Addressing Water Scarcity under Climate Change: An ESG-Oriented Integration of Technology, Equity, and Governance

Contents

1 Introduction

Water is the primary physical channel through which climate change is felt. Today 3.6 billion people live in areas that suffer water stress at least one month per year, and 2.2 billion still lack safely managed drinking services (UNESCO World Water Assessment Programme, 2023; WHO and UNICEF, 2022). Rising temperatures accelerate evapotranspiration, while altered jet streams make precipitation less predictable, deepening both drought and flood risk. Against this backdrop, the ESG (Environmental, Social, Governance) lens can knit together technology, equity, and rule-making:

1. **E – Reduce the physical gap** through low-carbon, climate-resilient technologies.
2. **S – Close the access gap** by targeting vulnerable groups and valuing water as a human right.
3. **G – Close the accountability gap** via mandatory disclosure, inclusive institutions, and smart finance.

2 Climate-Induced Scarcity: Why the Gap Widens

Climate change has profoundly disrupted the global hydrological cycle. Rising average temperatures increase evapotranspiration and shift precipitation regimes, while extreme events—such as flash floods, prolonged droughts, and glacial melt—have become more frequent and intense (IPCC, 2022). These changes not only reduce the total availability of freshwater resources but also undermine the predictability and temporal stability of water supply. Seasonal snowpack, aquifers, and glacier-fed rivers—once reliable buffers—are declining in both volume and regularity.

Globally, agriculture is the largest consumer of freshwater, accounting for approximately 70% of total withdrawals (FAO, 2017). This makes the sector particularly vulnerable to climate-induced scarcity, given its dependence on seasonal rainfall and aging irrigation systems. Meanwhile, water demand from non-agricultural sectors—such as thermal power generation, textile production, and mining—has surged due to industrial growth and urbanization (OECD, 2012). For instance, coal-fired power plants require millions of liters of water daily for cooling, and textile dyeing is water-intensive. Such expansion intensifies competition over limited water resources, often crowding out rural or ecological needs.

Figure 1 reveals the geographic variation in agricultural water dependence. Regions such as South Asia, North Africa, and parts of Latin America rely on agriculture for over 80% of their water withdrawals—making them particularly sensitive to climatic disruptions.

As shown in Figure 2, high-volume water extraction is concentrated in regions experiencing both population pressure and rapid industrialization, such as China, India, and the United States. When combined with climate variability, these pressures compound systemic water stress.

However, the impacts of climate-induced water stress are not evenly distributed. Arid and semi-arid regions—such as the Sahel, Central Asia, and the southwestern United States—are

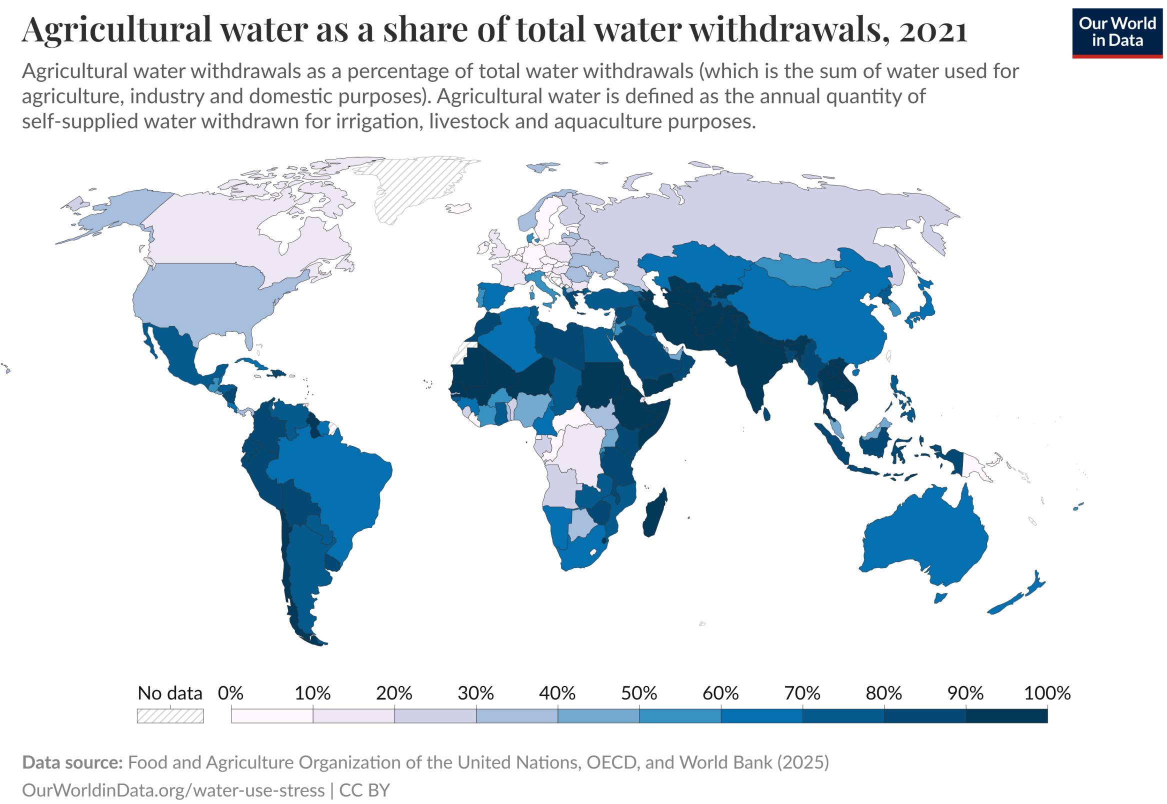

Figure 1: Agricultural water as a share of total water withdrawals, 2021. Source: FAO, OECD, World Bank via Our World in Data.

experiencing prolonged dry spells and aquifer depletion. Within these geographies, low-income communities and marginalized social groups often lack both physical infrastructure (e.g., piped water, storage tanks) and institutional support (e.g., responsive governance, credit access) (Sadoff and Muller, 2020). Rural households dependent on rain-fed agriculture or unregulated wells face dual vulnerabilities: hydrological volatility and policy neglect.

As a result, water scarcity is no longer just an environmental challenge; it is also deeply entwined with questions of equity, justice, and political representation. This dual character situates the crisis firmly within the ESG framework:

- **E (Environmental)** – degradation of watersheds, overuse of aquifers, and loss of ecological flow regimes;
- **S (Social)** – unequal access to water services, disproportionate burden on women and Indigenous groups, and displacement due to drought-induced migration;
- **G (Governance)** – weak basin-level coordination, lack of data transparency, and absence of inclusive decision-making mechanisms.

Understanding this widening gap—between physical availability and equitable distribution—is essential. It motivates a shift from traditional, infrastructure-driven solutions toward

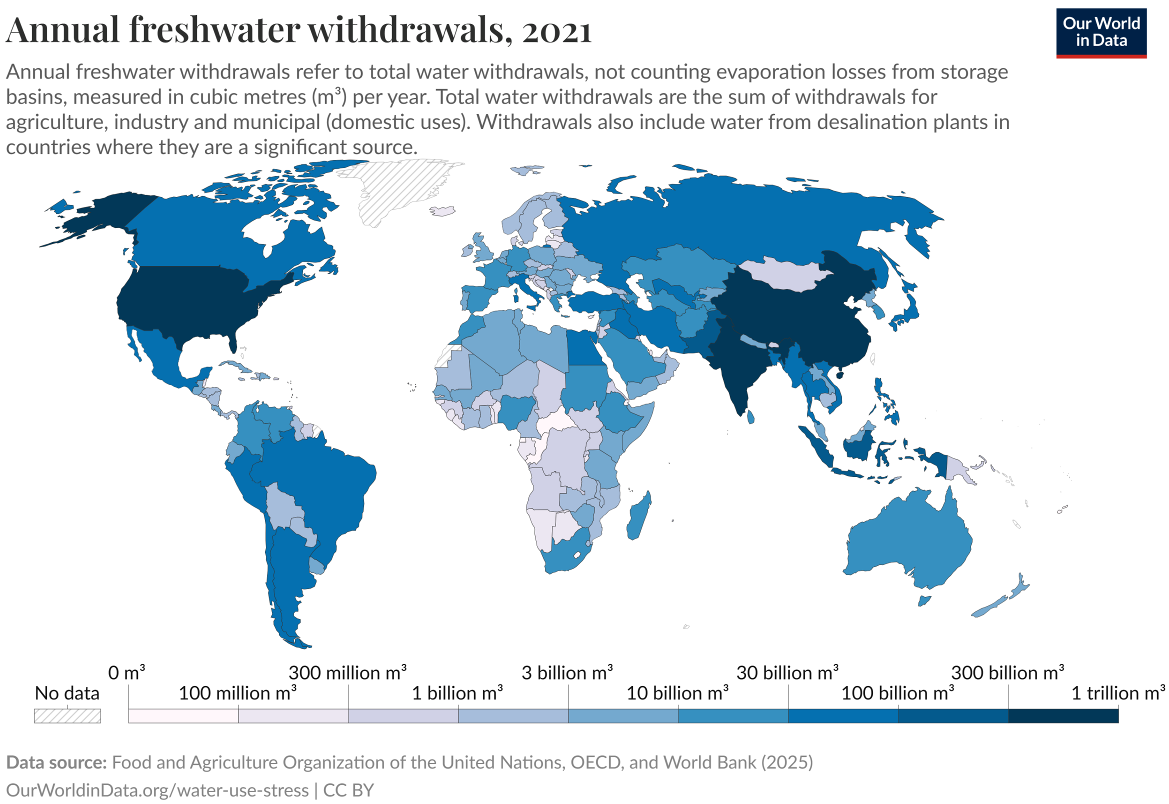

Figure 2: Annual freshwater withdrawals by volume (in m^3), 2021. Source: FAO, OECD, World Bank via Our World in Data.

integrated, ESG-aligned approaches that embed sustainable technology, social safeguards, and transparent governance into water resilience strategies.

3 Environmental Pillar: Shrinking the Physical Gap

Climate-induced water scarcity ultimately hinges on a single question: *is sufficient, good-quality water physically available at the right place and time?* The "E" in ESG therefore challenges governments, utilities, and firms to expand supply while lowering ecological footprints. Four complementary technology pathways—*predict, produce, protect, recycle*—illustrate how that physical gap can be narrowed.

3.1 Predict — Hydrological Analytics for Early Action

High-resolution GIS layers, reanalysis climate data, and machine-learning models (Random Forests, ANFIS, LSTM hybrids) now deliver flood- and drought-probability maps with lead times of days to weeks (Muñoz et al., 2021; Katipoğlu, 2023). Such forecasts allow operators in Cape Town, Chennai, and São Paulo to:

- pre-release or store reservoir volumes;

- stagger groundwater abstractions;
- trigger emergency demand-management protocols.

By moving from "react and repair" to "anticipate and adapt," these cities cut outage risk and allocate scarce water more equitably—advancing both the environmental and social arms of ESG.

3.2 Produce — Solar-Powered Desalination

Where local sources are exhausted, desalination becomes a backstop. Conventional reverse osmosis, however, is energy-intensive. Recent Portuguese pilots show that coupling RO membranes with dedicated PV arrays trims levelised water cost by 33 % versus grid electricity (Apolinário, 2024). Laboratory prototypes of solar electrodialysis now achieve 94 % energy efficiency and 5 m^3 day^{-1} output—sufficient to meet drinking-water needs of a 1 000-person village (Chu, 2024). By harvesting free solar energy, these systems simultaneously decarbonise supply (E) and extend service to off-grid communities (S).

3.3 Protect — Renewable-Integrated Treatment Microgrids

Water safety collapses when treatment plants lose power. Hybrid microgrids that blend rooftop PV, lithium-ion batteries, and AI pump scheduling now keep chlorine contact times stable during blackouts while trimming annual electricity use 20–30 % (Achite, 2022). Deployed across peri-urban centres in Kenya, India, and the Philippines, these resilient nodes:

- meet WHO water-quality targets during grid failures;
- lower operating expenditure through demand-side optimisation;
- demonstrate bankable emission reductions for green-bond financing.

3.4 Recycle — Circular Economy and Leakage Control

Water reuse. Singapore's *NEWater* scheme already covers 40 % of city-state demand and targets 55 % by 2060 through advanced membrane bioreactors (Singapore, 2023). Life-cycle analysis indicates each cubic metre of NEWater emits 0.33 kg CO_2-eq—half that of imported raw water after treatment (NEW citation: `lca2024_singapore`).

Non-revenue water (NRW). Globally, utilities lose $39 billion annually in NRW. Cities such as Barcelona, Johannesburg, and Manila deploy acoustic AI sensors and dynamic pressure zoning, cutting losses 15–35 % within five years (IWA, 2024). Every litre saved is a litre never abstracted—protecting rivers and cutting pump energy (E) while freeing supply for underserved users (S).

Synthesis. Predictive analytics avert crises; solar desalination and microgrids generate new, low-carbon volumes; circular systems stretch every drop. Together these routes illustrate how environmental innovation can turn a fixed water pie into an expandable, climate-resilient resource—laying the physical foundation on which social fairness and governance accountability can build.

4 Social Pillar: Bridging the Access Divide

Water is a fundamental human right, yet billions still face daily barriers to secure, affordable, and safe water access. While environmental innovations expand the physical water supply, social equity determines who benefits from it. The "S" in ESG calls for identifying and correcting structural disparities in water distribution, affordability, and rights recognition. This section explores how spatial, economic, and identity-based exclusions can be addressed through inclusive ESG metrics and corporate practices.

4.1 Mapping Spatial and Socio-Economic Inequity

Access to water is highly stratified across both geography and socio-economic status. Studies show that the poorest 20% of households in several LMICs are up to 50% less likely to have safely managed water services than wealthier groups (Yang et al., 2013; Dongzagla et al., 2022). These disparities are especially acute in informal settlements and remote areas where infrastructure investment is lacking.

Climate shocks such as droughts or floods disproportionately affect those with limited coping mechanisms. In many regions, the burden of water collection falls on women and girls, who spend a combined 200 million hours daily collecting water—undermining education and economic opportunities (Kakinuma and Wada, 2024).

4.2 Corporate Water Footprints and Community Backlash

Large-scale corporate water extraction can deepen local scarcity and provoke community backlash. In California, Nestlé continued withdrawing over 60 million gallons annually from Strawberry Creek during drought emergencies, triggering lawsuits and reputational damage (Sun, 2015). Similar outcomes occurred in India, where Coca-Cola plants were shut down after community protests over water depletion and pollution (Kumar and Saleth, 2018).

Globally, over $16.7 billion in corporate value has been lost due to unresolved water conflicts, with $336 billion in assets exposed to escalating risks (OECD and CDP, 2023). ESG-aligned firms must audit water footprints not only for operational efficiency but also for local community impact.

4.3 From Voluntary Disclosure to Active Stewardship

With investor pressure mounting, companies are increasingly disclosing water risks. In 2023, over 4,800 firms submitted data to the CDP Water Security Questionnaire—a 23% increase from the previous year (CDP, 2023). These disclosures help firms identify physical, reputational, and regulatory water risks.

Companies like Intel and Ørsted, who received CDP's A-list designation, showed improved capital market performance and investor trust (Ali et al., 2020). This indicates that proactive water stewardship is both ethically and financially sound.

4.4 Gender and Indigenous Rights

Indigenous communities manage over 20% of global ecosystems yet often lack legal rights to water within ancestral territories. Projects that ignore their customary governance—such as dams or mining—can cause displacement and long-term ecological harm (Fund, 2022).

Similarly, women are underrepresented in water governance, despite being primary household users. Gender-disaggregated data and participatory mechanisms in ESG reporting can support both SDG 5 (gender equality) and SDG 6 (clean water access) (Fröhlich et al., 2017).

Free, Prior, and Informed Consent (FPIC) protocols are essential for safeguarding Indigenous sovereignty and building resilient ESG-aligned water strategies.

In sum, bridging the social access divide requires more than infrastructure—it demands ethical recognition, participatory governance, and redistribution of power. The "S" pillar of ESG compels both public and private actors to ensure that water access is not merely expanded but equitably and justly delivered.

5 Governance Pillar: Aligning Incentives and Standards

Robust governance is the backbone of sustainable water management. While environmental technologies and social equity mechanisms address the "what" and "for whom," governance structures define the "how." The "G" in ESG pertains not only to corporate boardroom composition, but more broadly to systems that ensure transparency, accountability, and long-term alignment of private incentives with public goods.

5.1 Mandatory ESG Disclosure

Evidence shows that ESG disclosure—especially concerning water—remains underdeveloped in many public utilities. A study of 38 Andalusian water enterprises found low quality and quantity of ESG reporting, with disclosure largely dependent on organizational size and transparency culture (Martínez-Martínez et al., 2024). This signals a need for enforceable mandates. Similarly, research emphasizes that realistic legal mechanisms and institutional training are critical to enhancing ESG water disclosure compliance (Andrades et al., 2023).

5.2 Integrated Water Resource Management (IWRM)

IWRM offers a systematic approach to coordinating land, water, and related resources across sectors. Studies show that IWRM enhances institutional cooperation, stakeholder trust, and sustainability outcomes (Hooper, 2009; Mitchell, 2015; Bertule, 2018). Yet, implementation remains uneven due to governance gaps, especially in transboundary or informal water systems

5.3 Economic Instruments and Blended Finance

Blended finance is gaining traction as a way to close the infrastructure funding gap while aligning ESG goals. While specific studies on ESG-labeled water bonds are still emerging, global analyses confirm that enabling financial mechanisms like green bonds or tiered pricing significantly improve investment flow and water-use efficiency (Rees et al., 2008; Tinoco, 2022).

5.4 Digital Governance and Water Data Commons

Digital technologies—including AI simulations, open-data platforms, and digital twins—are improving transparency and regulatory monitoring. Publicly accessible data systems help establish accountability across jurisdictions and support adaptive policy (Panteleev, 2024). Such systems lower information asymmetry for investors and provide real-time insight into compliance and risk.

Taken together, the governance pillar ensures that technical and social progress is sustained through institutional legitimacy and strategic alignment. Strong disclosure mandates, cross-sectoral planning, financial innovation, and digital transparency provide a resilient foundation for ESG water governance.

6 Synthesis and Outlook

Effective water resource management in the context of climate change demands the coordinated integration of technology, social inclusion, and institutional accountability. This paper has proposed an ESG-oriented framework in which:

- **Environmental innovation (E)**—such as predictive hydrology, PV-powered desalination, and circular water systems—expands the physical availability of clean water in a low-carbon and climate-resilient manner.
- **Social equity (S)** ensures that the benefits of these innovations are distributed fairly, particularly to historically marginalized communities, by embedding gender-aware, rights-based, and participatory mechanisms.
- **Governance mechanisms (G)** enforce transparency, institutional coordination, and long-term planning through tools such as mandatory ESG disclosure, blended finance, and digital water regulation.

This tri-pillared approach creates a mutually reinforcing system: technologies are more scalable when socially accepted and institutionally supported; equitable outcomes are more durable when grounded in environmental and regulatory legitimacy; and governance systems are more adaptive when informed by real-time data and inclusive dialogue.

Yet key challenges remain. Fragmented water risk data, inconsistent ESG metrics, and financing gaps in low-income settings hinder implementation at scale. Addressing these barriers requires an interdisciplinary and forward-looking research agenda focused on:

- **Techno-economic evaluation:** Modeling lifecycle cost, energy intensity, and investment returns of PV–RO + AI microgrid systems under different climatic and tariff scenarios.
- **Regulatory impact assessment:** Using quasi-experimental methods (e.g., DiD, synthetic control) to evaluate how ESG mandates like the EU CSRD influence corporate water stewardship and disclosure behavior.
- **Vulnerability mapping:** Integrating satellite-based hydrological data with socio-economic survey layers to inform targeted interventions, drought insurance schemes, and adaptive safety nets.

In sum, achieving SDG 6 (Sustainable Development Goal 6: universal access to clean water and sanitation) —*"Ensure availability and sustainable management of water and sanitation for all"*—will depend not just on infrastructure investment, but on the intentional alignment of ESG principles. When environmental sustainability, social justice, and good governance are treated as co-equal priorities, water scarcity can be transformed from a structural constraint into an opportunity for innovation and resilience.

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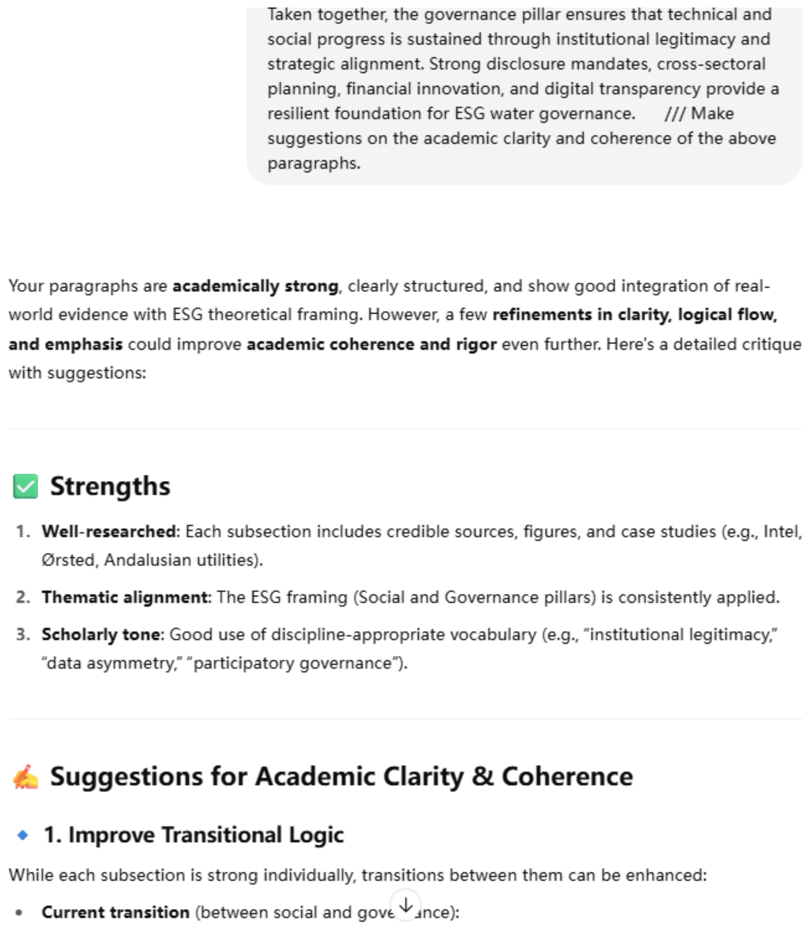
Appendix: Statement on AI Use

This essay was composed with the assistance of OpenAI's ChatGPT (GPT-4 model). The model was used for academic support in the following ways:

- Conducting grammar and style checks to improve clarity and correctness.
- Providing suggestions to enhance academic coherence, logical flow, and emphasis across sections.
- Reviewing and correcting LaTeX syntax to ensure structural integrity.
- Recommending high-quality and credible sources for images, maps, and data visualizations related to water scarcity and climate change.

Illustrative examples of AI-assisted outputs are shown in the following figures:



Taken together, the governance pillar ensures that technical and social progress is sustained through institutional legitimacy and strategic alignment. Strong disclosure mandates, cross-sectoral planning, financial innovation, and digital transparency provide a resilient foundation for ESG water governance. /// Make suggestions on the academic clarity and coherence of the above paragraphs.

Your paragraphs are **academically strong**, clearly structured, and show good integration of real-world evidence with ESG theoretical framing. However, a few **refinements in clarity, logical flow, and emphasis** could improve **academic coherence and rigor** even further. Here's a detailed critique with suggestions:

✅ Strengths

1. **Well-researched**: Each subsection includes credible sources, figures, and case studies (e.g., Intel, Ørsted, Andalusian utilities).
2. **Thematic alignment**: The ESG framing (Social and Governance pillars) is consistently applied.
3. **Scholarly tone**: Good use of discipline-appropriate vocabulary (e.g., "institutional legitimacy," "data asymmetry," "participatory governance").

✍️ Suggestions for Academic Clarity & Coherence

🔹 1. Improve Transitional Logic

While each subsection is strong individually, transitions between them can be enhanced:

- **Current transition** (between social and gove↓ance):

Figure 3: Suggestions for improving academic clarity and coherence.

and equitable distribution
is critical. It motivates a transition from traditional supply-side engineering toward inte-
grated, ESG-aligned approaches that combine sustainable technologies, social safeguards,
and transparent governance. /// Please help me check if there are any grammar problems in this paragraph

Your paragraph is overall very well-written and clear. Below are **minor grammar and style improvements** to enhance clarity and flow, while preserving your content:

✅ Revised Version (with suggested edits in bold and explanations below):

\section*{2\quad Climate-Induced Scarcity: Why the Gap Widens}

Climate change has profoundly disrupted the global hydrological cycle. Rising average temperatures increase evapotranspiration and shift precipitation regimes, while extreme events—such as flash floods, prolonged droughts, and glacial melt—have become more frequent and intense \citep{IPCC2022}. These changes not only reduce the total availability of freshwater resources but also undermine the predictability and temporal stability of water supply. **Seasonal snowpack, aquifers, and glacier-fed rivers—once reliable buffers—are declining in both volume and regularity.**

Globally, agriculture is the largest consumer of freshwater, accounting for approximately 70% of

Figure 4: Grammar and style revision suggestions for Section 2.

transformed from a structural constraint into an opportunity for innovation and resilience. /// Check if there are any issues with the usage of this latex grammar

Your LaTeX section titled **"Synthesis and Outlook"** is grammatically sound and **well-structured**. From a LaTeX syntax perspective, it compiles cleanly and semantically follows best practices. Below is a quick technical check and a few suggestions to polish it further:

✅ LaTeX Syntax and Structure Check

- `\section{Synthesis and Outlook}` — valid
- `\begin{itemize} ... \end{itemize}` — properly opened and closed
- Bold text within items via `\textbf{...}` — ✅ correct
- Em dash used in `–` (likely copied from Word) — you **may want** to convert this to proper LaTeX dash:
  - Use `---` for an em-dash (recommended in LaTeX).
- Inline math for `SDG~6` — ✅ correct
- Quotation marks around the SDG6 text: `\textit{"Ensure availability...}` — **can be improved** for typographic consistency (see below)

✨ Suggested Improvements (Optional)

1. **Proper dashes**: Replace all em-dashes (`–`) with `---` in LaTeX to prevent encoding issues:

latex 复制 编辑

Figure 5: Technical check and LaTeX syntax guidance.

is critical. It motivates a transition from traditional supply-side engineering toward inte-
grated, ESG-aligned approaches that combine sustainable technologies, social safeguards,
and transparent governance. /// On which website can one find appropriate pictures and data to support these arguments

To support your arguments in Section 2 *"Climate-Induced Scarcity: Why the Gap Widens"*, you can find high-quality **pictures**, **maps**, and **data visualizations** from the following trusted academic and international sources:

🌍 1. Intergovernmental Panel on Climate Change (IPCC)

- **Website**: https://www.ipcc.ch
- **What to find**:
  - Scientific graphs on evapotranspiration, hydrological cycle disruptions, and regional drought risk.
  - Summary figures from *AR6 Working Group II* on water and climate vulnerability.
- **Recommended**:
  - Browse the AR6 WGII Atlas for maps showing drought risk, water scarcity, and climate variability.

Figure 6: Recommended websites and datasets for supporting visual and empirical evidence.