

Water Quality Dynamics under Climate Change: Challenges in the Carbon Footprint Reduction of Water Treatment

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Research

- Membrane innovations for carbon capture and water recovery
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Awards

- Women in Science Award (TDTU, Vietnam)
- Frontier Champion, Leader in Innovation Fellowship, Distinguished International Associate (Royal Academy Engineering, UK)
- Top Research Scientists Malaysia 2022
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- 2023 Gas Science and Engineering Distinguished Scientists (Elsevier)
- Excellent Contribution, ASEAN IVO, 2024 (NICT, Japan).
- 1st Prize in GIST Catalyst (US Department)
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Impacts of climate change on water treatment

- Climate change intensifies hydrological variability, increasing droughts, floods, and water insecurity.
- Over 2.2 billion people lack safely managed drinking water; 80% of wastewater is discharged untreated.
- Warming of +1.5 °C by 2030 accelerates glacier melt, sea-level rise, and shifts in rainfall, worsening scarcity.
- By 2050, up to 5 billion people may face limited safe water access due to salinization and contamination.
- Water quality is declining from salinity intrusion, acidification, turbidity, and rising DOM, nutrients, and BOD, leading to eutrophication and harmful algal blooms.
- Water treatment faces higher complexity and energy use, contributing to the water sector's carbon footprint and challenging net-zero goals.



Water quality changes under global warming



Climate-Driven Salinity Intrusion Trends

- Global warming intensifies evaporation, sea-level rise, and hydrological imbalance in coastal and deltaic regions.
- In the Bengal Delta, salinity increased by 1–100 $\mu\text{S}/\text{cm}$ per year, exceeding 300 $\mu\text{S}/\text{cm}$ per year in western estuaries.
- Maximum salinity rose by $100 \pm 28 \mu\text{S}/\text{cm}$ per year, equal to ~ 1 ppt increase over 23 years.
- Strongest increases occurred in low-lying southwestern regions, where high tides rose 6.4 ± 2.6 mm per year.
- Inland salinity intrusion advanced at $94 \pm 25 \mu\text{S}/\text{cm}$ per year, forming a west-to-east salinity gradient.
- Drivers include sea-level rise, reduced river discharge, and tidal amplification affecting freshwater and agriculture.

Table 1. Climate-Driven Salinity Intrusion & Groundwater/Soil Salinization

Study Focus	Location/System	Key Climate Drivers	Major Water Quality Impacts	References]
Long-term salinity trends	Bengal Delta	Sea-level rise, tidal amplification	Salinity ↑ 1–100 μS/cm/yr; intrusion 94 μS/cm/yr; tides ↑ 6.4 mm/yr	Feist et al., 2024 [4]
Groundwater salinization modeling	Volturno River Basin	Sea-level rise, recharge decline	Saline front 20–40 m/yr; 12% aquifer degradation	Gaiolini et al., 2024 [5]
Soil salinity & SOC projections	Yellow River Delta	SSP119 & SSP245 warming	Salinization 83–96%; SOC 13–18 Tg	Haonan et al., 2024 [6]

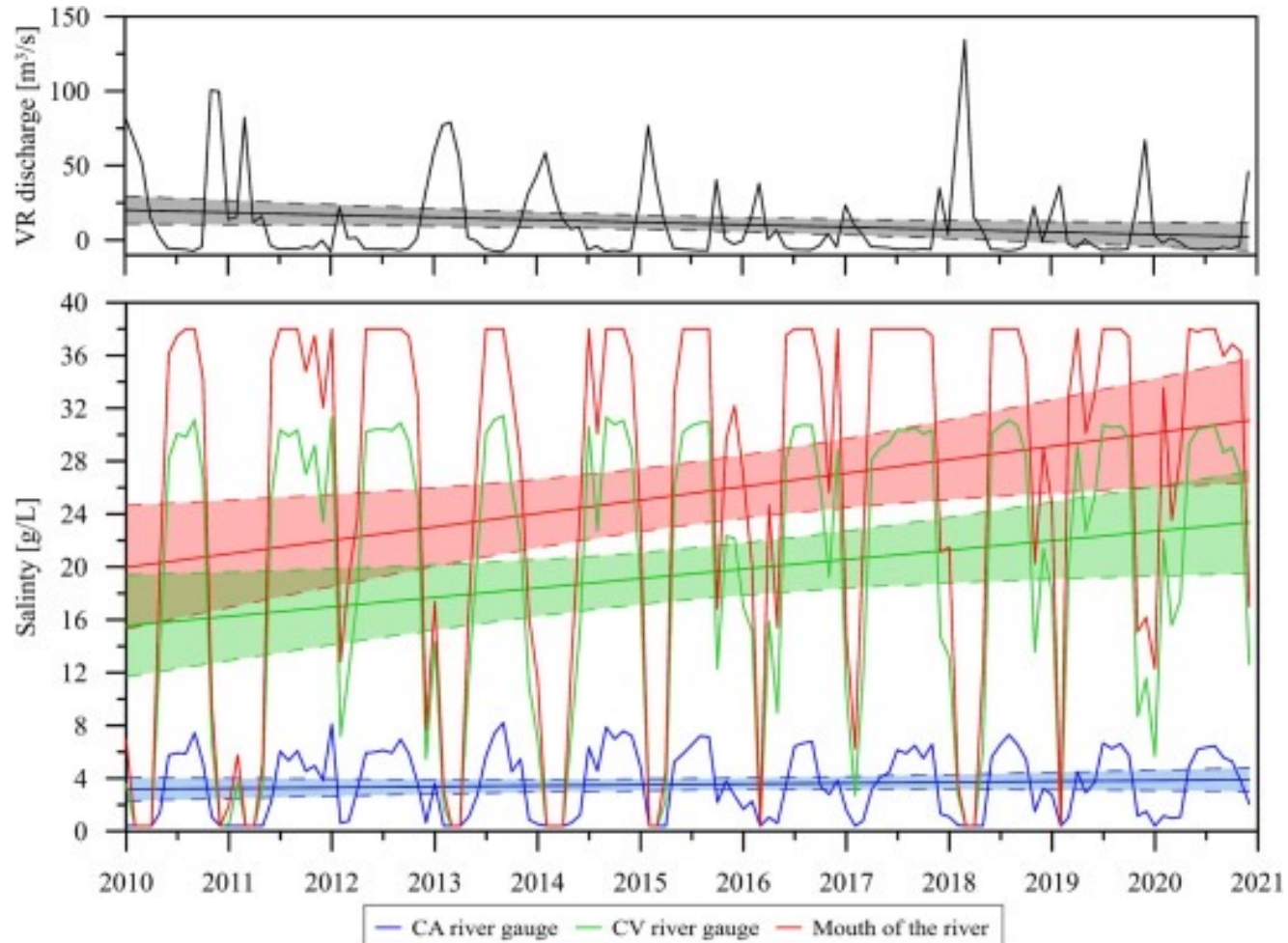


Fig. 1. (a) Volturno River (VR) discharge calculated at Canello Arnone (CA) river gauge and (b) salinity oscillation of CA river gauge, Castel Volturno (CV) river gauge, and mouth of the river within the main cross-sections, showing salinity and discharge linear trends (solid lines) with related 95% confidence intervals (shaded areas bounded by dashed lines) [5].

Groundwater and Soil Salinization Under Climate Change

- Groundwater modeling (SEAWAT) showed chloride levels from 100 to 12,000 mg/L, with saline fronts advancing 20–40 m per year.
- By 2100, sea-level rise (+0.6 m) and reduced recharge could increase saline intrusion depth by 35%, degrading 12% of aquifer volume. Managing extraction—reducing groundwater pumping by 25–30%—is critical to mitigate salinization risk.
- Soil modeling in the Yellow River Delta revealed 83.22% salinized area in 2023, with salt content 0.03–3.05%.
- Future projections: under SSP119, salinization peaks at 85.32% (2050); under SSP245, it reaches 95.84% (2050) before slight recovery.
- Soil organic carbon (SOC) trends diverge: SSP119 stabilizes near 14 Tg, while SSP245 increases to 17.77 Tg by 2100, indicating complex climate–soil interactions.



Climate-Driven Acidification and Estuarine Vulnerability

- Global warming accelerates water acidification, disrupting chemical balance, biodiversity, and nutrient cycles in estuaries.
- Long-term monitoring of 166 Australian estuaries showed 2.16 °C warming, 0.09 pH units/yr acidification, and 0.086 PSU freshening over 12 years.
- Lagoons and river-type estuaries warm and acidify fastest due to shallow depths and weak ocean exchange—up to 10× faster than global ocean predictions.
- Tropical coasts face compounded acidification from drought, salinity intrusion, sea-level rise, and land-use change.
- Brazilian semi-arid estuaries experience hypersalinity, reduced river inflow, heat waves, and mangrove migration, destabilizing ecosystems.
- Intensified eutrophication, hypoxia, and biodiversity loss alter biogeochemical cycles and magnify contaminant and nutrient impacts.

Table 2. Acidification, DOM Changes, Nutrient Dynamics & BOD/DO Responses

Study Focus	Location/System	Key Climate Drivers	Major Water Quality Impacts	References
Estuary warming & acidification	166 Australian estuaries	Warming, freshening	+2.16 °C; -0.09 pH/yr; lagoons warm fastest	Scanes et al., 2020 [7]
Tropical estuary responses	NE Brazil	Drought, sea-level rise	Hypersalinity, hypoxia, biodiversity loss	Soares et al., 2022 [8]
DOM meta-analysis	Global	MAT, nutrients	DOC ↑; humification varies; Chl-a major driver	Zhang et al., 2023 [13]
Nutrient load projections	Lake of the Woods	+1.5–3 °C GMT	Winter TP ↑ 118%; seasonal eutrophication	Fong et al., 2022 [14]
Reservoir eutrophication	Iran	RCP4.5/8.5	Temp ↑ 3–8%; TP ↑ 10–16%	Nazari-Sharabian et al., 2021 [15]
Satellite nutrient dynamics	South China Sea	SST rise, P discharge	TN:TP ↓ (19→13); P-driven eutrophication	Zhang et al., 2024 [16]
BOD/DO thermal sensitivity	Global rivers	Temperature rise	DO depletion ↑; oxid. faster than reaeration	Chapra et al., 2020 [17]
Seasonal DO & COD patterns	1,735 watersheds	Warming, rainfall	DO ↑ 3.7%; COD ↓ 1.8%; anthropogenic effects amplify shifts	Zhang et al., 2023 [18]
Groundwater chemistry	Jinan, China	Drought index, extraction	NO ₃ ⁻ ↑26×; SO ₄ ²⁻ ↑12×	Wu et al., 2024 [19]

Climate Impacts on DOM Dynamics

- Dissolved organic matter (DOM) quantity and quality shift with climate warming, land use, and hydrological change.
- Meta-analysis of 50 studies showed strong spatial and seasonal variation in DOC, a₂₅₄, HIX, and chlorophyll-a.
- Temperature strongly regulates DOM, with **mean annual temperature (MAT)** increasing DOC and altering DOM composition.
- Agricultural land use elevates DOC, while forested watersheds enhance DOM humification and carbon cycling stability.
- Warming and nutrient enrichment jointly intensify organic carbon release, altering nitrogen and phosphorus cycling.
- These combined changes accelerate eutrophication and oxygen depletion in rivers, lakes, and estuaries.

Nutrient Loading, Hydrology, and Eutrophication Under Climate Change

- In the Lake of the Woods watershed, climate warming (+1.5 to +3.0 °C) increases runoff by **7–36%** and winter/spring phosphorus loads by **up to 118%**.
- Seasonal shifts reduce summer NPS-TP by **0–20%**, altering conditions that favor harmful algal blooms.
- In Iran's Mahabad Reservoir, projected warming increases reservoir temperature by **3–8%** and TP concentration by **10–16%**, intensifying stratification and eutrophication.
- Downscaled models project **6–11%** less rainfall and **9–16%** lower streamflow, worsening nutrient retention.
- Remote sensing in the South China Sea shows TP rising faster than TN, lowering the TN:TP ratio (19.2 → 13.2) and shifting nutrient limitation.
- Satellite-AI frameworks now allow real-time nutrient anomaly detection, supporting early HAB warnings and coastal management.



Climate Impacts on BOD and Dissolved Oxygen Dynamics

- Biochemical oxygen demand (BOD) increases under warming as oxygen depletion accelerates faster than reaeration.
- Streeter–Phelps modeling shows reduced BOD assimilative capacity in global rivers as temperatures rise.
- Nitrogenous BOD is more sensitive to warming than carbonaceous BOD, worsening oxygen depletion.
- High-gradient mountain streams are highly vulnerable due to low oxygen saturation and higher metabolic demand.
- Warming-induced DO decline threatens cold-water fish species and increases ecological stress.
- Overall, climate warming leads to more frequent hypoxia, reducing the natural ability of rivers to process organic waste.

Seasonal Water Quality Shifts and Groundwater Impacts

- Across 1,735 watersheds, natural factors drive **52–89%** of seasonal changes in DO and COD, amplified by human pressures.
- Anthropogenic activities modify seasonal water quality trends by **22–158%** (DO) and **14–56%** (COD).
- Temperature and rainfall cycles explain **~47%** of seasonal variation, with land-use structure as a major driver in managed basins.
- Long-term data show COD decreasing by **1.8% per decade** and DO increasing by **3.7%**, yet summer quality still deteriorates.
- Groundwater records from Jinan reveal rising SO_4^{2-} (12×) and NO_3^- (26×) due to fertilizer, manure, and sewage pollution.
- Warming intensifies both groundwater recharge and contaminant infiltration, increasing aquifer vulnerability under climate change.

Climate Warming and the Intensification of Algal Blooms

- Even small temperature increases (< 2 °C) significantly accelerate microbial activity and nutrient cycling, triggering algal blooms in high-altitude lakes.
- Long-term monitoring of Pyrenean lakes showed rising acidity, TOC/TN, potassium, and hardness, reflecting cumulative climate-driven chemical shifts.
- Satellite observations across Lake Tihu, Chaohu, Dianchi, and Erie (2003–2021) revealed faster bloom spread due to **warming, reduced wind speed**, and stronger water-column stability.
- Blooms are now expanding **even without additional nutrient loading**, as warming enhances stratification and releases phosphorus from sediments.
- Remote sensing confirms widespread eutrophication linked to climate-induced physical changes rather than solely nutrient inputs.
- Interactions between warming, weaker mixing, and nutrient accumulation accelerate bloom propagation in both freshwater and marine systems.

Table 3. Algal Blooms, Climate Extremes & Paleo-Climate Evidence

Study Focus	Location/System	Key Climate Drivers	Major Water Quality Impacts	Authors et al., Year [Ref]
High-altitude lake chemistry	Pyrenees	Moderate warming (<2°C)	Bloom sensitivity ↑; TOC/TN ↑	Sentenac et al., 2023 [20]
Satellite HAB propagation	China & USA lakes	Warming, reduced wind	Faster bloom spread (2003–2021)	Wang et al., 2023 [21]
Sediment P release & HABs	Lake of the Woods	Stratification warming	P release ↑; blooms without added nutrients	Paterson et al., 2019 [22]; Carey et al., 2012 [23]
Climate extremes & rivers	Global (965 cases)	Heatwaves, droughts, floods	68% cases worsen DO, nutrients, pollutants	Muehlbauer et al., 2023 [24]
Paleo-HAB record	Guaymas Basin	Ocean–climate shifts	Diatom blooms ↑; storm activity ↑	Ai et al., 2024 [25]
HAB C/N physiology	Marine algal species	Temperature	C:N ↑ at high temp; metabolic shift	Wen et al., 2022 [26]
Future HAB projections	Global	SSP3-7.0 & SSP5-8.5	HABs intensify with +3.5–4.5 °C warming	Dove et al., 2024 [27]



Hydrological Extremes, Coastal Records, and Future Bloom Scenarios

- Analysis of **965 case studies** shows river water quality worsens during droughts/heatwaves (**68%**), floods (**51%**), and long-term warming (**56%**).
- Droughts reduce DO while concentrating algae, nutrients, salinity, and pollutants; floods mobilize sediments, metals, plastics, and nutrients.
- Coastal laminated sediments from the Guaymas Basin show past warming phases intensified diatom blooms, silica input, storms, El Niño activity, and upwelling.
- Temperature affects harmful algal bloom composition: **14–26 °C** optimizes dinoflagellate growth and carbon fixation, while higher temperatures raise C:N ratios.
- Future simulations show stronger blooms under high-emission scenarios (SSP3-7.0, SSP5-8.5), with warming of **3.5–4.5+ °C** by 2100 amplifying eutrophication risk.
- Without mitigation and adaptive water management, climate-driven warming, hydrological shifts, and human pressures will continue to destabilize freshwater and coastal ecosystems.

Carbon footprint changes of water treatment plants under global warming

Climate Stressors Impacting Water Treatment Performance

- Global warming alters raw water quality through higher temperatures, salinity, acidity, and extreme weather events.
- Key treatment processes—**coagulation, membrane filtration, and disinfection**—face increased organic load, fouling, and disinfection by-product risks.
- Warmer and more acidic conditions accelerate **microbial regrowth and biofilm formation**, raising pathogen risks in distribution systems.
- Extreme rainfall and drought increase turbidity, nutrients, and chemical demand, stressing plant capacity.
- Ensuring drinking water safety requires integrated **engineering, policy, and real-time digital monitoring** strategies.
- Climate adaptation must address both water quality deterioration and operational energy demands.



Carbon Footprint of Water and Wastewater Treatment Systems

- Global LCA studies show high emissions in rural and island systems: $0.18\text{--}0.79\text{ kg CO}_2\text{-eq/m}^3$ for drinking water and $0.51\text{--}1.14\text{ kg CO}_2\text{-eq/m}^3$ for wastewater treatment.
- Electricity use in **membrane bioreactors** and methane from **septic sludge** are major contributors to GHG emissions.
- Indonesia faces climate-driven water scarcity: only **10%** of rainfall recharges groundwater, and **70%** of rivers are polluted.
- Under **RCP 8.5**, sea levels may rise up to **2 m** by **2100**, threatening **67%** of Jakarta; water availability may drop further.
- Without at least **60% GHG reduction** by **2035**, over **150 million people** in low-lying areas face severe water stress.
- Decarbonization requires renewable energy, anaerobic digestion, and sludge-to-resource technologies.

Regional and Process-Level Differences in Treatment Plant Carbon Footprints

- Indonesian WTPs emit $0.360\text{--}0.384\text{ kg CO}_2\text{-eq/m}^3$, more than double Taiwanese WTPs ($0.108\text{--}0.184\text{ kg CO}_2\text{-eq/m}^3$) due to higher electricity use and limited sludge treatment.
- Chemical consumption contributes $0.087\text{--}0.101\text{ kg CO}_2\text{-eq/m}^3$, influenced by raw water quality and local regulations.
- Design choices matter: aluminum-based direct filtration emits $\approx 1,258\text{ t CO}_2\text{-eq/yr}$, six times more than iron-based contact filtration ($\approx 236\text{ t CO}_2\text{-eq/yr}$).
- High emissions linked to limewater and aluminum production highlight the importance of chemical selection.
- Carbon footprint assessment during early process design can reduce both emissions and operational costs by up to **30%**.
- Transitioning to renewable power, efficient filtration, and optimized coagulant strategies is essential for **net-zero water treatment**.

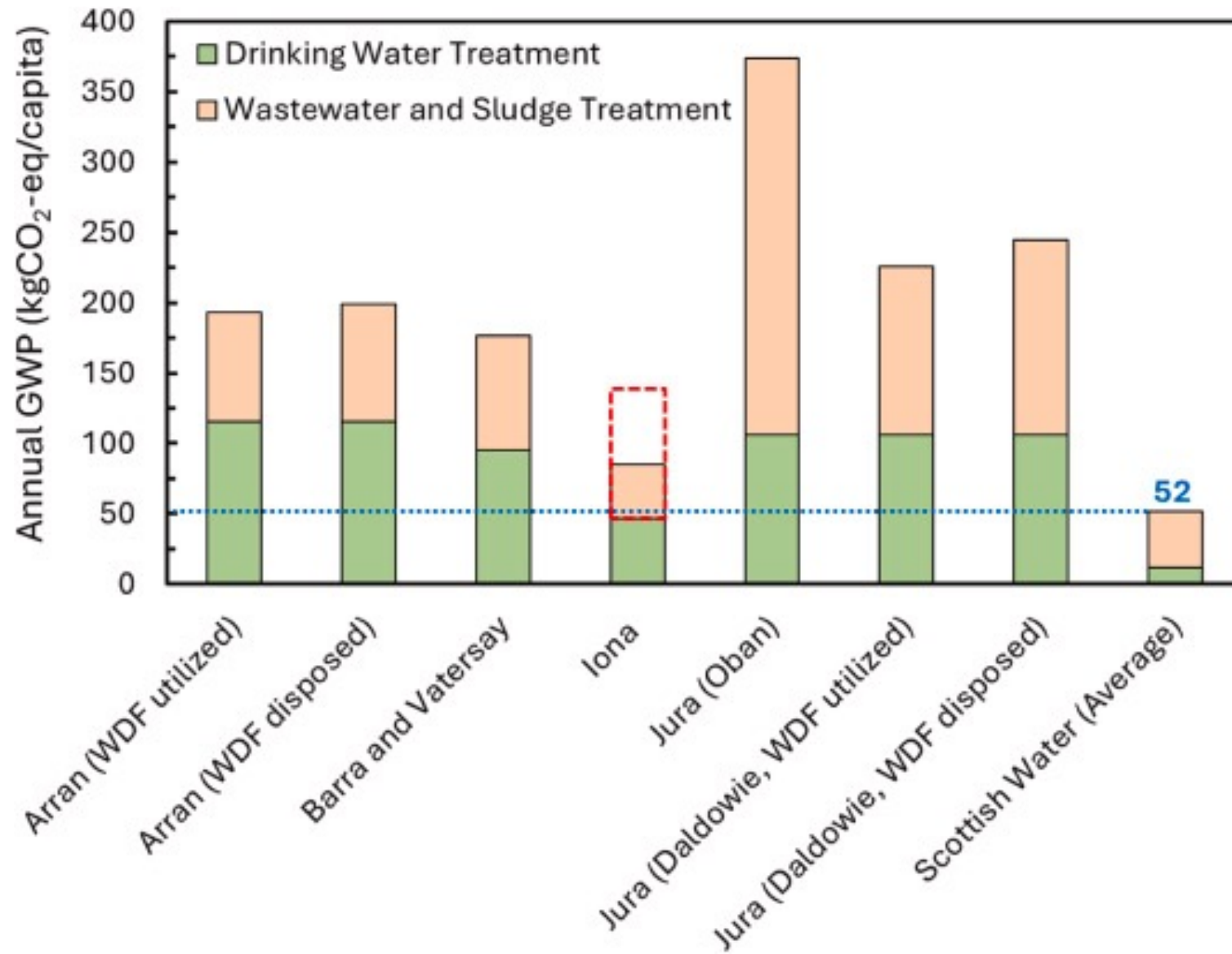


Fig. 2. Comparison of annual global warming potential (GWP/capita) for different islands with Scottish Water 2019 Sustainability report [29].

Carbon Footprint of Regional Water Supply & Desalination

- Desalination is the most energy- and carbon-intensive component of water supply systems, contributing $\approx 74\%$ of total GWP in Sicily.
- LCA results show emissions fell from $3.4 \rightarrow 2.8 \text{ kg CO}_2/\text{m}^3$ with a **17% reduction** in non-renewable energy use between 2009–2010.
- Thermal desalination technologies have far higher emissions than membrane systems:
 - MSF: $24 \text{ t CO}_2 / 1,000 \text{ m}^3$
 - MED: $19.2 \text{ t CO}_2 / 1,000 \text{ m}^3$
 - RO: $5.3 \text{ t CO}_2 / 1,000 \text{ m}^3$
- Reverse osmosis uses only $5\text{--}9 \text{ kWh}/\text{m}^3$, significantly lower than $15\text{--}25 \text{ kWh}/\text{m}^3$ for MSF, enabling major emission savings.
- Emissions can be reduced through renewable energy integration, energy-recovery devices, membrane optimization, and lowering water losses.
- Real-world example: Perth's seawater desalination plant operates entirely on **wind power**, demonstrating the feasibility of low-carbon desalination.

Table 3. Studies on Carbon Footprint of Water Treatment Plants (Section 3)

Focus Area	System / Country	Key Driver(s)	Main Findings	References
Climate stress on treatment	Global	Warming, extremes	↑ fouling, organic load, DBPs	Delpla et al., 2009 [28]
Rural/island treatment LCA	Scottish Islands	MBR energy, septic sludge	0.18–0.79 (DW), 0.51–1.14 (WW) kg CO ₂ /m ³	Gupta et al., 2022 [29]
National water stress & emissions	Indonesia	RCP 8.5	Sea-level rise +2 m; 150M affected	Kurniawan et al., 2023 [30]
WTP LCA comparison	Indonesia & Taiwan	Electricity mix, sludge	Indo: 0.36–0.384; Taiwan: 0.108–0.184 kg CO ₂ /m ³	Ouattara et al., 2024 [31]
Coagulation design & emissions	Nordic Europe	Chemical production	Al-DF = 1258 vs Fe-CF = 236 t CO ₂ /yr	Pellikainen et al., 2020 [32]
Regional water supply LCA	Sicily	Desalination	74% GWP; 3.4→2.8 kg CO ₂ /m ³	Borghini et al., 2013 [33]
Desalination technology review	Global	Thermal vs RO	MSF 24 t; MED 19.2 t; RO 5.3 t CO ₂ /1000 m ³	Li et al., 2021 [34]

Future Perspectives – Pathways to Climate-Resilient, Low-Carbon Water Systems

- Climate change is degrading water quality while increasing the energy and carbon intensity of treatment operations.
- Future systems must integrate **climate-smart water management** with **low-carbon technologies** to achieve net-zero objectives.
- Promising solutions include **renewable-powered desalination**, hybrid **membrane-biofilm reactors**, and **nature-based wetlands** that also sequester carbon.
- AI, machine learning, and **digital twins** can optimize aeration, chemical dosing, and plant operations to cut energy use and emissions.
- Standardized **LCA and carbon accounting** frameworks are needed to guide policy, design, and investment decisions.
- Circular strategies—biogas recovery, nutrient reuse, and reclaimed water—help close the water-energy-carbon loop.

Conclusions – Toward a Net-Zero Water Sector

- Global warming has created an interconnected crisis linking **water quality decline, energy demand, and GHG emissions** in the water sector.
- Existing treatment plants, built for stable conditions, struggle with salinity, turbidity, microbial loads, and chemical contamination.
- As the water sector contributes **~5% of global GHG emissions**, achieving net-zero operations is an urgent priority.
- National strategies must integrate climate adaptation and mitigation, invest in resilient infrastructure, and incentivize renewable energy use.
- International cooperation—through the UN Water Action Decade and Global Water Partnership—can accelerate technology transfer for vulnerable regions.
- A holistic, interdisciplinary approach uniting engineering innovation, data-driven management, and climate governance is essential to transform water services for a warming world.



Thank you

Contact me if you need more information!

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