consistent with phased infrastructure expansion. Collectively, these patterns emphasize the growing value of proactive, engineering-driven water-management strategies—spanning system design, source selection, reuse integration, and performance monitoring—to support continued growth while aligning with evolving sustainability and regulatory expectations.

Figure 6 illustrates the share of Meta's total facility water withdrawal attributable to data-center operations between 2019 and 2024, which consistently represents a substantial majority of overall facility water use. Across the period shown, data center operations account for approximately 68% to 81% of total facility water demand, reflecting the central role that cooling systems play in supporting high-performance computing environments. This concentration highlights where the greatest opportunities for impact reside—namely within the design, optimization, and operation of data-center water systems themselves. As data center infrastructure continues to scale in size and technical complexity, the figure underscores the importance of specialized expertise in cooling-system design, alternative water sourcing, reuse integration, and performance optimization. Thoughtful, innovation-driven water-system planning enables operators to manage large water demands reliably while advancing long-term sustainability objectives.

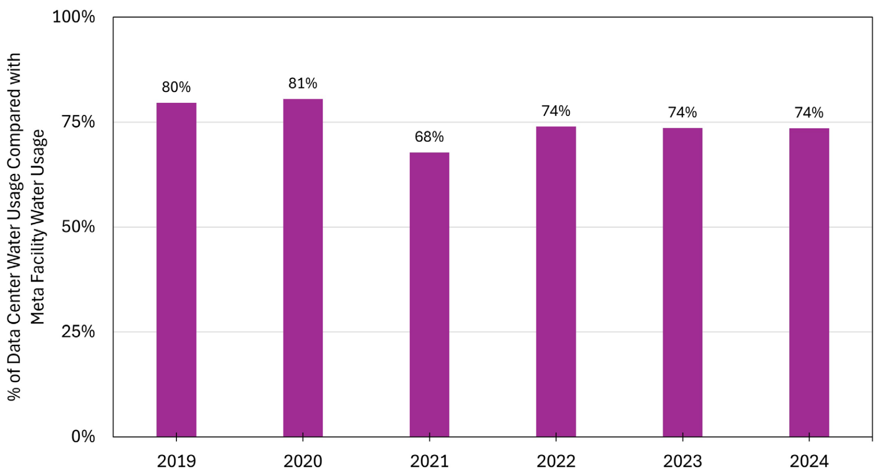

Figure 6. Share of Meta's total facility water withdrawal attributable to data-center operations from 2019 to 2024. The figure illustrates temporal trends in total water withdrawals as data-center capacity and cooling demand expanded across company facilities.

Figure 7 shows Apple's allocation of freshwater, recycled water, and alternative water sources from 2018 to 2024, providing uncommon transparency that distinguishes among water-sourcing pathways and information that can inform basin-level analysis and infrastructure planning. Over the period shown, freshwater remains the dominant source supporting data center operations, reflecting both the reliability requirements of cooling systems and the technical constraints associated with large-scale, high-availability facilities. At the same time, the growing presence of recycled and alternative water sources highlights ongoing efforts to diversify supply portfolios. These patterns further underscore the importance of smart, engineering-driven water-system design—integrating alternative sourcing, reuse strategies, and site-specific optimization—to reduce pressure on freshwater resources while enabling continued growth in data-center capacity and AI-driven innovation.

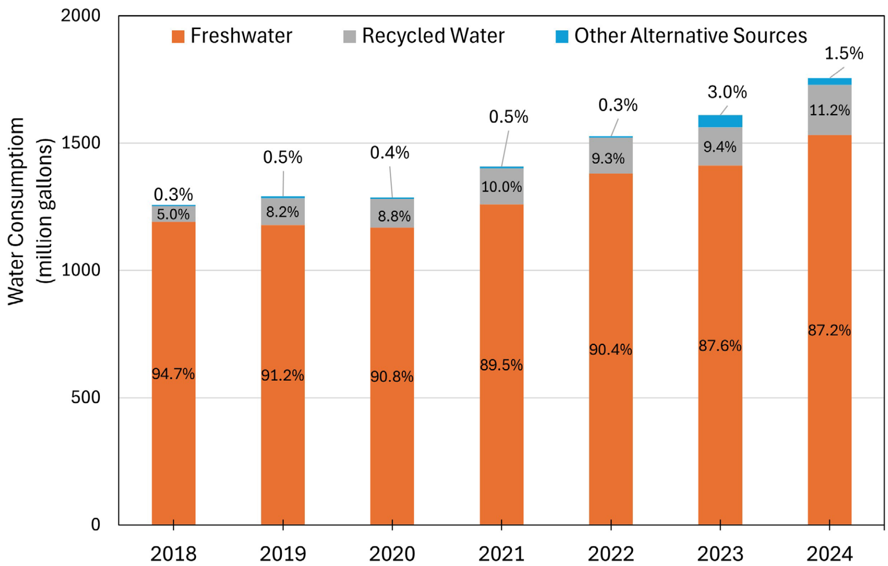

Figure 7. Distribution of Apple's water consumption across freshwater, recycled water, and alternative water sources from 2018-2024.

What emerges from this review is not a narrative of constraint, but one of opportunity: the scale and visibility of data-center water use now position engineering innovation as a primary lever for sustainable growth. Corporate disclosures illuminate where water is used; policy signals where accountability is rising; and the literature clarifies which technical pathways are most effective. Bridging these domains requires high-quality, systems-level water-engineering expertise capable of transforming transparency into performance. With this foundation established, the following section focuses on the water-management characteristics that enable data centers to support continued AI expansion while advancing long-term water stewardship.

3. Water Management of U.S. Data Centers: Challenges and Adaptations

A recurring theme across the available literature is the disconnect between rapidly evolving engineering practices and the slower development of regulatory frameworks governing water use and discharge. While sustainability metrics such as Power Usage Effectiveness (PUE) and Water Usage Effectiveness (WUE) are increasingly reported, they do not directly address local water availability, wastewater quality, or cumulative watershed impacts. Recent life cycle assessment research reinforces the need to align technological innovation with environmental policy by demonstrating how advanced cooling technologies can reduce water consumption when evaluated across the full system boundary [11]. However, translating these insights into appropriate enforceable standards and best practices remains an unresolved challenge.

3.1. Water Sources and Regional Dependence

While the future projections of water usage can be daunting, it is important to note that the water supply for power generation may be geographically separate and distinct from the water supply for cooling operations. If power supply originates in a different geographic region that the facility requiring cooling, each assessment of potential water use impacts would likely need independent evaluation but would also distribute the usage over a larger area.

Data centers typically obtain cooling and make-up water from three primary sources: surface water, groundwater, and reclaimed or recycled water. In practice, sourcing decisions depend on regional hydrology, utility infrastructure, water rights regimes, and regulatory frameworks. However, the absence of standardized public reporting makes it difficult to determine which sources dominate in many regions. Sourcing choices carry important implications if they occur in water-stressed basins. Regions of the western and central United States, where groundwater depletion and surface-water scarcity are already significant concerns, are also hubs for new data-center development. In such settings, incremental industrial withdrawals can intensify competition with municipal, agricultural, and ecological water demands.

Reclaimed water is often cited as a mitigation strategy, but its use is governed almost entirely at the state level. The U.S. Environmental Protection Agency (USEPA) provides non-binding Guidelines for Water Reuse in 2012 [39], while formal reuse regulations vary widely among states [40]. This regulatory fragmentation creates uncertainty for data-center developers and limits the ability to deploy standardized reuse-based cooling designs across jurisdictions.

3.2. Water Consumption and Wastewater Discharge

Cooling systems transform incoming make-up water into a combination of consumptive evaporation and wastewater discharge. In open-loop evaporative cooling systems, most thermal rejection is achieved through evaporation, while the remaining fraction is discharged as cooling-tower blowdown, with smaller losses due to drift and windage. Using commonly applied assumptions for cycles of concentration (approximately five), blowdown volumes may be on the order of one-quarter of evaporative losses, implying that the majority of on-site cooling water is consumed rather than discharged to wastewater treatment plants or returned to the watershed. Blowdown effluent typically exhibits elevated temperature and dissolved solids, which can trigger regulatory oversight based on effluent water quality standards [41].

Wastewater generated by data-center cooling operations may be: (i) discharged directly to surface waters under a National Pollutant Discharge Elimination System (NPDES) permit; (ii) conveyed to publicly owned treatment works (POTWs) as an industrial discharge; or (iii) managed through on-site treatment and limited reuse where permitted. EPA guidance clarifies that both surface discharges and significant industrial users discharging to POTWs fall within Clean Water Act permitting and pretreatment frameworks [41] [42]. Thermal limits, chemical constraints, and capacity limitations of POTWs frequently introduce permitting friction, extended review timelines, and site-specific operational requirements.

From an industrial cooling-water perspective, cooling-tower make-up water is typically "conditioned" to reduce fouling, scaling, corrosion, and biological growth that can compromise heat-transfer efficiency and equipment reliability. The same conditioning practices also shape the chemical profile of cooling-tower blowdown and therefore influence NPDES permitting limits and POTW acceptance as an industrial discharge. The conditioning steps typically include particulate control and filtration; hardness and alkalinity management (scale prevention); corrosion control; biofouling control; and cycles of concentration (CoC) management. As a result, cooling-tower blowdown typically reflects (i) concentrated source-water constituents (salts, hardness, silica, alkalinity); (ii) treatment-program constituents (corrosion/scale inhibitors, dispersants, biocides and their byproducts); and (iii) materials-of-construction constituents mobilized by corrosion (metals).

The parameters most relevant for discharge permitting and POTW compatibility screening include: flow (average/peak) and variability; temperature; pH (and alkalinity/acidity); total dissolved solids (TDS), conductivity, and salinity; chloride and sulfate; hardness, silica, and scaling indices; total suspended solids (TSS) and turbidity; metals (e.g., copper, zinc, iron, nickel, chromium where applicable); nutrients (ammonia, nitrate, total nitrogen, orthophosphate/total phosphorus); residual oxidants/disinfectants (e.g., total residual chlorine/bromine, chlorine dioxide) and non-oxidizing biocides (as applicable); and oil & grease/total petroleum hydrocarbons (where relevant). Early characterization of these parameters, paired with the planned chemical program and target cycles of concentration, supports more predictable permitting by allowing regulators and POTWs to evaluate treatability, toxicity potential, thermal impacts, and headworks loading well before final design and commissioning.

3.3. Permitting Related to Water Sourcing, Consumption, and Discharge

As discussed above, data center development and operations are presented with unique challenges based on the volume of water required to support cooling system operation and the discharge of the associated wastewater effluent generated from cooling processes. These challenges often coalesce during the permitting of development or the ongoing facility operations. Rather than one consistent set of standards for data center environmental operations and compliance, these facilities are often regulated by numerous different permitting limitations that correspond with the local environmental and community setting.

The challenge of allocating water resources can be watershed- and aquifer-specific, particularly in more arid areas where water resource usage can result in drawdown within the aquifer or public water supply. Because the potential impacts of water usage are directly limited by water supply, data center developers are faced with a large variance in procedural and regulatory requirements driven by state and local regulations that try to address conditions unique to that geography. Groundwater withdrawal volumes permitted are limited based on aquifer testing and resulting impacts on groundwater supply and aquifer drawdown. Surface water withdrawal volumes permitted are limited to ensure that stream flows are not adversely impacted by the withdrawal. And lastly, public water supplies are limited by the supplier and associated infrastructure to serve the data center development.

As a result, data center development cannot have single set of design criteria that optimize standard engineering designs across the country. Instead, data center design often requires customization in order to meet the water supply and water quality requirements of the proposed siting. The choices each data center developer makes with regards to: size, density, cooling technology, water source, power source and location often dictate the associated requirement for various environmental permits, which can range from water allocation permits or contracts with local water utilities NPDES wastewater discharge permits or significant indirect user (SIU) permits.

Permitting limitations can require an improvement/upgrade in water supply and disposal infrastructure to serve the data center facility that can potentially lead to the need to acquire additional land use permits and entitlements, which provide further opportunity for insertion of additional regulatory and stakeholder conditions. For example, in Louisiana, Meta has pledged: 1) to match its electricity use with 100% clean and renewable energy and will be working with Entergy to bring at least 1,500 MW of new renewable energy to the grid through its Geaux Zero Program; 2) to contribute up to $1 million a year to Entergy's "the Power to Care" low-income ratepayer support program [9]; and to invest more than $200 million in local infrastructure improvements, including roads and water systems [9].

Additionally, wastewater discharges from data center cooling systems are presented with limitations under the NPDES permit program and the excessive discharge volumes can lead to increased permitting timelines and operational constraints. Although the NPDES is a Federal permitting program, jurisdiction has been delegated to many states across the nation, presenting varying effluent limitations based on local constraints. These constraints can be attributed to processing and permit limitations imposed on the receiving POTWs and treatment systems and infrastructure that have limited processing capability or capacity to treat the increased wastewater effluent. Data center operations are potentially impacted through strict, site-specific limits on thermal pollution and chemical discharge, that may require use of more efficient, water-conscious cooling technologies, such as dry coolers.

While a seemingly plausible solution to the wide-spread limitations on water use and discharge would be reuse, based on the limited information on the reported quality of water required to support data center cooling systems, there is no option to reuse the wastewater effluent through additional cycles of cooling. Off-site water reuse is then subject to varying regulations, primarily governed at the state level because there are no federal regulations specifically for reclaimed water. Instead, the EPA provides only non-binding Guidelines for Water Reuse. A total of 37 out of 50 states have established formal regulations for reclaimed water, with participation significantly higher in water-scarce regions like the Pacific and Mountain West compared to the Midwest [43]. Some states have developed comprehensive, multi-sector frameworks for reclaimed water, while others operate on a case-by-case basis or rely on informal guidelines, not allowing for continuity or standardization of data center discharge system designs. While most regulating states allow for agricultural use of reclaimed water, only 23 states permit irrigation of both food and non-food crops. Furthermore, Direct Potable Reuse (DPR)—treating wastewater to drinking standards without an environmental buffer—is only recently being codified by pioneering states like Colorado [43] and California [44].

More generally, data center developments are increasingly struggling to secure land use permits due to a widening rift between state-level economic incentives and local-level regulatory scrutiny. While state policies often aggressively court these projects, local officials are trying to manage the development through outdated zoning ordinances, procedural gaps, and lengthy review cycles that can extend approval timelines from months to years. Additional delays in permit approval are frequently compounded by organized stakeholder opposition. By early 2026, over 180 activist groups nationwide have mobilized to block or delay an estimated $162 billion in data center projects [45]. These groups cite critical concerns over surging electricity prices, excessive water consumption in drought-prone regions, noise pollution, and the loss of rural character. Consequently, even well-capitalized projects face heightened risks of moratoriums or outright permit denials as local governments prioritize community impact and resource preservation over industrial expansion.

4. Recommendations

While there is little willingness to prevent technological progress and community access to the advancements that data centers enable, as with many industrial facilities, there is a resistance to incorporating them into local communities. Across all strands of the literature reviewed, engineering emerges as a central mechanism for addressing the interconnected challenges of energy efficiency, water use, and environmental protection. Advances in cooling system design, water reuse, and waste heat recovery offer clear pathways for reducing resource intensity, but their effectiveness depends on coordinated research, transparent reporting, and regulatory alignment.

There are major engineering trade-offs between cooling technology selections versus local water availability and discharge constraints. For example, shifting from evaporative cooling toward dry/air-cooled or more closed-loop configurations can materially reduce consumptive losses and blowdown volumes, but typically increases fan and/or chiller energy, which can shift impacts to the power sector (including indirect water use associated with electricity generation) and may increase operating cost and grid dependence. Another potential option is to increase the use of reclaimed water. This approach can reduce reliance on potable sources and improve community acceptance, but higher total dissolved solids (TDS) and variable chemistry can increase scaling and corrosion risk, often requiring more robust pretreatment, tighter monitoring, and potentially more conservative cycles of concentration that increase blowdown. Similarly, the cooling water could be operated at higher cycles of concentration (CoC) to reduce make-up water demand, which will increase the TDS concentrations in blowdown. In areas where POTW industrial limits (e.g., TDS, chloride, metals) or surface-water effluent limits are stringent, data centers may need to consider lower CoC, side-stream treatment, blowdown minimization/segregation, or alternative heat-rejection strategies.

In order to tap into researchers and academic resources to develop solutions to these engineering challenges, representative and quantitative data on source-water pretreatment requirements and cooling-system wastewater characteristics are critical. While withdrawal volumes are increasingly reported, limited information exists on influent conditioning processes, chemical additives, and the composition of cooling-system effluents. Research that characterizes these streams across cooling technologies, operating conditions, and climates would directly inform engineering design and regulatory review.

Similarly, representative and quantitative data on wastewater characteristics from various cooling approaches and wastewater streams would allow researchers to be part of advancing innovation in data-center-specific pretreatment and wastewater treatment approaches, building on existing knowledge of industrial water treatment while addressing the unique hydraulic, chemical, and thermal profiles associated with large-scale cooling operations. Evaluating on-site pretreatment, selective constituent removal, and treatment strategies aligned with reuse or discharge requirements represent a high-value opportunity for applied research.

Thus, navigating environmental concerns confronting U.S. data centers related to water quantity and quality will require cooperations from multiple stakeholders. Data center developers and operators need to interface between engineering systems, regulatory oversight, and public relations. Successful integration would create a single risk-management framework connecting engineering, policy, and regulations.

4.1. Developer Stakeholders—Where and How to Build

At the planning and investment stage, data center developers play a decisive role in shaping the long-term environmental footprint, regulatory risk profile, and community acceptance of new facilities. Early decisions regarding site selection, cooling technology, water sourcing, and power infrastructure determine not only operational efficiency but also exposure to permitting delays, stakeholder opposition, and future regulatory tightening. These trade-offs between cooling technology selection, water availability, and discharge limitations are summarized in a decision framework, as shown in **Table 3**.

Traditionally, data center site selection emphasizes power availability and fiber connectivity. By integrating basin level water availability, existing withdrawal pressures, and wastewater infrastructure capacity into site selection decisions, data center developers could potentially minimize cumulative watershed impacts and permitting friction. As states and local governments begin to scrutinize consumptive use and wastewater discharge more closely, proactive avoidance of high-risk geographies reduces exposure to moratoria, litigation, and reputational harm.

Water supply needs can potentially be mitigated through a feasibility evaluation of advanced alternative or hybrid cooling approaches including water side economizers, closed loop systems, or direct liquid cooling. The increased water supply and/or treatment costs required for siting in marginal geographic locations should be factored into the viability of data center development.

Just like any other significant development project, early engagement with local stakeholders and utilities helps address concerns related to water security, infrastructure capacity, and cumulative impacts, particularly where water use and infrastructure strain are perceived as disproportionate to local benefits. Clear communication is supported with transparent quantitative data (e.g., projected water withdrawals, wastewater volumes, and mitigation strategies) reduces the likelihood of prolonged entitlement disputes and reactive design changes. Aligning engineering design with emerging disclosure and conservation requirements can materially reduce permitting timelines and operational constraints.

From an investment perspective, water risk should be treated as a material factor equivalent to power interconnection or land availability. The uneven progression of water focused legislation across states, combined with growing public scrutiny, suggests that regulatory risk will continue to increase rather than stabilize. Developers that prioritize sites with resilient water supplies, established reuse frameworks, and predictable permitting pathways are better positioned to scale operations without costly retrofits, compliance surprises, or community backlash [46].

Table 3. A decision framework to align cooling choices to locater water availability and discharge constraints.

Local constraint (dominant)	Cooling strategy tendency	Primary engineering focus
Water-scarce basin or limited allocation/high marginal cost of make-up water	Dry or hybrid (operate dry most hours; evaporative assist for extremes); maximize economizers and higher-temperature liquid loops where feasible	Manage energy penalty and peak-load resilience; quantify indirect water impacts from added electricity; ensure redundancy for heat waves
Discharge-constrained (tight POTW limits, limited capacity, or stringent NPDES/thermal limits)	Lower-blowdown designs: dry/hybrid, closed-loop systems, or evaporative with enhanced blowdown management	Control blowdown volume and chemistry: Cycle of Concentraion (CoC) optimization, side-stream treatment, segregation, and clear compliance pathway (SIU or NPDES)
Reclaimed water available and politically preferred, but variable chemistry	Evaporative or hybrid using reclaimed water (with fit-for-purpose pretreatment); consider blending and seasonal mode changes	Scaling and corrosion control, monitoring, and robust O&M; evaluate whether reclaimed-water-driven CoC reductions increase blowdown and affect discharge compliance
Water and discharge both constrained (common in growth corridors)	Prioritize water-minimizing cooling plus targeted on-site treatment for limited residuals; design for expandability and phased compliance	Integrate water balance and discharge strategy into entitlements; develop contingency plans (alternate source, seasonal operations, or capacity offsets)

4.2. Operator Stakeholders

When the operators manage water withdrawal, wastewater discharge, and cooling system performance in separate domains, it is challenging to respond to regulatory triggers or evolving permitting requirements. For example, indirect water use associated with electricity generation can rival or exceed on-site water consumption, while cooling system design governs both consumptive losses and regulated discharges. An integrated management system can provide unified operational oversight.

Although water reporting requirements remain fragmented, the legislative review shows a clear directional trend toward increased disclosure, conservation practices, and coordination with local water providers. If operators voluntarily develop internal tracking systems for water withdrawals, sources, consumptive losses, and wastewater characteristics in anticipation of mandatory reporting, facilities can rapidly respond to information requests or new disclosure rules. This will lower compliance costs and reduce enforcement risk as regulatory momentum builds.

Pursuing treated effluent reuse, alternative water sourcing, and optimized cycles of concentration will reduce reliance on potable water supplies. Ultimately, it further stresses our natural resources to continue to expect that, at the current growth rate, our technical approach to water use for data centers can be easily sustained. Therefore, meeting such growth is expected to require innovations that achieve significant decreases in water consumption, significant increases in water reuse, and/or non-water based cooling strategies. Understanding state and local-specific regulatory frameworks will help form feasible and practicable reuse strategies.

In addition, facility audits, public records requests, or community reviews could increase with intensified public attention to data center water use. Maintaining defensible documentation on water balances, discharge pathways, and compliance history reduces legal and reputational exposure. Facilities designed and operated with adaptability in mind, capable of meeting tighter discharge limits or expanded reporting requirements, will be more resilient as water governance continues to evolve.

4.3. Regulatory Stakeholders

Predictability is of significant value in investment assessments and associated risk. Therefore, establishing appropriate and consistent national standards for wastewater discharge, water-use metrics, and development approvals creates the predictable regulatory environment needed for scalable data center growth. Adoption of uniform benchmarks, such as WUE, gives developers clear sustainability targets and reduces the financial and operational uncertainty that comes with navigating a patchwork of local rules. While regulators should not be expected to tailor water policies to a single industry, the essential role data centers play in supporting daily life underscores the value of standardized requirements. A national framework that still accommodates local constraints would streamline permitting and reinforce sound engineering practices across the country.

Furthermore, unified wastewater protocols facilitate innovative water reuse and circularity, such as using treated effluent for cooling, which minimizes the strain on municipal resources and fosters stronger community trust through transparent environmental stewardship.

In addition to creating predictability, consistent local approval processes and dedicated zoning frameworks empower municipalities to evaluate data center proposals with greater technical rigor and transparency. When expectations are clearly defined, project teams can tailor their designs to meet local priorities from the outset—whether related to water management, energy use, or community integration—reducing the need for redesigns or prolonged negotiations. This clarity also helps local agencies allocate staff and resources more efficiently, shortening review timelines and improving coordination across planning, environmental, and utility departments. Ultimately, a streamlined and well-structured local process not only accelerates responsible development but also strengthens public confidence by demonstrating that growth is being managed thoughtfully and consistently.

5. Conclusions

This review examined the intersection of U.S. data-center growth with emerging concerns related to water quantity and water quality, with a focus on cooling system operations, indirect water use associated with electricity generation, and permitting constraints governing water sourcing and wastewater discharge. The literature synthesis demonstrates that while data-center energy demand has received attention, water use and wastewater characteristics remain under-documented despite their relevance to facility siting, regulatory review, and community acceptance. Concentrated regional growth, coupled with expanding high-density and AI-driven workloads, has scrutiny of both consumptive water use and cooling-system discharges within specific watersheds and utility systems.

The analysis further highlights that current regulatory and reporting frameworks have not evolved at the same pace as data-center development. State-level legislative activity related to data centers remains uneven, with water-focused provisions primarily emphasizing disclosure rather than enforceable limits. Corporate sustainability disclosures offer valuable high-level insights into water withdrawal trends and illustrate proactive corporate efforts toward transparency and sustainability. Across the literature, at gap exists in the characterization of source-water pretreatment requirements and cooling-system effluents—information that is critical for both engineering design and regulatory evaluation.

Collectively, these findings indicate that navigating environmental concerns related to data-center water use will require integrated, engineering-driven approaches that align cooling technology selection, water sourcing, and wastewater management with local regulatory and infrastructure constraints. Improving transparency and data availability around water quality and wastewater characteristics, alongside continued innovation in cooling and reuse strategies, will be essential to support continued data-center growth while managing water-resource impacts in a predictable and technically defensible manner.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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