

Assessing Water Consumption and Cooling Efficiency Challenges Associated with Large-Scale Data Centre Growth and Operations

Prindal Rawal
DePaul University
USA

Abstract: The rapid expansion of cloud computing, artificial intelligence, digital services, and high-performance computing has accelerated the development of large-scale data centres worldwide, increasing concerns about their dependence on water-intensive cooling systems. Although cooling is essential for maintaining reliable computing environments and preventing equipment failure, growing facility capacity can substantially increase water withdrawals and consumption, particularly in regions experiencing water scarcity and climate-related resource pressures. This study assesses water consumption and cooling-efficiency challenges associated with large-scale data centre growth and operations. It examines cooling-system design, climatic conditions, computing intensity, facility location, water usage effectiveness, and the relationship between water and energy efficiency. The analysis evaluates conventional cooling towers, air cooling, liquid cooling, immersion technologies, recycled-water utilization, and closed-loop systems as alternative approaches for reducing freshwater dependence. Particular attention is given to balancing thermal performance, electricity consumption, operational reliability, and regional water availability. The study develops a sustainability-oriented perspective for improving cooling efficiency while minimizing water-related environmental impacts throughout expanding data centre infrastructure and operations.

Keywords: Data Centres; Water Consumption; Cooling Efficiency; Water Sustainability; Digital Infrastructure; Thermal Management

1. INTRODUCTION

1.1 Large-Scale Data Centre Growth and Increasing Resource Demand

Rapid digitalization is accelerating the construction and expansion of data centre infrastructure required to support cloud computing, artificial intelligence, high-performance computing, streaming platforms, and increasingly data-intensive services [1]. Growth in computational workloads requires greater server capacity, storage, networking equipment, and specialized processors capable of supporting complex and continuously operating applications [5]. Increasing deployment of high-density computing infrastructure consequently raises both facility electricity consumption and heat generation [2]. This relationship is particularly significant for AI and high-performance computing, where concentrated processor loads can create substantially greater rack-level thermal densities than conventional computing environments [6]. Maintaining equipment within acceptable operating temperatures therefore requires corresponding expansion and optimization of heat-removal infrastructure [3]. Cooling requirements can involve chillers, cooling towers, pumps, air-handling systems, evaporative processes, or increasingly liquid-based technologies depending on facility architecture and climatic conditions [8]. Data centre expansion should therefore be understood not only as growth in computing capacity but also as increasing demand for interconnected energy, cooling, and water resources [7].

1.2 Water Consumption as an Emerging Data Centre Sustainability Challenge

Water consumption emerges principally from the requirement to remove heat generated by continuously operating

computing equipment and supporting electrical infrastructure [2]. Direct facility water consumption occurs when cooling systems use water for heat rejection, particularly through evaporative cooling towers, humidification processes, or related thermal-management operations [3]. The overall water footprint can, however, extend beyond the facility boundary. Electricity supplied to data centres may involve water consumption or withdrawal during power generation, creating an indirect water footprint associated with facility electricity demand [5]. Consequently, cooling technologies that reduce direct water consumption may still produce wider water implications when they increase electricity requirements [6]. This energy–water interaction makes assessment of data centre sustainability more complex than considering facility water withdrawals independently [1]. Geographic context is equally important because identical water consumption can have substantially different environmental consequences depending on local water availability [7]. Development in drought-prone or water-stressed regions can intensify competition among industrial, municipal, agricultural, and ecological requirements, making water-efficient cooling and responsible resource planning increasingly important [8].

1.3 Aim, Scope, and Analytical Direction

This article assesses water-consumption and cooling-efficiency challenges associated with large-scale data centre growth, emphasizing the interaction between thermal management, facility operation, and regional resource sustainability [3]. The analysis compares cooling technologies according to their water and energy implications while examining Water Usage Effectiveness (WUE) as a principal indicator of facility-level water performance [1]. Because water and electricity requirements are interconnected, the assessment considers how cooling choices can generate trade-

offs between reduced water consumption and increased energy demand [6]. Climatic and geographical conditions are incorporated because temperature, humidity, water availability, and regional electricity characteristics influence cooling-system performance and environmental consequences [4]. Particular attention is given to water scarcity and the implications of locating water-intensive facilities within constrained watersheds [7]. The analysis additionally evaluates alternative water sources, including reclaimed or non-potable supplies, alongside operational optimization and advanced cooling approaches [8]. These dimensions are ultimately integrated into a resource-management perspective connecting cooling efficiency, water conservation, energy performance, siting, and long-term infrastructure sustainability [2].

electricity requirements while increasing dependence on water resources [11]. Chilled-water architectures circulate water through facility cooling loops, although their consumptive impact depends on whether heat rejection ultimately relies on wet cooling, dry cooling, or hybrid systems [9]. Additional water may be required for humidification, equipment maintenance, and other facility processes [12]. Importantly, water withdrawal should be distinguished from water consumption. Withdrawal represents water removed from a source, whereas consumption describes the portion not immediately returned because of evaporation or other losses [13]. This distinction is essential because facilities can withdraw substantial volumes while consuming different proportions depending on cooling architecture, water-reuse practices, operating conditions, and local climate [15].

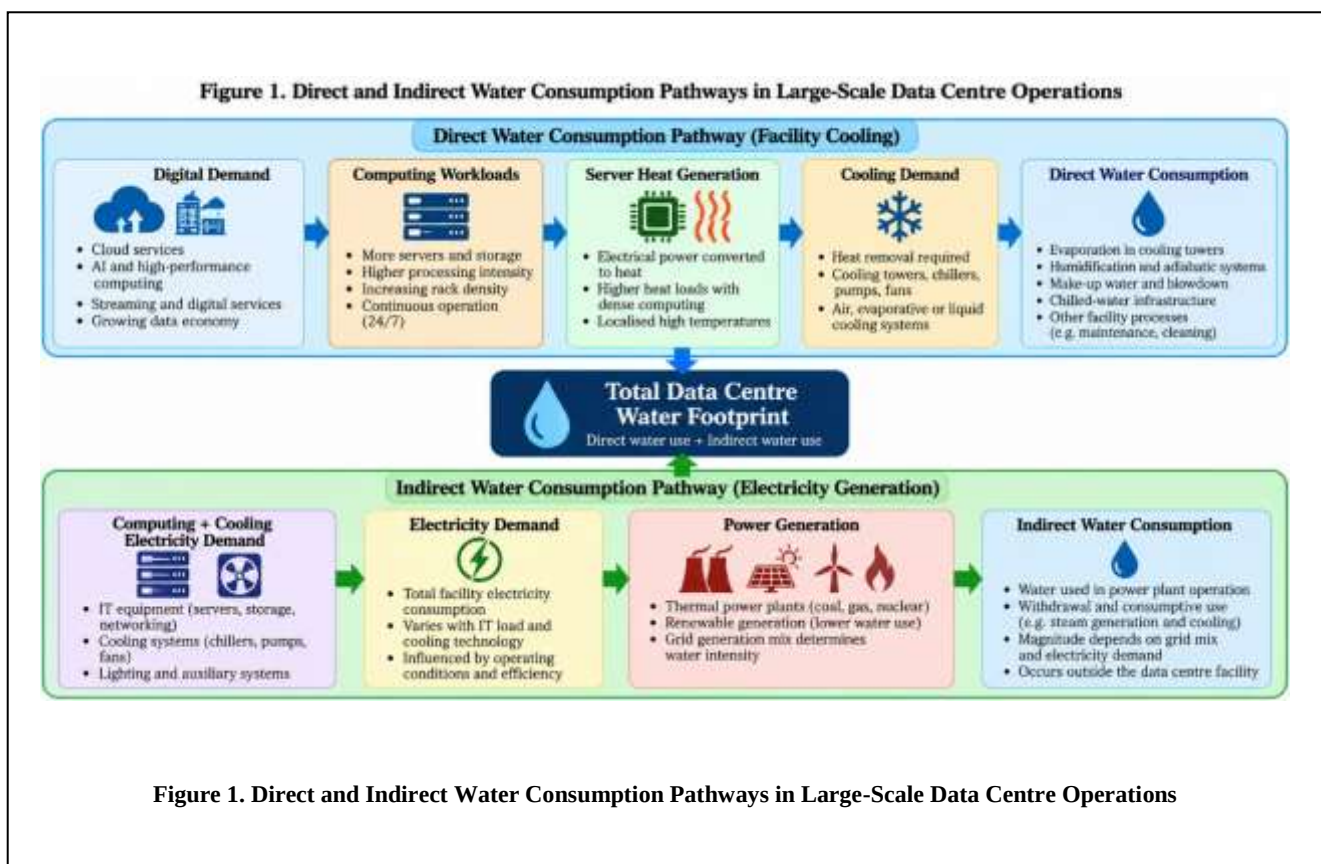


Figure 1. Direct and Indirect Water Consumption Pathways in Large-Scale Data Centre Operations

2. WATER CONSUMPTION PATHWAYS IN DATA CENTRE OPERATIONS

2.1 Direct Water Consumption for Cooling

Direct water consumption in data centres is primarily associated with thermal-management systems that remove heat generated by servers and supporting equipment [6]. Cooling towers reject heat through evaporation and therefore require continuous make-up water to replace evaporative losses, drift, and water discharged during blowdown to control dissolved solids [8]. Evaporative and adiabatic cooling systems similarly use the latent heat of water evaporation to reduce air temperature, potentially lowering cooling

2.2 Indirect Water Footprint of Electricity Consumption

The water footprint of a data centre extends beyond water physically delivered to the facility because electricity production can itself require substantial water resources [7]. Thermal power plants may withdraw water for steam-cycle processes and condenser cooling, while consumptive losses can occur through evaporation within cooling systems [10]. Consequently, electricity used by servers, storage systems, networking equipment, chillers, pumps, fans, and auxiliary infrastructure can generate an indirect water footprint outside the data centre boundary [14]. Its magnitude depends strongly on total electricity consumption and the generation technologies supplying the relevant grid [8]. A grid dominated

by water-intensive thermal generation can therefore associate data centre electricity demand with greater indirect water requirements than a generation mix relying more extensively on comparatively low-water renewable resources [11]. This relationship also creates potential trade-offs between direct and indirect water consumption. For example, replacing water-intensive evaporative cooling with electrically intensive mechanical cooling may reduce on-site water consumption while increasing electricity demand and its associated upstream water footprint [12]. Comprehensive assessment should therefore evaluate facility cooling and electricity sourcing as interconnected components of total operational water demand [15].

2.3 Measuring Data Centre Water Performance

Water Usage Effectiveness (WUE) provides a standardized basis for relating facility water consumption to the energy consumed by IT equipment, helping operators compare water performance across operating periods or facilities [8]. However, WUE alone cannot describe the complete water implications of large-scale data centre development [11]. Total annual water consumption remains necessary because an improving efficiency ratio can coexist with increasing absolute consumption when computing capacity expands rapidly [14]. Complementary indicators can include water consumption per unit of computational workload, enabling water demand to be associated more directly with useful digital output [10]. Freshwater dependency can distinguish potable or freshwater withdrawals from reclaimed, recycled, or alternative water supplies, while water-stress-weighted consumption can provide greater environmental context by assigning greater significance to consumption occurring within water-constrained regions [13]. These indicators should be interpreted alongside cooling architecture, climate, workload intensity, and electricity-generation characteristics [15]. Combining absolute and normalized measures consequently prevents apparent efficiency improvements from obscuring resource growth and provides a more robust basis for evaluating operational performance, regional water pressure, and long-term data centre sustainability [12].

3. COOLING TECHNOLOGIES AND THERMAL MANAGEMENT EFFICIENCY

3.1 Air-Based and Conventional Mechanical Cooling

Air-based cooling remains a widely established approach for maintaining acceptable thermal conditions within conventional data centres [13]. Computer-room air-conditioning and air-handling systems circulate conditioned air through server spaces, typically using raised floors, ducts, fans, and hot- or cold-aisle arrangements to transfer heat from IT equipment [14]. Mechanical refrigeration may subsequently remove this heat through compressor-based systems, increasing facility electricity consumption as cooling demand rises [16]. Chilled-water systems transfer heat through water loops connecting computer-room equipment

with chillers and external heat-rejection infrastructure, providing reliable cooling for larger facilities [18]. Where cooling towers are used for heat rejection, however, water consumption becomes an additional operational requirement [20]. Economizers can reduce mechanical cooling requirements by exploiting suitable outdoor air or low external temperatures for free cooling during favorable climatic conditions [17]. Their effectiveness therefore depends strongly on ambient temperature, humidity, air quality, and geographical location [15]. Although conventional air systems are mature and operationally familiar, their effectiveness becomes increasingly constrained as rack power density increases [19]. Higher airflow requirements, fan energy, localized hot spots, and heat-transfer limitations can make purely air-based architectures less suitable for increasingly dense AI and high-performance computing environments.

3.2 Evaporative and Water-Based Cooling Systems

Evaporative cooling exploits the latent heat associated with water evaporation to reduce air temperature and can substantially decrease reliance on energy-intensive mechanical refrigeration under suitable environmental conditions [14]. In direct evaporative systems, water evaporates into the supply-air stream, simultaneously reducing air temperature and increasing humidity [17]. Indirect evaporative configurations separate the evaporative process from the data-centre air stream through a heat exchanger, enabling cooling benefits while limiting direct moisture introduction into IT environments [18]. Cooling towers similarly reject heat by bringing circulating water into thermal contact with ambient air, causing a portion of the water to evaporate and remove heat from the remaining flow [20]. These approaches can improve cooling-energy efficiency and reduce compressor electricity requirements, particularly in climates with favorable wet-bulb conditions [15]. Their environmental advantage, however, can be accompanied by increased dependence on local water resources [13]. Evaporation represents consumptive water loss, while blowdown is necessary to control accumulating dissolved minerals and contaminants [16]. Water quality therefore affects scaling, corrosion, biological growth, treatment requirements, and achievable cycles of concentration [19]. Performance is also climatically sensitive: hot and humid conditions can reduce evaporative cooling effectiveness precisely when thermal loads are elevated [14]. Consequently, lower cooling electricity consumption must be evaluated against freshwater availability, treatment requirements, seasonal conditions, and regional water scarcity.

3.3 Liquid and Immersion Cooling Technologies

Increasing processor and rack densities are accelerating interest in liquid-based cooling because liquids can transfer heat more effectively than air and can remove heat closer to its source [17]. Direct-to-chip systems circulate coolant through cold plates attached to high-heat components such as CPUs, GPUs, and accelerators, reducing dependence on high-

volume airflow while supporting dense computing configurations [18]. Rear-door heat exchangers provide an intermediate architecture in which liquid-cooled heat exchangers mounted behind server racks capture heat from exhaust air before it enters the wider room environment [13]. Immersion cooling moves heat removal still closer to electronic components by submerging compatible hardware in electrically non-conductive fluids [19]. Single-phase systems maintain coolant in liquid form and transfer absorbed heat through circulation and external heat exchangers, whereas two-phase systems use fluid boiling and condensation to exploit phase-change heat transfer [20]. These technologies are particularly relevant to AI training and high-performance computing because conventional air cooling becomes progressively difficult as equipment-level heat flux and rack density increase [14]. Closed-loop liquid configurations can also reduce direct dependence on continuously supplied cooling water where heat is rejected through dry or hybrid external systems [15]. However, water savings depend on the complete heat-rejection architecture rather than the internal coolant loop alone [16]. Infrastructure retrofits, fluid compatibility, leak management, maintenance procedures, capital costs, and heat-reuse integration must therefore be considered when evaluating liquid cooling as a scalable sustainability strategy [17].

Table 1. Comparative Characteristics of Major Data Centre Cooling Technologies

Cooling Technology	Water Requirement	Energy Requirement	Cooling Capacity	Major Advantage	Principal Limitation
Air cooling	Low–moderate	Moderate–high	Moderate	Established technology	High-density limitations
Chilled water	Moderate–high	Moderate	High	Reliable cooling	Water and energy demand
Evaporative cooling	High	Relatively low	High	Energy efficiency	Water consumption
Direct-to-chip	Low/closed-loop dependent	Low–moderate	Very high	High heat removal	Infrastructure conversion
Immersion cooling	Low direct water dependence	Potentially low	Very high	Dense computing support	Deployment complexity

4. THE ENERGY–WATER NEXUS OF DATA CENTRE COOLING

4.1 Cooling Efficiency and Electricity Consumption

Cooling-system selection directly influences data centre electricity demand because thermal-management equipment constitutes a major component of non-IT energy consumption [17]. As server power density increases, greater quantities of heat must be transferred from processors and subsequently rejected from the facility, increasing the importance of efficient cooling architectures [20]. Conventional mechanical systems consume electricity through chillers, compressors, pumps, fans, and air-handling equipment, whereas economizers can reduce these auxiliary requirements when ambient conditions permit [18]. Cooling efficiency consequently affects Power Usage Effectiveness (PUE), since reductions in cooling electricity decrease total facility energy relative to IT-equipment energy [21]. However, cooling performance is influenced by climate, server utilization, rack density, temperature setpoints, airflow management, and heat-rejection configuration [23]. Hot or humid ambient conditions can increase mechanical cooling requirements or reduce opportunities for economization [22]. Conversely, effective containment, variable-speed equipment, liquid cooling, and intelligent thermal control can reduce auxiliary energy requirements [24]. Cooling efficiency should therefore be evaluated dynamically rather than as a fixed property of a particular cooling technology [19].

4.2 Water–Energy Trade-offs Across Cooling Strategies

Cooling strategies frequently create trade-offs between water conservation and electricity efficiency because the processes that minimize one resource do not necessarily minimize the other [18]. Evaporative cooling illustrates this interaction clearly: evaporation can provide efficient heat rejection with comparatively low mechanical-energy requirements, thereby reducing compressor operation and improving facility PUE [20]. The corresponding disadvantage is consumptive water loss, which can increase WUE and create sustainability concerns where freshwater supplies are constrained [23]. Conversely, air-cooled chillers and dry heat-rejection systems can substantially reduce direct water consumption but may require greater fan and compressor electricity, particularly during high ambient temperatures [21]. Hybrid cooling architectures attempt to balance these objectives by shifting between wet and dry operating modes according to weather conditions, water availability, and thermal requirements [17]. These relationships demonstrate why PUE and WUE should not be interpreted independently [24]. A facility achieving lower PUE through water-intensive evaporative cooling may simultaneously worsen its direct water footprint, while lower WUE achieved through dry cooling may increase electricity consumption [22]. Integrated assessment should therefore consider absolute energy and water consumption alongside both efficiency ratios, allowing operators to identify whether resource savings in one domain are producing unintended burdens in another [19].

4.3 Carbon Implications of Cooling Decisions

Cooling decisions also influence greenhouse-gas emissions because changes in cooling electricity requirements alter the quantity of grid electricity consumed by the facility [20]. The carbon consequence depends not only on additional kilowatt-hours but also on the carbon intensity of electricity available when cooling demand occurs [21]. A water-saving transition from evaporative heat rejection to electrically intensive mechanical or dry cooling may therefore reduce direct freshwater consumption while increasing emissions if the additional electricity is supplied predominantly by fossil-fuel generation [24]. Conversely, the carbon penalty may be substantially lower where electricity is supplied by renewable or other low-carbon resources [23]. Climatic conditions can further influence this relationship because periods of extreme heat may simultaneously increase cooling electricity requirements and stress electricity systems [17]. Sustainability assessment should consequently connect cooling technology, WUE, PUE, electricity consumption, water scarcity, and grid carbon intensity rather than optimizing any indicator separately [22]. Such integrated evaluation helps prevent interventions that improve facility water performance while unintentionally transferring environmental impacts from regional water resources to the electricity system and

associated atmospheric emissions [18].

5. WATER SCARCITY, LOCATION, AND OPERATIONAL RISK

5.1 Geographic and Climatic Drivers of Water Demand

Data centre water requirements are strongly influenced by geographic and climatic conditions because ambient temperature and humidity determine both cooling intensity and the effectiveness of available heat-rejection technologies [23]. Higher temperatures increase thermal-management requirements and can raise water consumption in evaporative systems or electricity consumption in mechanical cooling configurations [26]. Humidity is particularly important because elevated wet-bulb temperatures reduce the effectiveness of evaporative cooling and economization [24]. Seasonal variability further changes the balance between cooling demand and water availability, potentially producing maximum resource requirements during hot, dry periods when local supplies are already constrained [28]. Drought conditions can intensify these pressures by reducing surface-water availability, groundwater recharge, and permissible withdrawals [29]. Local hydrology—including watershed characteristics, aquifer conditions, recharge rates, and competing abstractions—therefore determines whether facility water demand is environmentally sustainable [27].

Figure 2. Energy–Water–Cooling Sustainability Nexus in Data Centre Operations

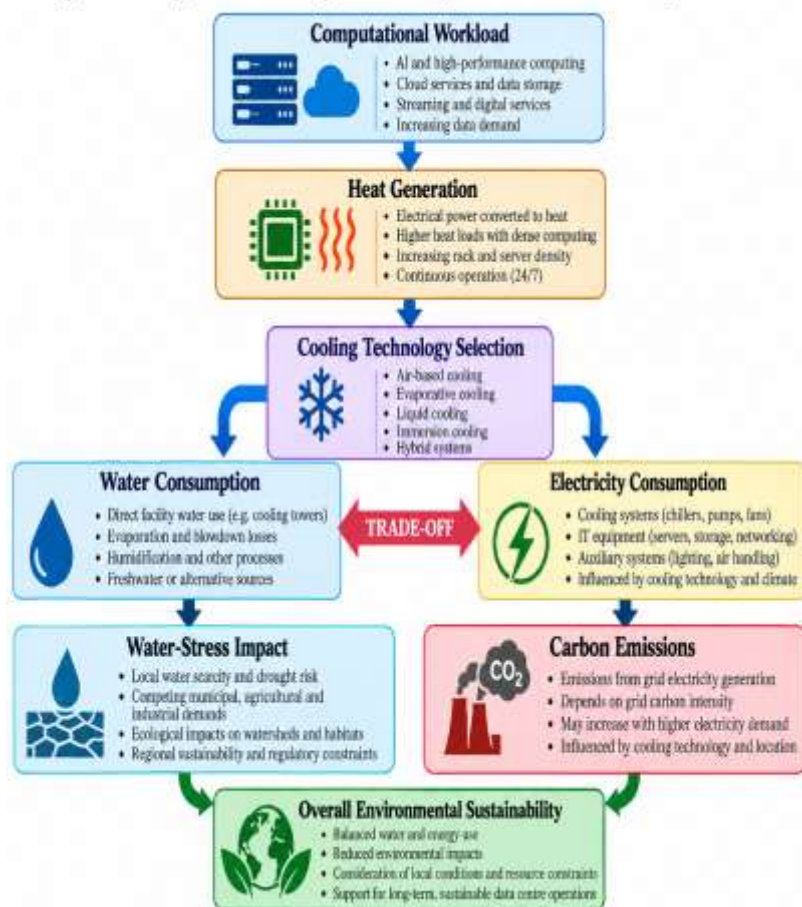


Figure 2. Energy–Water–Cooling Sustainability Nexus in Data Centre Operations

Consequently, cooling performance cannot be evaluated independently of location: identical facilities may create substantially different water impacts depending on climate, seasonal availability, hydrological conditions, and the vulnerability of surrounding water resources [30].

5.2 Data Centre Growth in Water-Stressed Regions

Large data centres can become particularly consequential when developed within regions already experiencing water stress because facility demand enters an existing system of competing resource requirements [24]. Municipal users require dependable supplies for domestic consumption and public services, while agriculture, manufacturing, energy production, and other industries may simultaneously depend on the same watershed [26]. Ecological requirements further constrain available abstraction because rivers, wetlands, groundwater systems, and aquatic habitats require sufficient water quantity and quality to maintain environmental functions [29]. Rapid development of multiple facilities can therefore create cumulative pressures that may not be apparent when projects are evaluated individually [28]. Watershed-level assessment provides a stronger sustainability perspective by comparing projected facility consumption with local availability, seasonal variability, existing withdrawals, ecological requirements, and future demand [30]. Such assessment should also distinguish freshwater consumption from reclaimed or alternative supplies [27]. Strategic siting and water-resource planning can consequently reduce competition for scarce freshwater while preventing operational efficiency improvements from masking increasing absolute pressure on vulnerable regional water systems [25].

5.3 Climate Change and Long-Term Water Security

Climate change introduces additional uncertainty into long-term data centre water management because cooling infrastructure may operate under environmental conditions different from those assumed during facility design [26]. Increasing average temperatures and more frequent extreme-heat events can raise cooling loads while simultaneously reducing the performance of some economizer and heat-rejection strategies [28]. More persistent or severe droughts can constrain water availability, increase competition among users, and potentially expose water-dependent cooling systems to operational restrictions [29]. Changes in precipitation timing and intensity may further alter reservoir storage, river flows, groundwater recharge, and seasonal water reliability [27]. These interacting pressures make historical climatic averages insufficient as the sole basis for long-lived infrastructure planning [30]. Facility resilience therefore requires consideration of future temperature ranges, drought scenarios, water-supply uncertainty, and potential regulatory constraints when selecting sites and cooling architectures [23]. Adaptive approaches including diversified water sources, lower-water cooling technologies, reuse systems, and flexible operating strategies can reduce exposure to changing conditions and strengthen long-term continuity of digital

services under increasingly uncertain regional water-resource conditions [25].

6. WATER CONSERVATION AND COOLING OPTIMIZATION STRATEGIES

6.1 Alternative and Non-Potable Water Sources

Reducing dependence on freshwater requires diversification of the water sources used for data centre cooling [27]. Reclaimed municipal wastewater can substitute for potable supplies in cooling towers and other suitable heat-rejection processes when appropriately treated to meet operational water-quality requirements [29]. Treated industrial wastewater can provide another local source where compatible industrial facilities and distribution infrastructure are available [30]. Rainwater harvesting may supplement cooling supplies in locations with suitable precipitation patterns, collection areas, and storage capacity, although seasonal variability limits its reliability as a primary source [28]. Alternative sources can therefore reduce competition with municipal and ecological freshwater requirements while improving facility resilience during water shortages [31]. Their suitability nevertheless depends on treatment requirements, salinity, mineral concentrations, microbial quality, infrastructure availability, regulatory conditions, and transportation distances [32]. Water-source selection should consequently consider both quantity and quality rather than simply replacing freshwater volumes, ensuring that treatment energy, chemical requirements, costs, and environmental consequences do not undermine overall sustainability benefits [33].

6.2 Closed-Loop Cooling and Water Reuse

Closed-loop cooling can reduce water requirements by continuously recirculating coolant rather than relying on repeated withdrawal and discharge [28]. In liquid-cooled systems, heat-transfer fluids circulate between computing equipment and heat exchangers, allowing recovered coolant to be reused while limiting direct evaporative losses [30]. Recirculating chilled-water systems similarly conserve water when appropriately integrated with low-water or dry external heat rejection [32]. Within cooling towers, optimized cycles of concentration can reduce blowdown volumes by allowing water to circulate more times before discharge [29]. Effective treatment remains necessary to control scaling, corrosion, microbial growth, and contaminant accumulation that could otherwise reduce heat-transfer performance or equipment reliability [31]. Leak detection, automated metering, pressure monitoring, and preventive maintenance can further minimize unintended losses [27]. Recovery and treatment technologies may additionally permit selected wastewater streams to re-enter cooling processes. However, closed-loop operation does not eliminate water impacts automatically; overall performance remains dependent on heat-rejection design, water quality, treatment requirements, and local operating conditions [33].

6.3 Intelligent Cooling and Operational Optimization

Digital monitoring and intelligent control can reduce unnecessary cooling by aligning thermal-management output more closely with real-time computing conditions [29]. Distributed sensors can continuously measure server inlet temperatures, humidity, pressure, airflow, coolant temperatures, equipment utilization, and localized thermal gradients [31]. AI-enabled control systems can process these data to dynamically adjust chillers, pumps, fans, cooling towers, and temperature setpoints according to actual heat loads rather than conservative fixed operating conditions [30]. Workload-aware cooling can further coordinate computational activity with thermal capacity, reducing localized hot spots and avoiding excessive cooling of lightly utilized equipment [28]. Predictive maintenance algorithms can identify deteriorating pumps, blocked filters, abnormal temperatures, leakage, or declining heat-transfer performance before failures increase resource consumption [32]. Real-time environmental optimization can also incorporate outdoor temperature, humidity, electricity conditions, and water availability when selecting operating modes [27]. Intelligent cooling therefore improves sustainability by treating thermal management as an adaptive process capable of jointly reducing avoidable electricity and water consumption [33].

6.4 Heat Recovery and Circular Resource Management

Data centres continuously convert electricity into heat, creating opportunities to recover thermal energy rather than treating it solely as a waste product requiring removal [30]. Captured server heat can potentially support district-heating networks, nearby buildings, industrial processes, greenhouses, or other applications where temperature and demand characteristics are compatible [32]. Liquid cooling can strengthen heat-recovery opportunities by capturing heat at higher coolant temperatures and closer to computing components [29]. Practical effectiveness nevertheless depends on heat quality, seasonal demand, distance to users, distribution infrastructure, and the energy required for heat upgrading or transport [31]. Heat recovery should therefore be integrated with water reuse, efficient cooling, and alternative-water sourcing within broader circular-resource management [28]. Such integration shifts sustainability from isolated consumption reduction toward productive reuse of energy and water flows [33]. Data centres can consequently become components of interconnected resource systems rather than facilities that independently consume electricity and water while rejecting waste heat [27].

Table 2. Water Conservation and Cooling-Efficiency Strategies for Sustainable Data Centres

Strategy	Primary Objective	Water Benefit	Energy Implication	Key Constraint
Reclaim	Reduce freshwater	High	Context	Treatment/infrastructure

Strategy	Primary Objective	Water Benefit	Energy Implication	Key Constraint
Reclaimed water	Reuse		dependent	Availability
Closed-loop cooling	Minimize losses	High	Technology dependent	Capital requirements
Liquid cooling	Improve heat removal	Potentially high	Potential reduction	Retrofitting
AI cooling control	Optimize operation	Moderate	Reduced consumption	Data/control requirements
Free cooling	Reduce mechanical cooling	Variable	High energy benefit	Climate dependent
Heat recovery	Recover waste energy	Indirect	Improves system efficiency	Heat-demand proximity

7. INTEGRATED FRAMEWORK FOR WATER-SUSTAINABLE DATA CENTRE OPERATIONS

7.1 Framework Architecture and Sustainability Dimensions

An integrated framework for data centre water sustainability should connect five interacting dimensions: computational demand, cooling performance, water availability, energy consumption, and environmental impact [32]. Computational demand establishes the underlying thermal load because workload intensity, server utilization, and equipment density determine heat generation requiring removal [34]. Cooling performance determines how effectively this heat is transferred and rejected while influencing both water and electricity requirements [36]. Water availability introduces geographical constraints, particularly where freshwater resources are seasonally limited or exposed to competing demands [38]. Energy consumption must be incorporated because water-conserving cooling technologies can alter facility electricity requirements and associated upstream resource impacts [37]. Environmental impact consequently emerges from interactions among absolute water consumption, local water stress, electricity use, carbon intensity, and infrastructure scale [39]. Rather than optimizing these dimensions independently, the framework treats them as interconnected variables whose relationships change according to facility characteristics and external conditions [40]. Sustainable cooling therefore requires balancing computational requirements with thermal efficiency, resource

availability, energy performance, and location-specific environmental consequences [35].

7.2 Integrated Water and Cooling Performance Indicators

Performance assessment should combine efficiency ratios with absolute and location-sensitive resource indicators [32]. WUE quantifies facility water consumption relative to IT energy use, while PUE indicates the relationship between total facility energy and IT-equipment energy [34]. Neither metric alone reveals the complete environmental burden of expanding facilities [37]. Absolute annual water consumption is therefore necessary to identify whether overall resource demand is increasing despite efficiency improvements [38]. Freshwater dependency distinguishes reliance on potable or freshwater resources from reclaimed and alternative supplies, while water-stress exposure places consumption within its regional scarcity context [39]. Cooling-system efficiency provides information about the energy required for heat removal, and water reuse rate indicates the proportion of water recirculated or recovered [36]. Workload-normalized indicators can further relate water and electricity consumption to useful computational activity [40]. Combining these measures enables simultaneous assessment of resource efficiency, operational scale, local environmental pressure, and computing productivity rather than allowing improvement in one indicator to obscure deterioration elsewhere [33].

7.3 Technology Selection and Location-Sensitive Decision-Making

Cooling technologies should not be arranged into a universal sustainability hierarchy because their performance depends strongly on local environmental and operational conditions [34]. Air-based or dry cooling may reduce direct water dependence but can require greater electricity under high ambient temperatures [37]. Evaporative cooling may provide efficient heat rejection in suitable climates while creating substantial water requirements that become problematic in water-stressed locations [38]. Liquid and immersion technologies can support increasingly dense computing environments, although their overall water performance depends on external heat-rejection architecture [36]. Technology selection should therefore evaluate temperature, humidity, seasonal variation, water availability, grid characteristics, server density, and facility scale collectively [39]. Future climate conditions should also be incorporated because increasing temperatures, drought risk, and changing water availability may alter the long-term suitability of cooling configurations [40]. Location-sensitive decision-making consequently requires lifecycle comparison of alternative technologies under present and projected operating conditions, ensuring that thermal performance is balanced against water scarcity, electricity consumption, carbon implications, reliability, and infrastructure requirements [35].

7.4 Operational Optimization and Sustainability Governance

Sustainable water management requires governance mechanisms that translate technical performance into continuous operational improvement [32]. Facility monitoring should track water withdrawals, consumptive use, cooling performance, electricity demand, reuse rates, and relevant environmental conditions [36]. Transparent disclosure can establish accountability while enabling operators, regulators, communities, and other stakeholders to understand absolute resource requirements and efficiency trends [38]. Quantifiable water targets should incorporate freshwater reduction, reuse, and exposure to local scarcity rather than focusing exclusively on WUE [39]. Adaptive cooling controls can respond dynamically to workload, weather, water availability, and energy conditions [37]. Periodic resource-risk assessments should additionally evaluate drought, climate change, infrastructure constraints, and competing watershed demands [40]. Integrating these processes into management systems creates a continuous cycle of measurement, risk identification, optimization, disclosure, and reassessment that aligns operational performance with long-term sustainability objectives [34].

Figure 3. Integrated Water and Cooling Sustainability Framework for Large-Scale Data Centres

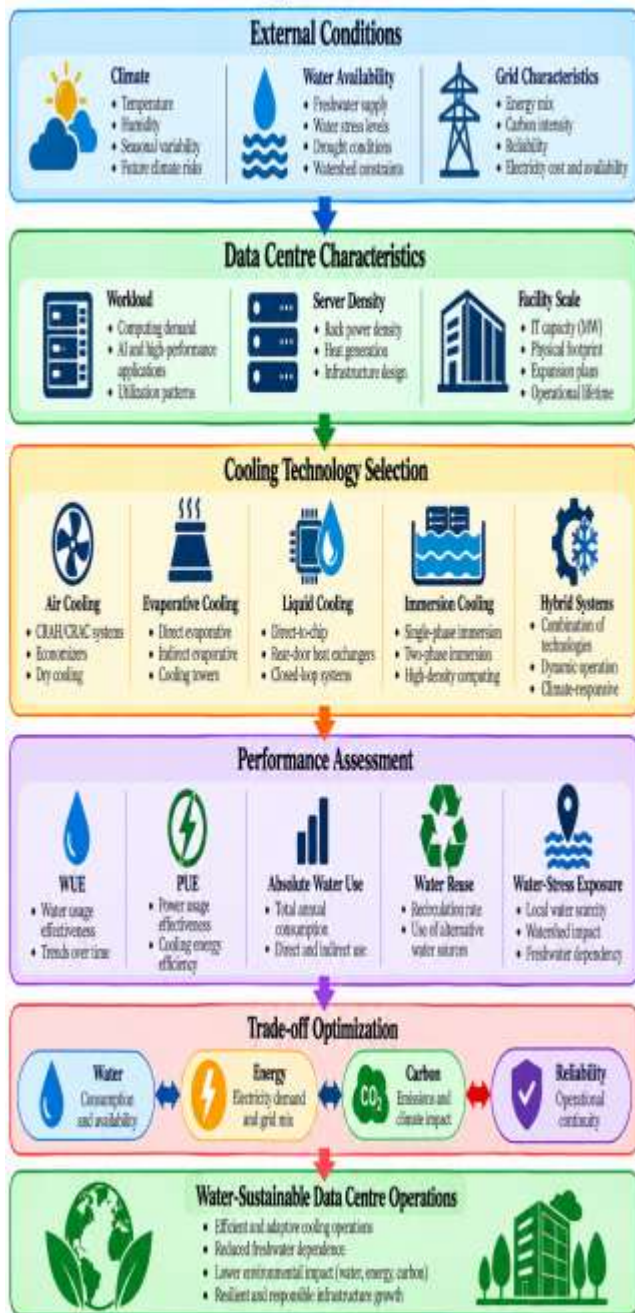


Figure 3. Integrated Water and Cooling Sustainability Framework for Large-Scale Data Centres

8. FUTURE DIRECTIONS AND SUSTAINABILITY PRIORITIES

8.1 Emerging Cooling and Water-Management Technologies

Future cooling development will increasingly respond to the high thermal densities associated with AI accelerators and other computationally intensive hardware [34]. Advanced direct-to-chip liquid cooling can remove heat closer to processors, while immersion systems provide opportunities to

support very high-density computing with reduced dependence on conventional airflow [36]. Hybrid architectures can dynamically combine wet and dry cooling according to climatic conditions, water availability, and thermal demand [38]. Smart controls and digital twins can further optimize cooling by predicting thermal behavior and evaluating operational adjustments before implementation [37]. Water-recovery technologies can increase recirculation and reduce freshwater requirements, while advanced treatment may expand opportunities for reclaimed-water utilization [39]. Heat-reuse systems provide an additional pathway for recovering server-generated thermal energy for surrounding applications [40]. Collectively, these technologies could shift thermal management from resource-intensive heat rejection toward adaptive, integrated management of water, energy, and recoverable heat [32].

8.2 Reporting, Governance, and Research Priorities

Future sustainability governance should strengthen transparency regarding where, when, and how data centres consume water [32]. Standardized WUE methodologies would improve comparability, but reporting should also disclose absolute consumption, freshwater dependency, alternative-water use, and relevant watershed conditions [38]. Watershed-sensitive planning can help prevent apparently efficient facilities from imposing disproportionate pressure on locally scarce resources [39]. Climate-risk assessment should similarly examine future heat, drought, precipitation, and water-supply scenarios when evaluating long-lived infrastructure [37]. Improved facility-level disclosure would enable regulators and communities to evaluate cumulative resource implications as regional data centre clusters expand [40]. Research should additionally connect specific computational workloads with associated cooling, water, electricity, and carbon requirements rather than relying predominantly on aggregate facility indicators [36]. Such integrated measurement would clarify the resource implications of emerging AI workloads and support more rigorous comparison of cooling technologies, operational strategies, siting decisions, and long-term sustainability outcomes [35].

9. CONCLUSION

9.1 Synthesis of Water and Cooling Challenges

Rapid data centre growth is increasing the resource requirements associated with computing infrastructure. Expanding server capacity and rising processing densities generate greater heat loads, creating corresponding demand for effective cooling. Depending on the technology employed, heat removal can require substantial freshwater consumption or additional electricity, which itself carries an indirect water footprint through power generation. These relationships create an interconnected water–energy challenge in which reducing one resource requirement can increase another. Environmental consequences are particularly significant where expanding facilities coincide with drought, limited freshwater availability, competing water demands, or increasing climatic

pressures. Sustainable cooling therefore requires assessment beyond individual facility-efficiency indicators.

9.2 Pathway Toward Water-Sustainable Data Centre Growth

Water-sustainable data centre growth requires combining efficient cooling with alternative water supplies, closed-loop systems, advanced liquid cooling, intelligent thermal controls, and water-recovery technologies. Infrastructure planning should additionally consider local climate, watershed conditions, electricity characteristics, computing density, and future water-security risks when selecting locations and cooling architectures. Transparent reporting of water withdrawals, consumption, reuse, and freshwater dependency can strengthen accountability and support continuous improvement. Critically, declining WUE should not automatically be interpreted as declining environmental impact when infrastructure expansion causes absolute water consumption to increase. Long-term sustainability therefore requires integrated energy–water decision-making that balances efficiency, resource availability, operational reliability, and environmental constraints.

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