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Impact of Water Consumption in Data Centers: An Analysis of Cooling Techniques and Sustainable Optimization Strategies

A Review of Water Use Effectiveness, Cooling Technologies, and Practical Conservation Measures

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Abstract - *Data centers provide the computing infrastructure behind cloud services, online platforms, enterprise systems, and artificial intelligence. Their servers release substantial heat, which must be removed to maintain reliable operation. Depending on the cooling design, heat rejection can require significant quantities of water, particularly in systems that rely on evaporation. This paper reviews the relationship between data-center water consumption, cooling techniques, and sustainable optimization strategies. It distinguishes direct on-site water use from indirect water use associated with electricity generation and introduces Water Usage Effectiveness (WUE) as a useful but incomplete performance metric. The review compares air cooling, evaporative cooling, free cooling, direct-to-chip liquid cooling, immersion cooling, and hybrid systems. Recent literature indicates that water use varies widely with server efficiency, utilization, climate, electricity supply, and heat-rejection design; therefore, no single cooling method is optimal for every site. The paper recommends combining transparent water accounting, climate-aware cooling selection, higher coolant temperatures where technically feasible, recycled or non-potable water where safe, leak detection, workload optimization, and continuous monitoring. As this manuscript is a literature-based review, it does not claim to present original experimental measurements or a new facility-level dataset. Its purpose is to synthesize reported evidence and outline a practical framework for reducing water intensity while maintaining energy efficiency and operational resilience.*

Keywords - Data centers, water consumption, cooling techniques, Water Usage Effectiveness (WUE), liquid cooling, sustainability, water conservation, AI infrastructure.

INTRODUCTION

Data centers house computing equipment that processes, stores, and transfers digital information. Demand for cloud computing, streaming, online transactions, and AI workloads has increased the importance of reliable, high-density computing infrastructure. Nearly all electricity used by IT equipment ultimately becomes heat, and this heat must be transferred away from processors and other components. Cooling is therefore essential for performance, equipment life, and service continuity.

Water enters the data-center sustainability discussion in two main ways. Direct water use occurs at the facility, for example when cooling towers evaporate water to reject heat. Indirect water use occurs beyond the site boundary, especially when water is consumed during electricity generation. These categories should not be confused: a facility that uses little water on site may still have an indirect water footprint associated with its power supply. The balance between water and electricity is also important because some evaporative systems can reduce cooling electricity while increasing direct water consumption.

The challenge is not simply to minimize water use at any cost. Operators must balance water availability, electricity demand, local climate, reliability, capital cost, and the thermal requirements of modern processors. This paper reviews cooling options and identifies

strategies that can reduce water use without treating water and energy as separate problems.

PROBLEM STATEMENT AND RESEARCH GAP

Data-center growth and higher rack power densities create pressure to improve cooling performance. Traditional reporting often emphasizes energy efficiency, especially Power Usage Effectiveness (PUE), while water impacts may receive less attention or be reported using inconsistent boundaries. Water Usage Effectiveness (WUE) provides a complementary metric, but it does not by itself describe absolute water consumption, local water scarcity, or indirect water use from electricity.

Recent research shows that water use per computing workload can vary substantially according to server

efficiency, utilization, electricity source, cooling system, climate, and infrastructure design [1]. This means that replacing one cooling technology with another is not automatically sufficient: the outcome depends on how the complete facility is configured and operated. The research gap addressed here is the need for a concise, integrated comparison of cooling methods and operational strategies that considers both water and energy trade-offs.

LITERATURE REVIEW

Lei et al. examined determinants of data-center water use at workload level and reported variations exceeding 10,000-fold across the modeled cases. Their analysis identified server efficiency, electricity-related water factors, utilization, cooling type, infrastructure efficiency, climate, inactive servers, and refresh cycles as important determinants [1]. This supports a system-wide approach rather than a single-technology solution.

Aili et al. studied radiative free cooling integrated with data-center cooling systems. Their modeled configurations showed that savings depend on the point at which free cooling is integrated: one configuration achieved average energy savings of about 20%, while another achieved average water savings of about 84% under the study's Singapore climate assumptions [2]. These values are specific to the modeled systems and should not be generalized to every facility.

Karimi et al. modeled energy and water use for cooling systems in hot-arid climates. Their work highlights that economizers and evaporative cooling can save energy and water during certain operating hours, while pre-cooling for air-cooled chillers may reduce electricity use but increase on-site water consumption [3]. The study illustrates the importance of hourly weather conditions and control strategies.

Guidance on sustainable procurement describes WUE as annual site water consumption divided by annual IT equipment energy, expressed in litres per kilowatt-hour [4]. It also emphasizes that water and energy metrics should be considered together. Taken together, these sources suggest that cooling performance must be evaluated using a clearly stated boundary, local climate data, and transparent assumptions.

RESEARCH QUESTIONS AND OBJECTIVES

This review addresses the following questions: (RQ1) Which cooling techniques are commonly used in data centers? (RQ2) How do these techniques differ in direct water use and energy implications? (RQ3) Which operational and infrastructure strategies can reduce water intensity? (RQ4) How should operators measure progress without overlooking indirect water use or local water stress?

The objectives are to explain the main pathways of data-center water consumption; compare conventional and emerging cooling methods; summarize WUE and its limitations; identify sustainable optimization measures; and propose a practical decision framework for operators and future researchers.

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RESEARCH METHODOLOGY

Research Design

A qualitative literature-review approach was used. The review draws on peer-reviewed journal articles and technical guidance identified through web research. Priority was given to sources that discuss data-center water use, cooling-system trade-offs, WUE, and sustainable cooling. This is not a systematic review with a registered protocol, nor does it include new laboratory testing or primary facility measurements.

Scope and Analysis

The analysis compares air cooling, evaporative cooling, free cooling, direct-to-chip liquid cooling, immersion cooling, and hybrid arrangements. Each method is considered in terms of direct water demand, electricity implications, climate dependence, deployment considerations, and operational risks. Published numerical results are reported with their study context rather than combined into a new pooled estimate.

Key Metric: Water Usage Effectiveness

WUE is commonly expressed as:

WUE = Annual site water consumption (litres) / Annual IT equipment energy (kWh)

A lower WUE indicates less site water consumed per unit of IT energy, but WUE should be reported alongside absolute annual water consumption, PUE, water source, and local water-stress context. WUE values can be misleading if different facilities use different reporting boundaries or if off-site electricity-related water use is excluded.

COOLING TECHNIQUES AND WATER IMPACT

Table I. Qualitative comparison of cooling approaches. Actual performance depends on system design, climate, and reporting boundary.

Technique	Water profile	Strengths and constraints
Air cooling	Often low direct water use when paired with dry heat rejection.	Mature and relatively simple; performance can be limited at high rack densities and hot ambient conditions.
Evaporative cooling	Uses water through evaporation and system blowdown.	Can reduce electricity for heat rejection; water demand varies with climate and operating set points.
Free cooling / economizers	Can reduce water use when outside air or ambient conditions allow non-evaporative heat rejection.	Climate-dependent; filters, humidity control, and temperature limits require attention.
Direct-to-chip liquid cooling	Coolant may circulate in a closed loop; facility water use depends on the heat-rejection plant.	Efficient heat transfer for dense processors; requires leak management and compatible hardware.
Immersion cooling	Can operate with closed-loop heat rejection and very low site water use in dry configurations.	High heat-transfer potential; fluid compatibility, maintenance, and deployment cost must be considered.
Hybrid systems	Water and energy use vary as dry, free, and evaporative modes are combined.	Flexible across seasons; controls must optimize the water-energy trade-off.

Air Cooling

Air cooling uses fans, heat sinks, and air-conditioning equipment to move heat away from IT hardware. In dry systems, it can require little direct water on site. However, fan and chiller electricity can be substantial, particularly when ambient conditions are hot or equipment density is high. Improving airflow management through containment, blanking panels, optimized fan control, and removal of hot-air recirculation can reduce cooling demand without introducing additional water consumption.

Evaporative Cooling

Evaporative systems reject heat by allowing a portion of water to evaporate. This can provide effective cooling and may lower electricity demand compared with some mechanically cooled alternatives. The trade-off is direct water consumption, together with blowdown and treatment needs. Their suitability depends on wet-bulb temperature, water availability, water quality, and operating policy. In water-stressed locations, their energy benefit must be weighed against local water impacts.

Free Cooling

Free cooling uses favorable outdoor conditions to reduce or avoid compressor-based cooling. Depending on design, it can use outside air, ambient water loops, or heat exchangers. It is most useful when the climate provides sufficient hours below the required cooling temperature. Free cooling is not universally water-free: some designs still rely on evaporative equipment during warmer periods. Weather-aware control and seasonal operation are therefore essential.

Direct Liquid and Immersion Cooling

Direct-to-chip systems circulate coolant near high-heat components, while immersion systems place hardware in a dielectric fluid. These methods can move heat more effectively than air alone and can support higher chip power densities. Their site water use depends on the facility heat-rejection system: a closed loop connected to dry coolers can reduce direct water consumption, while an evaporative heat-rejection plant may still consume water. Liquid cooling should therefore be evaluated as part of the full cooling chain, not as a guarantee of zero water use.

DATA ANALYSIS AND INTERPRETATION

The reviewed evidence supports three broad conclusions. First, water intensity is not determined by cooling technology alone. Server efficiency and utilization affect the amount of electricity and therefore heat needed for a given workload. Second, water and energy can move in opposite directions: evaporative cooling may lower electricity use while increasing on-site water consumption. Third, climate and heat-rejection design influence whether a facility can rely on dry or free cooling for part or all of the year [1]–[3].

The 2024 radiative free-cooling modeling study reported annual-average energy savings of around 20% for direct free cooling of data-hall return air and water savings of around 84% for a different configuration integrated before the chiller condenser, under its modeled Singapore conditions [2]. These figures are evidence that configuration matters, not universal savings guarantees. Similarly, hot-arid climate modeling shows that pre-cooling can save energy but increase site water use [3].

Consequently, a responsible evaluation should report absolute water use and WUE together, describe the cooling configuration, state the local climate and water source, and

disclose whether electricity-related water is included. Comparisons that omit these details may produce misleading rankings.

7.1 Quantitative Evidence Reported in the Reviewed Literature

The numerical evidence available in the reviewed sources is limited and comes from published modeling studies rather than a common facility dataset. Aili et al. [2] reported approximately 20% annual-average energy savings for direct free cooling of data-hall return air and approximately 84% annual-average water savings for a different configuration integrated before the chiller condenser, under modeled Singapore conditions. These results are presented separately because they refer to different system configurations and different outcome measures. They should not be interpreted as a direct comparison or as guaranteed savings for other data centers.

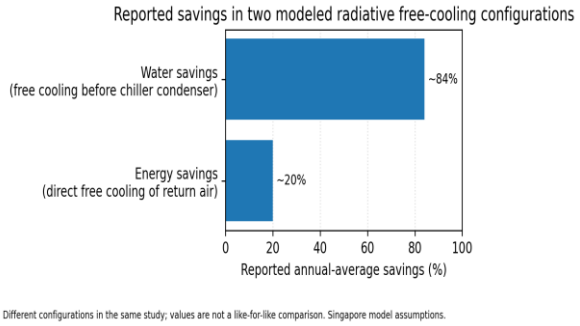


Fig. 1. Reported energy and water savings for two distinct modeled radiative free-cooling configurations [2].

Lei et al. [1] reported that modeled water use per computing workload varied by more than 10,000-fold across the cases examined. This wide spread indicates that workload-level water use is highly sensitive to the combined effects of server efficiency, utilization, electricity-related water factors, cooling design, climate, and infrastructure assumptions. The reported range is a measure of variation across modeled cases; it is not a probability distribution, an average, or a universal prediction.

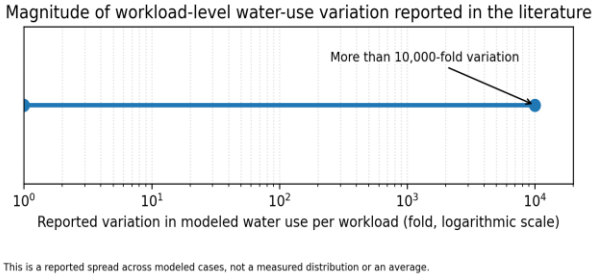


Fig. 2. More-than-10,000-fold variation in modeled workload-level water use reported by Lei et al. [1].

7.2 Review-Based Hypotheses / Propositions

Because this manuscript is a literature-based review and contains no original facility measurements or primary dataset, the following hypotheses are framed as propositions for future empirical validation. They are not reported as statistically tested or accepted findings in this review.

H1. Cooling architecture and direct water intensity

Facilities using non-evaporative heat rejection are expected to have lower direct site-water intensity than facilities relying mainly on evaporative heat rejection, when climate and IT workload are controlled.

Variables: direct site water use, WUE, cooling type. Suggested validation: compare facilities with matched climate and workload using regression or matched-group analysis.

H2. IT utilization and workload-normalized water use

Higher IT equipment utilization is expected to be associated with lower water use per unit of useful computing workload, when server efficiency and cooling configuration are considered.

Variables: utilization, water per workload unit, server efficiency. Suggested validation: correlation and multivariable regression using time-aligned facility and workload data.

H3. Climate as a moderator

The relationship between cooling configuration and water intensity is expected to vary by local climate and water availability.

Variables: cooling type, WUE, wet-bulb temperature, water-stress indicator. Suggested validation: interaction-term regression or stratified comparisons across climate and water-stress zones.

H4. Completeness of water-footprint reporting

Reporting WUE together with absolute site water use and electricity-related indirect water use is expected to provide a more complete footprint assessment than WUE alone.

Variables: WUE, absolute site water, indirect electricity-related water. Suggested validation: compare estimates and facility rankings under site-only and expanded system boundaries.

7.3 Statistical Analysis Plan for Future Primary Data

A future empirical study should collect facility-level observations across multiple seasons and climate zones. The dependent outcomes should include annual site water consumption and WUE (L/kWh), with indirect electricity-related water reported separately where reliable grid-water factors are available. Explanatory variables should include cooling architecture, IT energy, workload or utilization, server efficiency, ambient wet-bulb temperature, water source, and local water-stress conditions. Descriptive statistics (mean, median, standard deviation, and range) should summarize each group. Multiple regression can test H1–H3, including climate-by-cooling interaction terms for H3. H4 can be evaluated by comparing site-only and expanded water-footprint estimates and examining whether facility rankings change. Report effect sizes, 95% confidence intervals, model diagnostics, and p-values; use a pre-specified significance threshold (for example, 0.05) and account for multiple comparisons where necessary. No p-values, sample sizes, or inferential results are supplied here because the current review has no primary dataset.

SUSTAINABLE OPTIMIZATION STRATEGIES

Cooling-System Design

Select cooling architecture using local hourly climate data and water-stress information. Where technically feasible, increase coolant supply temperatures within equipment limits, improve heat-exchanger performance, use dry coolers or free cooling during favorable conditions, and adopt hybrid controls that switch operating modes according to the relative cost of water and energy. Avoid assuming that the lowest PUE automatically represents the most sustainable option.

Water Reuse and Quality Management

Where local regulations and treatment systems permit, consider reclaimed or non-potable water for suitable cooling applications. Track water quality, scaling, corrosion, biological growth, and blowdown requirements. Reuse should be assessed against local supply reliability and treatment impacts; it is not appropriate to assume that every alternative water source is available or safe at every site.

Operational Optimization

Use sensors and building-management systems to monitor flow, temperature, pressure, cooling-tower cycles of concentration, leaks, and abnormal water demand. Tune set points seasonally and maintain equipment to prevent avoidable losses. Consolidate workloads where possible, reduce idle server capacity, and improve IT utilization so that less energy and heat are required per unit of useful computing. These measures align with the system-level determinants identified in recent research [1].

Measurement and Governance

Publish annual site water consumption, WUE, PUE, water source, cooling method, and reporting boundary. Where data are available, estimate indirect water use associated with electricity and explain the assumptions. Set targets that account for local water stress rather than relying only on a global intensity threshold. Independent verification and consistent measurement periods improve comparability across facilities.

RECOMMENDATIONS

For data-center operators, the priority should be a site-specific water-energy assessment before replacing cooling equipment. Facilities in water-stressed areas should evaluate dry heat rejection, closed-loop liquid cooling, reclaimed water, and seasonal controls. Facilities in cooler climates may benefit from free cooling, while high-density AI facilities should examine direct liquid or immersion approaches together with the downstream heat-rejection design.

For policymakers and industry bodies, consistent definitions and disclosure of WUE, absolute water consumption, and water source would improve transparency. Procurement criteria should reward both water and energy performance and should consider local watershed conditions. For researchers, future work should compare full-year measured performance across climates and cooling architectures, including the effect of electricity generation and the lifecycle impacts of coolants and infrastructure.

LIMITATIONS AND FUTURE SCOPE

This paper is a literature-based review and does not present original measurements, interviews, or a primary dataset. Published studies use different climates, system boundaries, operating assumptions, and modeling methods; their numerical results cannot be directly pooled without further harmonization. Some reported performance figures are model-specific and should not be interpreted as guaranteed savings for operational facilities.

Future research should collect transparent, time-resolved data from facilities in different climate zones; compare direct and indirect water footprints; test combined water-energy-carbon indicators; and examine the reliability, cost, and lifecycle implications of closed-loop liquid cooling, immersion fluids, radiative cooling, and reclaimed-water systems. Research focused on Indian data centers could also assess regional water stress, seasonal humidity and temperature, grid characteristics, and the availability of treated wastewater.

CONCLUSION

Water consumption is an increasingly important sustainability issue for data centers because cooling demand grows with computing activity and higher-density hardware. The review shows that no single cooling technique is best in every situation. Evaporative systems can reduce cooling electricity but consume water; dry and free-cooling systems can reduce site water use where climate and design allow; and liquid or immersion cooling can improve heat transfer but still depend on the facility's heat-rejection architecture.

The most effective strategy is an integrated one: improve server utilization and efficiency, select cooling technology for local climate and water availability, reuse suitable water where safe, optimize controls, detect leaks, and disclose WUE alongside absolute water use and energy metrics. WUE is useful for tracking water intensity, but it should not replace local water-risk analysis or transparent reporting of indirect water impacts. Future site-level measurements are needed to quantify achievable savings and validate the best combinations of technologies.

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