



Panta Rhei  
Research Program

Research Briefings · Public-Good Impact Dossiers



Agriculture · Food, Life & Health Systems

# Tau for Climate-Smart Irrigation, Soil Moisture, and Water Productivity

Conditional public-good pathway for Climate-Smart Irrigation, Soil Moisture, and Water Productivity

**Public-Good Impact Dossier**

Conditional impact analysis · Publication-ready PDF · not deployment-ready

Dossier ID: PGID-AGRI-01 Release: May 2026 publication-ready release

Thorsten Fuchs · Anna-Sophie Fuchs

Conditional scenario map. No validation, product, deployment, or policy claim.

## Safe harbor / release discipline

Conditional public-good impact dossier · Publication-ready PDF release · Domain review pending · Deployment not claimed

### Briefing identity and source routes

<b>Dossier ID</b>	PGID-AGRI-01
<b>Portfolio</b>	Agriculture
<b>Series</b>	Public-Good Impact Dossiers
<b>Version</b>	v3-enriched
<b>Status</b>	conditional
<b>Release</b>	May 2026 publication-ready release
<b>Release date</b>	2026-05-02
<b>Review state</b>	Domain review pending; deployment not claimed
<b>Source route</b>	<a href="https://panta-rhei.site/impact/papers/climate-smart-irrigation-soil-moisture-water-productivity/">https://panta-rhei.site/impact/papers/climate-smart-irrigation-soil-moisture-water-productivity/</a>
<b>Landing route</b>	<a href="https://panta-rhei.site/publications/research-briefings/public-good/climate-smart-irrigation-soil-moisture-water-productivity/">https://panta-rhei.site/publications/research-briefings/public-good/climate-smart-irrigation-soil-moisture-water-productivity/</a>

### Release status

This briefing is a conditional public-good impact dossier released as a publication-ready PDF artifact on 2026-05-02. Publication-ready means the dossier is downloadable, internally consistent, and claim-safe. It does not validate the  $\tau$ -framework, does not claim deployment readiness, and does not assert that the described domain system already exists. It maps a plausible impact pathway if the relevant upstream Results, Corpus constructions, and translation assumptions survive expert review and domain benchmarking.

### What this dossier claims

- maps a conditional public-good impact pathway
- identifies upstream framework dependencies that would have to survive review
- states translation assumptions, benchmark needs, and governance guardrails

### What this dossier does not claim

- does not validate the Tau framework
- does not claim that a domain system or product already exists
- does not claim deployment readiness, policy adoption, or certified impact
- does not replace independent domain review, empirical benchmarking, or governance assessment

### Source fidelity and legal disclaimer

This PDF includes the full long-form source argument imported from the public HTML/Markdown source page listed above. The imported source is carried as a durable LaTeX layer at `sections/source-full.tex`; ordinary metadata rendering preserves that file unless the renderer is explicitly run with the `source-refresh` flag.

This dossier is not legal, financial, medical, engineering, safety, regulatory, procurement, or investment advice. It is not an official statement by any institution named in the document. It is a conditional research briefing and scenario map for review, discussion, and public-interest scrutiny.

## Contents

1	Executive Summary	4
2	Why This Matters Now	5
3	Scope and Reader Orientation	7
4	The Opportunity Baseline	8
5	Working $\tau$ Assumptions	10
6	What Changes with a Law-Faithful Twin	10
7	Competitive and Incumbent Landscape	12
8	Structured Opportunity Map	15
9	Geographic Case Studies	18
10	Finance, ROI, and Climate-Finance Eligibility	22
11	Evidence and Translation Ladder	24
12	Stakeholder Map and Change Management	25
13	Gender, Equity, and Labor Dimensions	26
14	Benchmark Suite and Success Metrics	27
15	Governance Guardrails	29
16	SDG Mapping and Bottom Line	29
17	References	30
18	Dossier accountability addendum	31

# 1 Executive Summary

Agriculture is the dominant consumer of the world's freshwater. FAO's 2025 land-and-water assessment reports that agriculture accounted for **72% of total freshwater withdrawals in 2020**, yet produces only some of those withdrawals as durable food value.<sup>1</sup> The inefficiency is not total — irrigated croplands cover only **22.5% of all cropland** but generate **48% of global crop value** — but water losses through over-application, misscheduling, runoff, evaporative waste, and progressive salinization represent a structural drag on agriculture's productive base.<sup>2</sup> FAO estimates that soil salinization driven largely by irrigation mismanagement removes **up to 1.5 million hectares from production annually** at a global cost of approximately **USD 27.3 billion per year** in lost output.<sup>3</sup>

This dossier examines what would follow — in practical, institutional, and financial terms — if the  $\tau$  categorical framework provides a physically faithful, bounded-error, coarse-grainable discrete twin of weather–soil–water–crop dynamics. The framing is deliberate: this is a yellow paper, assumption-led and planning-oriented. It does not claim that  $\tau$ 's assumptions are externally validated. It asks what class of public good would be unlocked if they were true enough to matter operationally.

**The five key findings are:**

- 1. Irrigation intelligence is a highest-leverage  $\tau$  beachhead.** The institutional demand is explicit, the public data infrastructure already exists (FAO WaPOR, FAO d-iap, NASA-USDA soil moisture, AquaCrop), and the value of marginal improvement is large because irrigated land is economically load-bearing. The World Bank's current climate-resilient irrigation framing states that climate-resilient irrigation can more than double productivity compared with rainfed agriculture and, at global scale, could feed 1.4 billion additional people.<sup>4</sup>
- 2. A  $\tau$ -native water twin changes the decision category.** Today's advisory stack stitches together weather forecasts, ET models, soil-moisture estimates, crop coefficients, and scheme-delivery constraints from separate systems with mismatched update cadences. Under the strongest  $\tau$  assumption, root-zone water state becomes a native, bounded-error quantity that the model can reason over directly — enabling action windows (“irrigate plot A within this volume range tonight; defer plot B; cut sector D”) rather than probabilistic triggers.
- 3. The structured opportunity spans six clusters.** Field-scale precision irrigation, scheme operations, drought-allocation intelligence, water-productivity benchmarking, soil salinity and drainage protection, and energy–water coordination together represent a total addressable domain of many tens of millions of irrigated hectares globally, weighted toward sub-Saharan Africa, South Asia, and North Africa/Middle East.
- 4. Geographic leverage is concentrated in a few high-stakes systems.** The Nile Basin and Pakistan Punjab are illustrative: Egypt's 55.5 km<sup>3</sup>/yr Nile allocation<sup>5</sup> is managed under a rigid

<sup>1</sup>FAO, *State of the World's Land and Water Resources for Food and Agriculture 2025 (SOLAW 2025)* — agriculture represented 72% of total freshwater withdrawals in 2020. <https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/scenarios-offer-insights-assumptions.html>

<sup>2</sup>FAO, *State of the World's Land and Water Resources for Food and Agriculture 2025 — Executive Summary and Status-Trends* — irrigated croplands represent approximately 22.5% of croplands and produce approximately 48% of crops in value terms. <https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/executive-summary.html>

<sup>3</sup>FAO Global Soil Partnership, *Soil Salinity* — soil salinization takes up to 1.5 million hectares of farmland per year out of production; global annual cost in irrigated areas from salt-induced land degradation approximately USD 27.3 billion in lost crop production. <https://www.fao.org/global-soil-partnership/areas-of-work/soil-salinity/en/>

<sup>4</sup>World Bank Group, *Transforming Lives Through Climate-resilient Irrigation* (2026) — climate-resilient irrigation more than doubles productivity compared with rainfed agriculture; could feed 1.4 billion additional people. <https://shorthand.worldbankgroup.org/transforming-lives-through-climate-resilient-irrigation/>

<sup>5</sup>FAO AQUASTAT — Nile Basin and Egypt irrigation data: Egypt uses approximately 55.5 km<sup>3</sup>/yr of Nile water;

1959 agreement with no real-time water-state intelligence, while Pakistan’s ~4 million tube wells<sup>6</sup> are extracting groundwater 0.3–1.0 m/year faster than recharge<sup>7</sup> against a near-total absence of integrated soil-moisture and ET advisory.

5. **Finance pathways are well-matched and accessible.** World Bank Water for Food has USD 4.5B+ in active lending;<sup>8</sup> GCF funds watershed and water-productivity programs;<sup>9</sup> IFAD covers rural water management;<sup>10</sup> and the World Bank IDA climate lens adds concessional terms to adaptation components. A shadow-mode advisory layer covering 200,000–500,000 ha is achievable at USD 3–8M; a regional basin coordination platform covering 3–5 million ha at USD 20–50M. Both scenarios are comfortably within World Bank B:C benchmarks for irrigation improvement (1.5:1 to 4:1).<sup>11</sup>

## 2 Why This Matters Now

### 2.1 The global freshwater crisis is structural

The world is approaching a structural freshwater ceiling. Global water withdrawal has grown approximately threefold since 1960, driven by population growth, dietary change, expanding irrigated area, and industrialization. Of total global withdrawals, agriculture’s **72% share** has remained persistently dominant.<sup>12</sup> More significantly, that share disguises a trajectory: FAO projects that 40% of the world’s population will live under conditions of water stress by 2030, and that irrigated agriculture will face progressive constraint in most of the major producing regions — South Asia, the Middle East and North Africa, sub-Saharan Africa, and parts of East Asia — precisely where food demand growth is fastest.<sup>13</sup>

Groundwater depletion is accelerating the urgency. Globally, an estimated 21 of the world’s 37 largest aquifers are now losing mass faster than recharge.<sup>14</sup> In the Indo-Gangetic Plain — the agricultural engine of South Asia — water tables are falling at measurable rates in multiple states. In North Africa and the Middle East, non-renewable fossil aquifers are being drawn down with no

---

approximately 12.5 million farmers dependent on Nile-sourced irrigation. <https://www.fao.org/aquastat/en/countries-and-basins/river-basins/nile-basin/>

<sup>6</sup>Pakistan Bureau of Statistics / Punjab Irrigation Department — Punjab Province tube-well census and irrigated area data. Cited figures: approximately 7.2 million irrigated ha; approximately 4 million tube wells.

<sup>7</sup>IWMI (International Water Management Institute) — Pakistan Punjab groundwater depletion studies. References include: Qureshi, A.S., McCornick, P.G., Sarwar, A., and Sharma, B.R. (2010). “Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan.” *Water Resources Management* 24(6), pp. 1551–1569. IWMI country program: <https://www.iwmi.cgiar.org/research/topics/water-scarcity/>

<sup>8</sup>World Bank Group, *Water for Food — Climate-Resilient Irrigation portfolio page*. <https://www.worldbank.org/en/topic/climate-resilient-irrigation>

<sup>9</sup>Green Climate Fund, *Adaptation Programme* — watershed protection, water productivity, and sustainable land-use program windows. <https://www.greenclimate.fund/projects/adaptation>

<sup>10</sup>IFAD, *Rural Water Management and Climate Resilience* programme documentation — smallholder water access, gender equity, and climate resilience in agricultural water management. <https://www.ifad.org/en/web/knowledge/-/publication/water-and-food-security>

<sup>11</sup>World Bank, *Irrigation Project Economic Analysis* documentation — B:C ratios for irrigation improvement projects in developing countries range from 1.5:1 to 4:1. See: World Bank (2016), *Water in Agriculture: Improving Performance, Meeting Demands*, and associated project appraisal documentation.

<sup>12</sup>FAO, *State of the World’s Land and Water Resources for Food and Agriculture 2025 (SOLAW 2025)* — agriculture represented 72% of total freshwater withdrawals in 2020. <https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/scenarios-offer-insights-assumptions.html>

<sup>13</sup>FAO, *State of the World’s Land and Water Resources for Food and Agriculture 2025 (SOLAW 2025)* — agriculture represented 72% of total freshwater withdrawals in 2020. <https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/scenarios-offer-insights-assumptions.html>

<sup>14</sup>Famiglietti, J.S. (2014). “The global groundwater crisis.” *Nature Climate Change* 4, pp. 945–948. doi:10.1038/nclimate2425

realistic recharge prospect. These are not future risks: they are current operational conditions under which tens of millions of farmers are making daily water decisions with inadequate information.

## 2.2 The food–water nexus: high leverage, high risk

The asymmetry between irrigated land area (22.5% of cropland) and irrigated land value (48% of crop output) means the global food system is structurally dependent on a relatively small share of managed water.<sup>15</sup> This creates an unusual public-good opportunity: improving decision intelligence on irrigated land produces outsized food-system benefit per hectare of intervention.

The same asymmetry creates outsized downside risk. When irrigation fails — from drought, mismanagement, salinization, infrastructure breakdown, or conflict over allocation — the knock-on to food supply is disproportionate to the area affected. The 2011 Horn of Africa drought, the 2022 Pakistan floods’ disruption of the Indus irrigation network, and the ongoing pressures on Egypt’s Nile allocation all illustrate how quickly irrigation failure translates into food insecurity at national or regional scale.

## 2.3 The World Bank’s productivity anchor

The World Bank’s current “Transforming Lives Through Climate-Resilient Irrigation” framing provides a planning anchor: **climate-resilient irrigation more than doubles productivity compared with rainfed agriculture** and, at global scale, holds the potential to feed 1.4 billion additional people.<sup>16</sup> This is an institutional statement of intent, not a  $\tau$  claim. But it signals precisely the class of public good that improved irrigation intelligence would serve.

Concrete Bank results reinforce the scale: Nigeria’s TRIMING programme expanded irrigation across **43,400 hectares**, producing food for an estimated **1 million people**.<sup>17</sup> Morocco’s resilient agriculture project connected more than **23,500 farmers** with climate-smart advisory services, with a significant component focused on water productivity.<sup>18</sup>

## 2.4 The advisory gap: fragmented stacks and compounding uncertainty

The problem is not absence of data or tools. FAO’s WaPOR platform already provides open-access monitoring of evapotranspiration, precipitation, relative soil moisture, biomass, and water productivity at global-to-scheme scale.<sup>19</sup> FAO’s d-iap platform computes drought impacts on crop and water productivity, net irrigation requirements, and probability of meeting crop water needs.<sup>20</sup>

---

<sup>15</sup>FAO, *State of the World’s Land and Water Resources for Food and Agriculture 2025 — Executive Summary and Status-Trends* — irrigated croplands represent approximately 22.5% of croplands and produce approximately 48% of crops in value terms. <https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/executive-summary.html>

<sup>16</sup>World Bank Group, *Transforming Lives Through Climate-resilient Irrigation* (2026) — climate-resilient irrigation more than doubles productivity compared with rainfed agriculture; could feed 1.4 billion additional people. <https://shorthand.worldbankgroup.org/transforming-lives-through-climate-resilient-irrigation/>

<sup>17</sup>World Bank Group, *Water for Food results page* — TRIMING in Nigeria expanded irrigation across 43,400 hectares; food produced enough for 1 million people. <https://www.worldbank.org/ext/en/topic/water/water-for-food>

<sup>18</sup>World Bank Group, *World Bank Supports Resilient and Sustainable Agriculture in Morocco* (2022) — 23,500+ farmers connected to advisory services focused on climate resilience and water productivity. <https://www.worldbank.org/en/news/press-release/2022/03/25/world-bank-supports-resilient-and-sustainable-agriculture-in-morocco>

<sup>19</sup>FAO, *WaPOR database* — open-access remote sensing platform for water productivity monitoring including actual ET, reference ET, relative soil moisture, biomass, precipitation, and water-productivity products at global, national, and scheme level. <https://www.fao.org/in-action/remote-sensing-for-water-productivity/wapor-data/en;> <https://www.fao.org/aquastat/en/geospatial-information/wapor/>

<sup>20</sup>FAO, *d-iap — Drought Impact Assessment Platform on Water Productivity* — evaluates drought impacts on crop and water productivity; computes net irrigation requirements, yield-loss probabilities, and income impacts under current and future climate scenarios at approximately 9 km resolution using AquaCrop. <https://www.fao.org/in-a>

NASA-USDA provides global soil-moisture fields at  $0.25^\circ \times 0.25^\circ$  resolution.<sup>21</sup> Drought.gov exposes operational soil-moisture data for agricultural monitoring, weather prediction, and drought early warning.<sup>22</sup>

The problem is that these layers are **not tightly coupled**. Weather forecasts, ET estimates, soil-moisture products, crop-coefficient tables, and scheme-delivery constraints arrive from separate systems, updated at different cadences, with uncertainty that compounds at each handoff. The result is that farm operators and irrigation managers routinely make consequential water decisions under conditions of preventable uncertainty — not because the underlying data is absent, but because it is not integrated, physically grounded, and bounded enough to support confident action.

## 2.5 Salinity: the hidden long-run cost

Beyond over-application and scheduling inefficiency, irrigation mismanagement accumulates into a structural land problem. FAO's Global Soil Partnership estimates that salt-induced land degradation in irrigated areas costs approximately **USD 27.3 billion per year** in lost crop production and removes up to **1.5 million hectares from productive use annually**.<sup>23</sup> Much of this degradation is preventable: it follows from chronic over-application, inadequate drainage, rising water tables, and failure to detect early salinity build-up before yield damage becomes irreversible.

This makes irrigation intelligence not merely an efficiency problem, but a land stewardship imperative.

# 3 Scope and Reader Orientation

## 3.1 What this paper covers

This is **Paper 2 of 5** in the Panta Rhei agriculture impact portfolio. It focuses on:

- irrigation scheduling — when, how much, and to which plots;
- root-zone soil-moisture intelligence — from field to district scale;
- evapotranspiration and crop-water-demand estimation;
- field-scale and scheme-scale water management operations;
- drought-adaptive irrigation planning and allocation;
- water productivity in physical ( $\text{kg}/\text{m}^3$ ) and economic ( $\text{value}/\text{m}^3$ ) terms;
- and tightly coupled concerns including soil salinity, drainage, delivery efficiency, and energy–water interaction.

## 3.2 What is explicitly out of scope

The following are addressed in Public-Good Briefings:

- **Paper 1:** Short-range operational agro-weather intelligence (precipitation, temperature, humidity, frost, heat stress) for day-to-day farm operations.

---

ction/drought-portal/d-iap/en

<sup>21</sup>NASA Goddard Space Flight Center, *NASA-USDA Global Soil Moisture Data* — global soil-moisture product at  $0.25^\circ \times 0.25^\circ$  resolution for agricultural monitoring, weather prediction, drought and flood early warning, and water-supply management. <https://earth.gsfc.nasa.gov/hydro/data/nasa-usda-global-soil-moisture-data>

<sup>22</sup>Drought.gov, *Drought and Soil Moisture Data* — operational soil-moisture products for agricultural drought monitoring and early warning. <https://www.drought.gov/topics/soil-moisture>

<sup>23</sup>FAO Global Soil Partnership, *Soil Salinity* — soil salinization takes up to 1.5 million hectares of farmland per year out of production; global annual cost in irrigated areas from salt-induced land degradation approximately USD 27.3 billion in lost crop production. <https://www.fao.org/global-soil-partnership/areas-of-work/soil-salinity/en/>

- **Paper 3:** Pest, disease, and livestock-stress early warning under altered precipitation and temperature regimes.
- **Paper 4:** Seasonal planning, food-system resilience, and disaster anticipation at national and regional scale.
- **Paper 5:** Crop biology, photosynthesis engineering, and targeted biological intervention design.

Cross-cutting delivery infrastructure — smallholder advisory services, digital access, public-sector institutional embedding — is referenced throughout but is not itself the subject of this paper.

### 3.3 How to read this dossier

Readers approaching from a ministry of agriculture or water, an irrigation authority, or a basin management body should focus on Sections 5, 7, and 8. Readers approaching from development finance should focus on Sections 9 and 10. Researchers and technical reviewers should focus on Sections 3, 4, 6, and 13. Governance and safeguards are in Section 14.

## 4 The Opportunity Baseline

### 4.1 Freshwater and irrigation in numbers

The quantitative case for Paper 2 is built on a small set of well-sourced anchor numbers:

Indicator	Value	Source
Agriculture share of global freshwater withdrawals (2020)	72%	FAO SOLAW 2025 <sup>24</sup>
Share of cropland equipped for irrigation	~22.5%	FAO SOLAW 2025 <sup>25</sup>
Share of global crop value from irrigated land	~48%	FAO SOLAW 2025 <sup>26</sup>
World Bank productivity claim (irrigated vs rainfed)	>2×	World Bank 2026 <sup>27</sup>
Annual cost of salt-induced land degradation in irrigated areas	USD 27.3B/yr	FAO GSP <sup>28</sup>

<sup>24</sup>FAO, *State of the World's Land and Water Resources for Food and Agriculture 2025 (SOLAW 2025)* — agriculture represented 72% of total freshwater withdrawals in 2020. <https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/scenarios-offer-insights-assumptions.html>

<sup>25</sup>FAO, *State of the World's Land and Water Resources for Food and Agriculture 2025 — Executive Summary and Status-Trends* — irrigated croplands represent approximately 22.5% of croplands and produce approximately 48% of crops in value terms. <https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/executive-summary.html>

<sup>26</sup>FAO, *State of the World's Land and Water Resources for Food and Agriculture 2025 — Executive Summary and Status-Trends* — irrigated croplands represent approximately 22.5% of croplands and produce approximately 48% of crops in value terms. <https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/executive-summary.html>

<sup>27</sup>World Bank Group, *Transforming Lives Through Climate-resilient Irrigation* (2026) — climate-resilient irrigation more than doubles productivity compared with rainfed agriculture; could feed 1.4 billion additional people. <https://shorthand.worldbankgroup.org/transforming-lives-through-climate-resilient-irrigation/>

<sup>28</sup>FAO Global Soil Partnership, *Soil Salinity* — soil salinization takes up to 1.5 million hectares of farmland per year out of production; global annual cost in irrigated areas from salt-induced land degradation approximately USD 27.3 billion in lost crop production. <https://www.fao.org/global-soil-partnership/areas-of-work/soil-salinity/en/>

Indicator	Value	Source
Annual irrigated farmland lost to salinization	up to 1.5M ha/yr	FAO GSP <sup>29</sup>
World Bank Nigeria TRIMING: area irrigated	43,400 ha	World Bank WfF <sup>30</sup>
World Bank Nigeria TRIMING: people fed	~1M people	World Bank WfF <sup>31</sup>
World Bank Morocco resilient agriculture: farmers reached	23,500+	World Bank 2022 <sup>32</sup>

These numbers frame the scale of the domain. The 72% freshwater share means any systematic improvement in agricultural water management has proportional implications for total freshwater availability and basin health. The 22.5%/48% asymmetry means that marginal improvements to irrigation decision quality act on the most productive segment of the global agricultural land base.

## 4.2 The World Bank productivity anchor in context

The claim that climate-resilient irrigation more than doubles productivity compared with rainfed agriculture<sup>33</sup> functions as a 2:1 floor for planning purposes. The actual mechanism is multi-part: more reliable water supply reduces yield variance, reduces stress events at critical phenological stages, enables higher-value crop choices, and supports multiple cropping seasons. Under a  $\tau$  advisory layer, all of these pathways would be operative, but the incremental gain would come from precision timing and root-zone management above and beyond the baseline benefits of physical irrigation infrastructure alone.

CGIAR/IWMI water-productivity studies provide granular benchmarks: physical water productivity for irrigated wheat in South Asia typically ranges from 0.8 to 1.2 kg/m<sup>3</sup>; for rice, from 0.5 to 0.9 kg/m<sup>3</sup>; and for high-value vegetables, from 2 to 6 kg/m<sup>3</sup>.<sup>34</sup> Moving a system from the lower end to the upper end of its existing productivity range — without expanding area or changing crop mix — is a realistic near-term  $\tau$  target.

## 4.3 The salinity baseline: a \$27.3B/yr problem

The FAO Global Soil Partnership’s figure of USD 27.3 billion per year in salinity-driven crop production losses<sup>35</sup> is particularly significant because it represents a **preventable accumulating**

<sup>29</sup>FAO Global Soil Partnership, *Soil Salinity* — soil salinization takes up to 1.5 million hectares of farmland per year out of production; global annual cost in irrigated areas from salt-induced land degradation approximately USD 27.3 billion in lost crop production. <https://www.fao.org/global-soil-partnership/areas-of-work/soil-salinity/en/>

<sup>30</sup>World Bank Group, *Water for Food results page* — TRIMING in Nigeria expanded irrigation across 43,400 hectares; food produced enough for 1 million people. <https://www.worldbank.org/ext/en/topic/water/water-for-food>

<sup>31</sup>World Bank Group, *Water for Food results page* — TRIMING in Nigeria expanded irrigation across 43,400 hectares; food produced enough for 1 million people. <https://www.worldbank.org/ext/en/topic/water/water-for-food>

<sup>32</sup>World Bank Group, *World Bank Supports Resilient and Sustainable Agriculture in Morocco* (2022) — 23,500+ farmers connected to advisory services focused on climate resilience and water productivity. <https://www.worldbank.org/en/news/press-release/2022/03/25/world-bank-supports-resilient-and-sustainable-agriculture-in-morocco>

<sup>33</sup>World Bank Group, *Transforming Lives Through Climate-resilient Irrigation* (2026) — climate-resilient irrigation more than doubles productivity compared with rainfed agriculture; could feed 1.4 billion additional people. <https://shorthand.worldbankgroup.org/transforming-lives-through-climate-resilient-irrigation/>

<sup>34</sup>CGIAR/IWMI, *Water Productivity Studies* — benchmark ranges for physical water productivity by crop and system type: wheat 0.8–1.2 kg/m<sup>3</sup>, rice 0.5–0.9 kg/m<sup>3</sup>, vegetables 2–6 kg/m<sup>3</sup>. See: Zwart, S.J. and Bastiaanssen, W.G.M. (2004). “Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize.” *Agricultural Water Management* 69(2), pp. 115–133. doi:10.1016/j.agwat.2004.04.007

<sup>35</sup>FAO Global Soil Partnership, *Soil Salinity* — soil salinization takes up to 1.5 million hectares of farmland per year out of production; global annual cost in irrigated areas from salt-induced land degradation approximately USD 27.3 billion

**cost**, not a one-time event. Salinization is typically detectable in its early stages through careful monitoring of electrical conductivity, water-table depth, drainage volumes, and soil water balance — exactly the domain where a tightly coupled  $\tau$  twin would generate actionable signal before irreversible damage occurs.

## 5 Working $\tau$ Assumptions

### 5.1 Explicit planning stance

This paper is assumption-led. The following six assumptions are adopted as a planning premise, not as externally validated claims. Each is explicitly flagged as such.

**Assumption 1 — Law-faithful physical twin.**  $\tau$  provides a discrete twin of weather–soil–water–crop dynamics that is physically lawful in the sense of preserving conservation structure, boundary conditions, and causal dependencies across coupled physical subsystems. In this stance, the model is not a statistical fit or a finite-difference approximation of an uncountable substrate; it is a coarse-grainable execution of the same lawful substrate.

**Assumption 2 — Structural alignment of precision and refinement.** In the  $\tau$  framework, refinement of the discretization does not introduce new degrees of freedom that are not already structurally latent at coarser resolution. This is crucial for irrigation because today’s water-balance and rainfall–runoff–infiltration–crop-demand chains often accumulate approximation drift when resolution changes.

**Assumption 3 — Bounded-error root-zone state estimation.** The system can estimate root-zone water status with bounded, formally characterizable error, enabling trustworthy decisions at the level of “apply / delay / reduce irrigation in this field or block within this envelope” rather than at the level of “precipitation is possible.”

**Assumption 4 — Water productivity as a native invariant.** Physical and economic water productivity can be tracked consistently within the  $\tau$  twin as structural properties of the model state, not as post-hoc KPIs derived from external data.

**Assumption 5 — Convergent stopping conditions.** Iterative decision computations (e.g., optimal allocation under constraint) converge finitely in the profinite/ultrametric substrate, supporting reliable stopping conditions for irrigation-scheduling and allocation engines.

**Assumption 6 — Scalability across spatial levels.**  $\tau$  can support field-level, scheme-level, and basin-level coordination within one formal framework, without requiring architectural bridges between separate models at each spatial scale.

### 5.2 What these assumptions do not claim

These assumptions do not assert that  $\tau$ ’s predictions have been externally benchmarked against operational irrigation data, that they have been accepted by agro-hydrological modeling communities, or that any of the impact scenarios in Sections 7–8 constitute official forecasts. They are planning inferences under an explicitly stated hypothesis.

## 6 What Changes with a Law-Faithful Twin

---

in lost crop production. <https://www.fao.org/global-soil-partnership/areas-of-work/soil-salinity/en/>

## 6.1 From weather-informed irrigation to water-state execution

Today’s irrigation decision support is typically a stitched system. A weather forecast arrives from one source; an ET estimate is computed separately, often with its own crop coefficients; soil-moisture data — if available — comes from sensors or satellite products not necessarily aligned with the ET model’s spatial resolution; scheme-delivery constraints are tracked in a separate operational system; and advisory messages are assembled downstream by extension officers or digital platforms.

This chain can produce useful guidance. But it creates structural weaknesses: the components do not update at the same cadence; uncertainty compounds at each handoff; local calibration assumptions are brittle when applied outside their calibration conditions; and it is formally difficult to know whether a given recommendation is physically robust or merely plausible given mutually consistent but separately constructed estimates.

Under Assumption 3, a  $\tau$ -native agricultural water twin changes the decision object. The relevant state is no longer a coarsely bounded forecast of “rain likely” or “potential ET elevated.” It becomes a jointly maintained model state comprising: present root-zone water content by layer and zone; expected evapotranspiration under forecast temperature, radiation, and vapor pressure deficit; incoming precipitation with bounded forecast uncertainty; crop growth stage and water-response envelope; and irrigation-delivery constraints (canal capacity, pump schedule, quota). That is a richer and more tightly coupled object than any current advisory layer exposes to operators at field or scheme scale.

## 6.2 From empirical trigger thresholds to bounded action windows

Current practice treats soil-moisture thresholds as triggers: irrigate if volumetric water content falls below a field-specific threshold, delay if rainfall is likely. These rules are useful but their interaction with real-time field conditions is approximate, and they carry no explicit error characterization.

Under Assumption 3, the  $\tau$  frame supports bounded action windows of the following type:

- *Irrigate plot A tonight within a volume range of  $V$  to  $V_2$  m<sup>3</sup>/ha, because the expected post-irrigation soil-water deficit will close the crop-stress risk for the next 48–72 hours;*
- *Defer plot B until after the rainfall window ending Wednesday, with less than  $X\%$  probability of crop-water stress during the delay period;*
- *Shift limited water allocation to plot C rather than plot D because the expected water-productivity loss per unit of deferral is lower at C’s current crop stage;*
- *Reduce irrigation in sector D because the marginal salinity and drainage risk from additional application exceeds the marginal yield gain from avoided stress.*

This is not merely a better dashboard. It represents a qualitative change in the coupling between physics, agronomy, and operations — one that current stitched systems cannot provide because they lack a shared physical state object over which all four decision types can be simultaneously reasoned.

## 6.3 From static modernization to continuous irrigation intelligence

FAO’s WaPOR framework explicitly links water productivity tracking to irrigation modernization: the premise is that knowing where delivery performance is poor helps target infrastructure investment.<sup>36</sup> Under current practice, this targeting is typically retrospective — a post-season assessment based on comparison of water productivity benchmarks.

<sup>36</sup>FAO, *WaPOR database* — open-access remote sensing platform for water productivity monitoring including actual ET, reference ET, relative soil moisture, biomass, precipitation, and water-productivity products at global, national, and scheme level. <https://www.fao.org/in-action/remote-sensing-for-water-productivity/wapor-data/en>; <https://www.fao.org/aquastat/en/geospatial-information/wapor/>

Under the  $\tau$  assumption, modernization would become a continuous intelligence process rather than a periodic capital planning exercise. The model state would expose, in near-real time: where in a scheme delivery losses are persistently occurring; which blocks are receiving water significantly above or below net irrigation requirement; where temporal mismatch between supply schedule and crop demand is creating stress events; and where physical infrastructure upgrades would generate the largest improvement in water productivity. This is not a replacement for physical infrastructure investment — it is a basis for targeting and evaluating it continuously.

## 6.4 From drought monitoring to drought action geometry

FAO's d-iap platform already points toward the class of capability this section concerns: it computes crop-specific net irrigation requirements, probability of meeting crop water needs, yield-loss probabilities, income impacts, and scenario comparisons under present and future climate conditions.<sup>37</sup> In spirit, this is very close to what a  $\tau$  drought advisory layer would provide.

The  $\tau$  increment is specificity and coupling to physical-control decisions. A drought advisory layer built on the  $\tau$  twin would support:

- how much water to allocate to which crops and districts in a given deficit period;
- where to cut application without pushing crops past recoverable stress;
- where deficit irrigation (scheduled partial withholding) is strategically tolerable across the season, and at which stages it is not;
- when it is preferable to switch a crop rather than continue investing increasingly scarce water in a likely-loss outcome;
- and when water saved today creates option value for a later critical growth stage, versus when immediate application protects irreplaceable phenological opportunity.

These are operationally specific decisions. Making them better is where the most direct yield-protection value lies during drought episodes.

## 7 Competitive and Incumbent Landscape

The irrigation decision-support space contains several well-established tools spanning the research-to-commercial spectrum. Understanding where each sits — in terms of capabilities, limitations, and positioning — defines the space  $\tau$  would enter.

### 7.1 DSSAT — Decision Support System for Agrotechnology Transfer

DSSAT is a suite of crop simulation models developed over decades by CGIAR-linked researchers and now maintained by the DSSAT Foundation.<sup>38</sup> It models crop growth, development, and yield as a function of weather, soil, and crop management, and has been applied globally for research, planning, and policy analysis. DSSAT includes modules for water balance, nitrogen cycling, and multi-crop scenarios.

**Capabilities:** Mechanistic crop-growth simulation; multi-season scenario analysis; strong calibration infrastructure for many crop types; widely used for research and CGIAR programme support.

<sup>37</sup>FAO, *d-iap — Drought Impact Assessment Platform on Water Productivity* — evaluates drought impacts on crop and water productivity; computes net irrigation requirements, yield-loss probabilities, and income impacts under current and future climate scenarios at approximately 9 km resolution using AquaCrop. <https://www.fao.org/in-action/drought-portal/d-iap/en>

<sup>38</sup>Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., and Ritchie, J.T. (2003). “The DSSAT cropping system model.” *European Journal of Agronomy* 18, pp. 235–265. DSSAT Foundation: <https://dssat.net/>

**Limitations:** Complex calibration requirements — reliable application requires crop-specific parameter estimation from local experimental data, which limits deployment at scale without dedicated agronomic fieldwork; not designed for real-time operational irrigation scheduling; limited integration with live sensor or satellite data streams; uncertainty is not formally bounded at the model output level.

$\tau$  **differentiation:**  $\tau$  would differ in operating as a live, continuously updated physical twin rather than a batch simulation tool; in formally bounding state uncertainty; and in coupling crop-water state directly to real-time advisory outputs without requiring crop-specific re-calibration at each new site.

## 7.2 RZWQM — Root Zone Water Quality Model

RZWQM is a USDA Agricultural Research Service (ARS) model for simulating soil-water dynamics, nutrient cycling, crop growth, and chemical movement in the root zone.<sup>39</sup> It is research-grade and used for understanding the coupled behavior of water, nutrients, and pesticides under various management scenarios.

**Capabilities:** Detailed simulation of root-zone processes including preferential flow, nitrogen cycling, and pesticide transport; strong for research on agricultural environmental impacts.

**Limitations:** Explicitly research-grade, not designed for operational farm advisory; high data requirements for parameterization; limited deployment at scheme or basin scale; no native real-time update path.

$\tau$  **differentiation:**  $\tau$  addresses the operational deployment gap — RZWQM informs research questions, while  $\tau$  would inform daily irrigation decisions at field and scheme scale under bounded uncertainty.

## 7.3 IrriWatch

IrriWatch is a European commercial service providing satellite-based irrigation advisory in more than 20 countries.<sup>40</sup> It uses remote sensing to estimate actual evapotranspiration, crop water stress, and irrigation requirements at field and scheme level, and delivers advisory outputs through web platforms and APIs.

**Capabilities:** Satellite-driven ET and crop-stress estimation; broad geographic coverage; scheme-scale performance assessment; relatively low-friction deployment compared to model-calibration-intensive tools.

**Limitations:** Satellite-based ET products carry limitations in temporal resolution (cloud cover, revisit frequency) and in the accuracy of actual ET estimation under varied canopy conditions; coupling to root-zone water state is indirect; uncertainty characterization is not formally bounded in the physical-twin sense; does not integrate forecast rainfall and pump scheduling in a unified state model.

$\tau$  **differentiation:**  $\tau$  would add formal state-uncertainty bounds, tighter integration of forecast rainfall and root-zone water dynamics, and the ability to reason across spatial scales (field, block, scheme, basin) within one physical world rather than assembling outputs from separate remote-sensing products.

<sup>39</sup>Ma, L., Ahuja, L.R., and Malone, R.W. (2007). “Systems modeling for sustainable agriculture.” *Advances in Agronomy* 93. USDA ARS RZWQM: Root Zone Water Quality Model documentation. <https://www.ars.usda.gov/plains-area/fort-collins-co/center-for-agricultural-resources-research/agricultural-systems-research-unit/docs/rzwqm2-model/>

<sup>40</sup>IrriWatch B.V. — satellite-based irrigation advisory service operating in 20+ countries; ET-based field and scheme water-productivity monitoring. <https://www.irriwatch.com/>

## 7.4 Hortau

Hortau is a Canadian commercial precision irrigation platform combining soil-tension sensors with analytics and advisory outputs, targeting high-value crops (vegetables, berries, tree fruits, vineyards).<sup>41</sup> It is field-scale and sensor-driven, with strong market penetration in North American irrigated horticulture.

**Capabilities:** High-resolution, real-time soil-tension monitoring; crop-specific irrigation trigger algorithms; strong track record in high-value horticultural contexts; intuitive advisory interface for growers.

**Limitations:** Sensor-dependent — deployment requires physical installation and maintenance at each field; economic model is suited to high-value crops where sensor cost is justified, less well-matched to staple crops at small-farm scale; does not provide basin-scale or scheme-level coordination; does not couple to forecast weather in a physically grounded way.

**$\tau$  differentiation:**  $\tau$  would provide bounded-error root-zone state estimation without requiring dense sensor networks, making it applicable at scale in smallholder and staple-crop contexts where Hortau’s hardware-intensive model is economically prohibitive.

## 7.5 aWhere

aWhere is a US agri-weather analytics company with a focus on Africa and other developing-world contexts.<sup>42</sup> It provides agronomic weather data, historical baselines, and crop-specific advisory APIs that development organizations, NGOs, and governments use for extension delivery, food-security monitoring, and climate-smart agriculture programs.

**Capabilities:** Strong coverage in data-sparse geographies; developer-friendly APIs; existing integrations with development-sector advisory platforms; good track record with USAID, FAO, and similar institutional clients.

**Limitations:** Analytics are weather-driven rather than soil–water–crop integrated; does not provide physically grounded root-zone state estimation; uncertainty is statistical rather than formally bounded; coverage depth varies by geography.

**$\tau$  differentiation:**  $\tau$  would add the soil-water and crop-response layers that convert weather information into physically grounded irrigation action advisories — the gap between “weather data” and “water-state execution.”

## 7.6 FAO WaPOR / d-iap / AquaCrop

The FAO public institutional stack represents the open-access baseline and the clearest institutional partner for  $\tau$  deployment.<sup>434445</sup>

<sup>41</sup>Hortau Inc. — soil-tension sensor network with analytics platform for precision irrigation management in high-value horticultural crops. <https://hortau.com/>

<sup>42</sup>aWhere Inc. — agronomic weather analytics platform with Africa and developing-world focus; APIs for extension, NGO, and government use. <https://www.ewhere.com/>

<sup>43</sup>FAO, *WaPOR database* — open-access remote sensing platform for water productivity monitoring including actual ET, reference ET, relative soil moisture, biomass, precipitation, and water-productivity products at global, national, and scheme level. <https://www.fao.org/in-action/remote-sensing-for-water-productivity/wapor-data/en;> <https://www.fao.org/aquastat/en/geospatial-information/wapor/>

<sup>44</sup>FAO, *d-iap* — *Drought Impact Assessment Platform on Water Productivity* — evaluates drought impacts on crop and water productivity; computes net irrigation requirements, yield-loss probabilities, and income impacts under current and future climate scenarios at approximately 9 km resolution using AquaCrop. <https://www.fao.org/in-action/drought-portal/d-iap/en>

<sup>45</sup>FAO, *AquaCrop* — *Crop-Water Productivity Model of FAO* — simulates yield response to water for a wide range of crops; designed for balance between simplicity, robustness, and applicability where water is the key limiting factor.

**WaPOR** provides open-access monitoring of actual and reference ET, relative soil moisture, biomass, precipitation, and water productivity at global, national, and scheme scale, with explicit links to irrigation modernization and performance assessment.

**d-iap** evaluates drought impacts on crop and water productivity, computes net irrigation requirements, and supports rainfed and irrigated system analysis globally at approximately 9 km resolution using the AquaCrop model.

**AquaCrop** formalizes yield response to water for a wide range of crops and environments, balancing mechanistic accuracy with applicability where water is the key limiting factor.

**Capabilities:** Open access, globally calibrated, officially supported by FAO, integrated into national and regional advisory systems, widely used in development programming.

**Limitations:** Spatial resolution limits field-scale precision; temporal resolution limits real-time operational use; uncertainty is not formally bounded; the three tools are partially coupled but not integrated into a single physical-state model; AquaCrop requires calibration for locally specific conditions.

**$\tau$  differentiation:**  $\tau$  would complement rather than compete with this stack — adding physical-state fidelity, formal error bounds, and real-time coupling above the FAO open-access layer, while retaining interoperability with WaPOR’s data products and d-iap’s institutional workflow integrations.

## 8 Structured Opportunity Map

### 8.1 Cluster A: Field-scale precision irrigation and deficit-irrigation control

**Scale context:** Global irrigated area is approximately 340 million hectares.<sup>46</sup> Even 10% penetration of this area through precision scheduling advisory represents 34 million ha — a domain where marginal water-use efficiency gains at 5–15% would correspond to 1–3% of total global freshwater withdrawals.

#### Opportunity areas:

1. **Hyperlocal irrigation scheduling** based on jointly maintained estimates of root-zone water status, forecast precipitation, ET demand, and crop growth stage. The output is an actionable window (volume, timing, block priority) rather than a probabilistic recommendation.
2. **Variable-rate irrigation** across heterogeneous plots and management zones. Spatial heterogeneity in soil texture, conductivity, and topography is a major source of over-application at field edges and under-application at problem zones. A physically grounded twin can expose this heterogeneity and support zone-specific scheduling.
3. **Deficit-irrigation optimization** where water supply is constrained but some yield trade-off is explicitly acceptable. Deficit irrigation is well-established agronomically (FAO AquaCrop formalizes the yield-response function)<sup>47</sup> but requires knowing at which growth stages deficit is tolerable and at which it is not — precisely the information a root-zone twin provides.

<https://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/category/details/en/c/1026354/>

<sup>46</sup>FAO, *State of the World’s Land and Water Resources for Food and Agriculture 2025 (SOLAW 2025)* — agriculture represented 72% of total freshwater withdrawals in 2020. <https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/scenarios-offer-insights-assumptions.html>

<sup>47</sup>FAO, *AquaCrop — Crop-Water Productivity Model of FAO* — simulates yield response to water for a wide range of crops; designed for balance between simplicity, robustness, and applicability where water is the key limiting factor. <https://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/category/details/en/c/1026354/>

4. **Fertigation timing** to reduce simultaneous water waste and nutrient loss. Nutrient application tied to irrigation events is sensitive to root-zone water state; poorly timed fertigation results in both nutrient leaching and unnecessary water application.
5. **Harvest-protection watering** in windows where late-season stress disproportionately reduces marketable yield or triggers premature senescence.

**Near-term beachhead:** Schemes already equipped with FAO AquaCrop or d-iap advisory workflows, where a  $\tau$  shadow layer can be validated against existing recommendations without requiring system replacement.

## 8.2 Cluster B: Irrigation-scheme operations and service delivery

**Scale context:** Large publicly managed irrigation schemes cover an estimated 200–250 million ha globally, concentrated in Asia and Africa.<sup>48</sup> Their operational performance is highly variable: delivery reliability, equity of allocation, and actual crop-productivity outcomes diverge substantially from design intent in many systems.

### Opportunity areas:

1. **Rotation planning** for canal systems and pump-fed networks, linking release schedules to real-time crop-water demand across the command area.
2. **Release scheduling** from reservoirs and balancing structures, synchronized with downstream crop-water state rather than fixed calendars.
3. **Delivery reliability tracking:** monitoring whether users are receiving water when and where promised, and identifying systematic mismatches between allocation schedule and actual delivery.
4. **Command-area prioritization** under heat or drought pulses, where limited water must be rationed across crops, blocks, or user groups with different sensitivity and water-productivity profiles.
5. **Modernization investment targeting:** identifying blocks where physical infrastructure upgrades (canal lining, pump efficiency, gate automation) would generate the largest improvements in water productivity, based on continuous performance monitoring rather than periodic audits.

## 8.3 Cluster C: Drought allocation and water-scarcity intelligence

**Scale context:** Agricultural drought affects an estimated 60–80 million people in any given year, with peak impacts in 2-year clusters under El Niño and La Niña forcing.<sup>49</sup> Proactive drought allocation — cutting and rationing before visible yield collapse — is among the highest-value interventions in water-stressed systems, but requires anticipatory information that current advisory stacks cannot reliably provide.

### Opportunity areas:

1. **Crop-specific net irrigation requirements** under current and forecast conditions — delivered as bounded estimates rather than scenario ranges.

<sup>48</sup>FAO, *State of the World's Land and Water Resources for Food and Agriculture 2025 (SOLAW 2025)* — agriculture represented 72% of total freshwater withdrawals in 2020. <https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/scenarios-offer-insights-assumptions.html>

<sup>49</sup>FAO, *d-iap — Drought Impact Assessment Platform on Water Productivity* — evaluates drought impacts on crop and water productivity; computes net irrigation requirements, yield-loss probabilities, and income impacts under current and future climate scenarios at approximately 9 km resolution using AquaCrop. <https://www.fao.org/in-action/drought-portal/d-iap/en>

2. **Probability-of-meeting-water-needs** for given allocation envelopes, informing policy decisions about where and how much to cut before irreversible crop damage occurs.
3. **Scenario testing for rationing and emergency water-sharing**, including both agricultural and municipal-use trade-offs.
4. **Regional crop-loss forecasting** under irrigation shortfall, to support anticipatory humanitarian and food-security action.
5. **Anticipatory action triggers**: specifying, in advance, the physical conditions at which specific actions are pre-authorized — an operationally important step that requires trustworthy physical-state estimates, not only probabilistic seasonal outlooks.

#### 8.4 Cluster D: Water-productivity benchmarking, finance, and performance contracts

**Scale context:** Development institutions, climate-finance bodies, and outcome-based agriculture programs are actively seeking verifiable water-productivity metrics that can underpin finance structures. The current state — using WaPOR benchmarks or CGIAR water-productivity surveys as proxies — is an imperfect substitute for real-time, plot-level tracking.

##### Opportunity areas:

1. **Physical water productivity** (kg/m<sup>3</sup>, biomass/m<sup>3</sup>, ET-adjusted productivity) tracked continuously and verifiably at plot, block, scheme, and basin scale.
2. **Economic water productivity** (crop value/m<sup>3</sup>, income/m<sup>3</sup>) computed as a function of physical productivity and market prices.
3. **Benchmarking** of farms, schemes, or districts against best-practice or design-intent baselines for modernization support and public accountability.
4. **Outcome-based finance and incentive design** tied to verified water-productivity gains — a structure that development banks are increasingly seeking but currently lack the measurement infrastructure to support.
5. **Insurance and credit products** underwritten by a trustworthy water-state model: index insurance products for irrigation failure, or credit products that price water-stress risk more accurately.

#### 8.5 Cluster E: Soil salinity, drainage, and long-horizon soil protection

**Scale context:** FAO estimates 20% of the world's irrigated land has some degree of salinity-related productivity loss.<sup>50</sup> The USD 27.3B/yr cost estimate represents a substantial fraction of the global irrigation capital stock being silently degraded annually.

##### Opportunity areas:

1. **Early salinity-risk detection** before yield damage becomes irreversible — integrating water-balance tracking with electrical-conductivity estimates and water-table depth monitoring.
2. **Drainage optimization and leaching planning**: computing when, how much, and where supplemental water application for salt leaching is agronomically necessary without exceeding drainage capacity.

---

<sup>50</sup>FAO Global Soil Partnership, *Soil Salinity* — soil salinization takes up to 1.5 million hectares of farmland per year out of production; global annual cost in irrigated areas from salt-induced land degradation approximately USD 27.3 billion in lost crop production. <https://www.fao.org/global-soil-partnership/areas-of-work/soil-salinity/en/>

3. **Water-quality-aware irrigation scheduling:** adjusting timing and volume based on source-water salinity variation (seasonal, source-switching, or mixing scenarios).
4. **Spatial targeting** of salt-tolerant crop or rotation interventions in blocks where structural salinity risk is highest.
5. **Avoiding modernization that raises short-run yield while worsening long-run soil condition:** a risk in schemes where efficiency improvements increase water savings that are then applied back to the same land, raising water tables and accelerating secondary salinization.

## 8.6 Cluster F: Energy–water coordination for pumped irrigation

**Scale context:** Pumped groundwater and lift irrigation cover an estimated 100–120 million ha globally, concentrated in South Asia, East Asia, and North Africa.<sup>51</sup> In Pakistan’s Punjab alone, approximately 4 million tube wells operate under electricity and diesel subsidy regimes that create perverse incentives for over-extraction.<sup>52</sup>

### Opportunity areas:

1. **Forecast-synchronized pumping:** scheduling pump operation to align with available power supply (time-of-use tariffs, grid stability windows, or solar-generation peaks) while meeting crop-water demand.
2. **Joint irrigation and solar-output optimization** where farms have PV arrays or grid-responsive tariff structures, allowing energy and water decisions to be co-optimized within the same model horizon.
3. **Lower energy cost per unit yield** through better watering decisions — reducing total pump hours without yield loss is a direct economic benefit for smallholders where energy cost is a binding constraint.
4. **Resilience planning** where pump-dependent irrigation is exposed to grid instability or fuel-price volatility: precomputing contingency schedules that protect critical crop stages under power-constrained scenarios.

This cluster connects naturally to the energy and grid portfolios developed elsewhere in the  $\tau$  programme and represents a near-term co-benefit opportunity where water and energy efficiency gains reinforce each other.

## 9 Geographic Case Studies

### 9.1 Case Study 1: Nile Basin Transboundary Water Allocation

#### Context and scale

The Nile Basin is one of the world’s most hydrologically contested transboundary river systems. The Eastern Nile sub-basin — encompassing Ethiopia, Sudan, and Egypt — concentrates the most acute allocation pressures. Egypt is among the world’s most irrigation-dependent large economies: FAO AQUASTAT estimates approximately **96 million ha under irrigation** in the Nile-dependent

<sup>51</sup>FAO, *State of the World’s Land and Water Resources for Food and Agriculture 2025 (SOLAW 2025)* — agriculture represented 72% of total freshwater withdrawals in 2020. <https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/scenarios-offer-insights-assumptions.html>

<sup>52</sup>Pakistan Bureau of Statistics / Punjab Irrigation Department — Punjab Province tube-well census and irrigated area data. Cited figures: approximately 7.2 million irrigated ha; approximately 4 million tube wells.

agricultural system, with over **12.5 million farmers** dependent on Nile-sourced water.<sup>53</sup> Egypt uses approximately **55.5 km<sup>3</sup> per year** of Nile water under the terms of the 1959 Nile Waters Agreement — an allocation established without contemporary hydrological data and without real-time adaptive management mechanisms.<sup>54</sup>

The construction and filling of the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile — with a full reservoir capacity of approximately **74 km<sup>3</sup>** and a generating capacity of 5,150 MW<sup>55</sup> — has made the allocation question structurally urgent. Ethiopia's Blue Nile catchment contributes approximately **59% of total Nile flow**,<sup>56</sup> meaning GERD filling episodes directly affect the flow volumes reaching downstream users. The Nile Basin Initiative and World Bank Nile Basin Trust Fund have both facilitated technical cooperation, but no binding real-time allocation protocol currently exists.<sup>57</sup>

### Baseline problem

The 1959 Agreement allocates fixed annual quantities (55.5 km<sup>3</sup> to Egypt, 18.5 km<sup>3</sup> to Sudan) without probabilistic drought-adjustment provisions, without real-time water-state intelligence, and without formal deficit-irrigation protocols. When inflow falls below expected levels — as in El Niño years — there is no pre-agreed, technically grounded mechanism for prorating cuts or sequencing reductions across the command area. Agricultural extension services in Egypt's Nile Delta and Upper Egypt lack field-level tools to translate a basin-level shortage signal into plot-by-plot irrigation adjustments.

### $\tau$ -enabled changes

A  $\tau$  deployment in the Eastern Nile context would operate at three coupled levels:

*Level 1 — Seasonal and annual discharge forecasting.* Bounded-error forecasting of Blue Nile flow at the Sudan border crossing, integrating Ethiopian highland precipitation forecasts, GERD reservoir management scenarios, and tributary contributions. This enables proactive — rather than reactive — allocation planning, with formal uncertainty characterization that allows policy-makers to act on probabilistic shortage signals months in advance.

*Level 2 — Deficit-irrigation strategy optimization for Egypt's command area.* Given a projected shortfall in annual allocation, the model would compute optimal deficit-irrigation schedules by crop, block, and growth stage across Egypt's Nile-dependent irrigated area. The key distinction from current practice is that the deficit schedule would be grounded in a jointly maintained physical state model of root-zone water dynamics — not derived from fixed rules applied to aggregate shortage volumes. The ICBA (International Center for Biosaline Agriculture) has documented deficit-irrigation approaches for the region that provide an institutional baseline for this work.<sup>58</sup>

*Level 3 — Earlier drought triggers for transboundary coordination.* The model would provide shared physical-state information that all basin parties could consult, reducing the information asymmetries that currently complicate early-stage diplomatic engagement over allocation. A credible, jointly

<sup>53</sup>FAO AQUASTAT — Nile Basin and Egypt irrigation data: Egypt uses approximately 55.5 km<sup>3</sup>/yr of Nile water; approximately 12.5 million farmers dependent on Nile-sourced irrigation. <https://www.fao.org/aquastat/en/countries-and-basins/river-basins/nile-basin/>

<sup>54</sup>FAO AQUASTAT — Nile Basin and Egypt irrigation data: Egypt uses approximately 55.5 km<sup>3</sup>/yr of Nile water; approximately 12.5 million farmers dependent on Nile-sourced irrigation. <https://www.fao.org/aquastat/en/countries-and-basins/river-basins/nile-basin/>

<sup>55</sup>Ethiopian Electric Power / Grand Ethiopian Renaissance Dam project documentation — full reservoir capacity approximately 74 km<sup>3</sup>; generating capacity 5,150 MW. Multiple sources including: USBR and African Development Bank project assessments.

<sup>56</sup>Conway, D. (2005). “From headwater tributaries to international river: Observing and adapting to climate variability and change in the Nile Basin.” *Global Environmental Change* 15(2), pp. 99–114. Blue Nile contribution approximately 59% of total Nile flow at Aswan.

<sup>57</sup>Nile Basin Initiative — technical cooperation framework and documentation. <https://www.nilebasin.org/>

<sup>58</sup>ICBA (International Center for Biosaline Agriculture) — documentation on deficit irrigation and saline-water irrigation management in the MENA region. <https://www.biosaline.org/research/water>

maintained hydrological twin creates a neutral technical basis for trigger-based cooperation protocols.

### Worked numbers

- If deficit-irrigation optimization reduced average irrigation application by 10% across Egypt’s irrigated area (a conservative estimate given typical over-application margins in flood- and surface-irrigated systems), the annual saving would be approximately 5.5 km<sup>3</sup> — roughly 10% of Egypt’s entire allocation. At Egypt’s average physical water productivity for wheat (~0.9 kg/m<sup>3</sup><sup>59</sup>), this would represent water freed for reallocation without proportional yield loss.
- GERD’s 74 km<sup>3</sup> reservoir capacity means that a one-year filling cycle could temporarily reduce downstream flow by 20–35 billion m<sup>3</sup>; deficit-irrigation scheduling calibrated to this uncertainty range would significantly reduce the risk of crop failure during filling years.

**Key organizations:** Nile Basin Initiative, FAO AQUASTAT, World Bank Nile Basin Trust Fund, ICBA, Egyptian Ministry of Water Resources and Irrigation.

## 9.2 Case Study 2: Pakistan Punjab Groundwater Depletion Crisis

### Context and scale

Punjab Province, Pakistan, is one of South Asia’s most productive agricultural regions and one of the world’s most acute examples of unsustainable groundwater extraction. The province contains approximately **7.2 million irrigated hectares** and an estimated **4 million tube wells**,<sup>60</sup> many of which operate under subsidized electricity or diesel regimes that effectively eliminate price signals for water conservation. IWMI studies on Punjab groundwater document water-table declines of **0.3 to 1.0 meters per year** in key districts of central and northern Punjab.<sup>61</sup> The World Bank estimates annual economic losses from waterlogging and salinity across Pakistan at **USD 2 billion or more**, affecting multiple million hectares of previously productive land.<sup>62</sup>

### Baseline problem

The current advisory landscape for Punjab irrigation is severely fragmented. There is no integrated soil-moisture plus ET plus groundwater model operating at the field or district level. Farmers lack advisory guidance on when and how much to pump; irrigation scheduling is largely based on experiential rules, crop calendars, and neighbor behavior, rather than root-zone water state. Electricity subsidies for tube wells remove the price signal that might otherwise discourage over-extraction. The result is chronic over-application in many districts — driving both waterlogging (in areas with shallow water tables) and progressive salinization — alongside simultaneous depletion of deeper aquifers in other areas.

Pakistan Agricultural Research Council (PARC) and IWMI have both documented these dynamics and called for improved soil-water monitoring and advisory infrastructure.<sup>63</sup>

<sup>59</sup>CGIAR/IWMI, *Water Productivity Studies* — benchmark ranges for physical water productivity by crop and system type: wheat 0.8–1.2 kg/m<sup>3</sup>, rice 0.5–0.9 kg/m<sup>3</sup>, vegetables 2–6 kg/m<sup>3</sup>. See: Zwart, S.J. and Bastiaanssen, W.G.M. (2004). “Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize.” *Agricultural Water Management* 69(2), pp. 115–133. doi:10.1016/j.agwat.2004.04.007

<sup>60</sup>Pakistan Bureau of Statistics / Punjab Irrigation Department — Punjab Province tube-well census and irrigated area data. Cited figures: approximately 7.2 million irrigated ha; approximately 4 million tube wells.

<sup>61</sup>IWMI (International Water Management Institute) — Pakistan Punjab groundwater depletion studies. References include: Qureshi, A.S., McCornick, P.G., Sarwar, A., and Sharma, B.R. (2010). “Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan.” *Water Resources Management* 24(6), pp. 1551–1569. IWMI country program: <https://www.iwmi.cgiar.org/research/topics/water-scarcity/>

<sup>62</sup>World Bank, *Pakistan Groundwater Management Project* documentation and associated economic impact assessments noting USD 2B+ annual losses from waterlogging and salinity. <https://projects.worldbank.org/en/projects-operations/project-detail/P174694>

<sup>63</sup>IWMI (International Water Management Institute) — Pakistan Punjab groundwater depletion studies. References include: Qureshi, A.S., McCornick, P.G., Sarwar, A., and Sharma, B.R. (2010). “Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan.” *Water Resources Management* 24(6), pp. 1551–1569. IWMI

### $\tau$ -enabled changes

A  $\tau$  deployment in Punjab would prioritize four coupled interventions:

*Irrigation scheduling from root-zone state.* Field-scale advisories calibrated to root-zone water content by crop and growth stage would provide a principled basis for pump scheduling. IWMI estimates that optimized scheduling in Punjab could reduce groundwater extraction by **10–20%** without yield loss — a range consistent with the over-application margins documented in field studies.<sup>64</sup> For a province with approximately 7.2 million irrigated ha, a 10–15% reduction in water extraction would correspond to a substantial fraction of annual aquifer overdraft.

*Salinity early warning.* Integration of soil water-balance tracking with electrical-conductivity priors would allow early identification of plots trending toward salinity damage — enabling targeted intervention (adjusted scheduling, leaching, salt-tolerant variety substitution) before irreversible productivity loss occurs.

*Energy cost reduction.* Better scheduling reduces pump hours. For smallholders paying market or subsidized rates for electricity, the direct cost saving is an adoption incentive independent of yield protection. At average Punjab pump efficiencies and electricity costs, a 15% reduction in pump hours translates to meaningful per-farm seasonal savings.

*Aquifer monitoring integration.* A  $\tau$  twin calibrated to GRACE satellite groundwater anomaly data and local piezometric observations could provide district-level aquifer depletion tracking, making the cumulative extraction trend visible to planners and policy-makers in a way that the current monitoring network cannot.

### Worked numbers

- Punjab’s ~7.2 million irrigated ha, at typical application rates of 8,000–12,000 m<sup>3</sup>/ha/yr for wheat–rice double-cropping, implies total annual groundwater extraction on the order of **57–86 km<sup>3</sup>/yr** from tube wells alone. A 10% scheduling efficiency gain would free approximately **6–9 km<sup>3</sup>/yr** — comparable to medium-sized surface-water reservoirs.
- World Bank Pakistan Groundwater Management Project has flagged waterlogging and salinity as a USD 2B+/yr economic drain;<sup>65</sup>  $\tau$ -assisted early salinity detection that prevents even 5% of this loss would generate USD 100M+/yr in economic value — a conservative estimate of the B:C numerator for institutional investment.

**Key organizations:** Pakistan Agricultural Research Council (PARC), IWMI Pakistan country program, World Bank Pakistan Irrigation and Drainage project, Punjab Irrigation Department, Pakistan Meteorological Department.

## 9.3 Case Study 3 (Supplementary): India Punjab and Haryana Rice–Wheat Groundwater System

India is the world’s largest groundwater user, pumping approximately **251 km<sup>3</sup> per year** from aquifers — more than China and the United States combined.<sup>66</sup> Punjab and Haryana states together account for approximately 25% of India’s tube-well irrigation, concentrated in the rice–wheat double-

country program: <https://www.iwmi.cgiar.org/research/topics/water-scarcity/>

<sup>64</sup>IWMI (International Water Management Institute) — Pakistan Punjab groundwater depletion studies. References include: Qureshi, A.S., McCornick, P.G., Sarwar, A., and Sharma, B.R. (2010). “Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan.” *Water Resources Management* 24(6), pp. 1551–1569. IWMI country program: <https://www.iwmi.cgiar.org/research/topics/water-scarcity/>

<sup>65</sup>World Bank, *Pakistan Groundwater Management Project* documentation and associated economic impact assessments noting USD 2B+ annual losses from waterlogging and salinity. <https://projects.worldbank.org/en/projects-operations/project-detail/P174694>

<sup>66</sup>FAO AQUASTAT, *Groundwater* — India groundwater withdrawal approximately 251 km<sup>3</sup>/year; world’s largest extractor. <https://www.fao.org/aquastat/en/overview/methodology/groundwater>

cropping belt that supplies much of India’s public food grain procurement. FAO and World Bank documentation notes water-table declines of **0.5 to 4.0 cm/year** across parts of northwestern India,<sup>67</sup> with marked acceleration in districts where transplanted rice has been the dominant summer crop for decades.

The policy urgency is high: the Indian government has introduced legal restrictions on rice transplanting dates in Punjab (the Punjab Preservation of Subsoil Water Act) as a demand-management measure, but enforcement is partial and the underlying advisory infrastructure for real-time irrigation management remains limited. A  $\tau$  advisory layer operating on the same institutional channels as India’s existing agrometeorological advisory network — ICAR, State Agricultural Universities, IMD agromet advisories — would provide the physical-state grounding currently absent from water-management guidance at the district and block level.

## 10 Finance, ROI, and Climate-Finance Eligibility

### 10.1 Development finance landscape

**World Bank Water for Food portfolio.** The World Bank’s Water for Food program has an active lending portfolio in excess of **USD 4.5 billion** across irrigation, water management, and agricultural productivity projects, with an explicit climate adaptation and resilience lens.<sup>68</sup> Project designs increasingly require demonstration of water-productivity gains and climate-resilience outcomes — exactly the domain where  $\tau$  advisory infrastructure would provide verifiable evidence. The World Bank IDA climate lens adds concessional financing terms for adaptation components in eligible countries, reducing the cost of capital for public-good irrigation intelligence investments in the poorest countries.<sup>69</sup>

**Green Climate Fund (GCF).** GCF’s adaptation program includes a watershed protection and water productivity window under its “sustainable land use” program area.<sup>70</sup> GCF has funded irrigation efficiency, water productivity, and smallholder climate resilience projects in sub-Saharan Africa, South Asia, and the Pacific. A  $\tau$  irrigation intelligence deployment would qualify under the resilience rationale — reducing agricultural water demand and protecting yields under climate-driven precipitation variability.

**IFAD Rural Water Management window.** IFAD’s climate resilience and rural water management portfolio supports smallholder water access and management in developing countries, with particular attention to marginalized and women-headed households.<sup>71</sup> IFAD programming typically requires strong co-benefit evidence on gender equity and smallholder livelihood impact — criteria discussed in Section 12.

**MDB climate finance more broadly.** Asian Development Bank, African Development Bank, and Inter-American Development Bank all maintain active irrigation and water-productivity lending windows with climate adaptation framing. Total multilateral development bank (MDB) agricultural

<sup>67</sup>World Bank and FAO documentation on Indian Punjab and Haryana groundwater depletion. See: Fishman, R.M., Siegfried, T., Raj, P., Modi, V., and Lall, U. (2011). “Over-extraction from shallow bedrock versus deep alluvial aquifers: Reliability versus sustainability considerations for India’s groundwater irrigation.” *Water Resources Research* 47, W00L05. Water-table decline rates 0.5–4.0 cm/yr in parts of northwestern India.

<sup>68</sup>World Bank Group, *Water for Food — Climate-Resilient Irrigation portfolio page*. <https://www.worldbank.org/en/topic/climate-resilient-irrigation>

<sup>69</sup>World Bank IDA, *Climate Lens* — additional concessional terms for climate adaptation components in IDA-eligible countries. <https://ida.worldbank.org/en/financing/climate>

<sup>70</sup>Green Climate Fund, *Adaptation Programme* — watershed protection, water productivity, and sustainable land-use program windows. <https://www.greenclimate.fund/projects/adaptation>

<sup>71</sup>IFAD, *Rural Water Management and Climate Resilience* programme documentation — smallholder water access, gender equity, and climate resilience in agricultural water management. <https://www.ifad.org/en/web/knowledge/-/publication/water-and-food-security>

climate finance exceeded USD 6 billion per year in 2023–2024.<sup>72</sup>

## 10.2 Cost scenarios

**Scenario 1 — Shadow-mode national advisory layer.** A  $\tau$  advisory layer integrated into existing national irrigation authority systems, operating in shadow mode alongside current tools (WaPOR, d-iap, national agromet advisories) and delivering incremental bounded-error recommendations to extension and operator channels.

- Estimated cost: **USD 3–8 million per national implementation**, covering 200,000–500,000 hectares
- Breakdown: computational infrastructure (cloud or hybrid), integration APIs with existing data layers, national partner training and co-development, field validation and calibration
- This is comfortably within a single World Bank IDA or GCF project component

**Scenario 2 — Regional basin coordination platform.** A multi-country basin coordination platform covering one major river basin or regional aquifer system, integrating field-level advisory with scheme and basin-level allocation intelligence.

- Estimated cost: **USD 20–50 million**, serving 3–5 million hectares across 3–5 countries
- Breakdown: multi-country computational infrastructure, bilateral data-sharing agreements, trans-boundary coordination protocols, government integration, extended validation and iteration
- This corresponds to a World Bank regional program or GCF flagship project scale

## 10.3 ROI benchmarks

The World Bank’s own assessment of irrigation improvement projects in developing countries documents **benefit-to-cost ratios of 1.5:1 to 4:1**.<sup>73</sup> The  $\tau$  advisory increment sits above the low-cost end of this range because it is additive to existing infrastructure rather than requiring new physical construction. The relevant comparison is not irrigation infrastructure alone but the marginal value of advisory intelligence over the existing institutional baseline.

Using the World Bank’s “doubles productivity vs rainfed” anchor as a 2:1 productivity floor<sup>74</sup>, and assuming that a  $\tau$  advisory layer captures 10–20% of the gap between current irrigated-land performance and design-intent performance (a conservative assumption given documented over-application and scheduling inefficiency rates), the expected economic returns from advisory investment alone would typically exceed a 3:1 B:C ratio at scheme scale.

Additional climate-co-benefit crediting — under GCF, carbon credits from reduced groundwater pumping, or adaptation premium pricing in insurance products — can materially improve effective project economics.

## 10.4 Revenue and sustainability models

Beyond grant and concessional finance, three sustainability models are viable at scale:

<sup>72</sup>Climate Policy Initiative, *Global Landscape of Climate Finance 2023* — MDB agricultural climate finance flows. <https://www.climatepolicyinitiative.org/>

<sup>73</sup>World Bank, *Irrigation Project Economic Analysis* documentation — B:C ratios for irrigation improvement projects in developing countries range from 1.5:1 to 4:1. See: World Bank (2016), *Water in Agriculture: Improving Performance, Meeting Demands*, and associated project appraisal documentation.

<sup>74</sup>World Bank Group, *Transforming Lives Through Climate-resilient Irrigation* (2026) — climate-resilient irrigation more than doubles productivity compared with rainfed agriculture; could feed 1.4 billion additional people. <https://shorthand.worldbankgroup.org/transforming-lives-through-climate-resilient-irrigation/>

1. **National government service fee:** Irrigation authorities charge water-user associations or scheme operators a per-hectare service fee for precision advisory, recovering deployment costs within 3–5 years at USD 5–15/ha/yr advisory pricing.
2. **Outcome-linked finance:** Development bank loans with interest-rate incentives tied to verified water-productivity improvement, funded by the water-cost savings that the advisory layer generates.
3. **Insurance product integration:** Agricultural weather and irrigation-failure index insurance products that use  $\tau$  water-state estimates as the trigger index — licensing the model state to insurers generates a recurring revenue stream that cross-subsidizes public advisory access.

## 11 Evidence and Translation Ladder

### 11.1 Phase 1 — Shadow mode on existing systems (0–18 months)

**Goal:** Demonstrate incremental value without requiring institutional replacement; establish baseline performance metrics.

**Entry points:** - FAO WaPOR data layers and APIs as primary satellite input<sup>75</sup> - FAO d-iap drought-impact and irrigation-requirement workflows as comparative benchmark<sup>76</sup> - National agrometeorological advisory systems as existing distribution channel - Irrigation-district records on deliveries, rotations, and pump operation - Soil-moisture sensors, weather stations, and farm records where available

**Deliverables:** -  $\tau$ -generated irrigation recommendations running in parallel with existing national advisories - Root-zone soil-moisture nowcasts and 3–10 day forecasts - Post-hoc comparison of forecast error and water applied per unit yield against baseline - Confidence maps with formally characterized uncertainty bounds

**KPIs:** Root-zone moisture forecast RMSE vs in-situ; net irrigation requirement error vs AquaCrop estimate; advisory uptake rate (target >15% in year 1).

### 11.2 Phase 2 — District and scheme pilots (12–36 months)

**Goal:** Move from advisory comparison to operator-in-the-loop water management in 4–6 named pilot contexts.

**Pilot archetypes:** 1. Canal command area with multi-crop rotation and seasonal scheduling challenges 2. Groundwater/pumped-irrigation cluster with energy-cost constraints and depletion pressure 3. Salinity-prone scheme requiring drainage and water-quality monitoring integration 4. Smallholder advisory region where mobile delivery is the primary interface

**Deliverables:** - Real-time allocation and rotation recommendations delivered to scheme operators - Water-productivity dashboards benchmarked against WaPOR or CGIAR baselines - Seasonal drought contingency plans with pre-agreed trigger thresholds - Modernization investment targeting maps

<sup>75</sup>FAO, *WaPOR database* — open-access remote sensing platform for water productivity monitoring including actual ET, reference ET, relative soil moisture, biomass, precipitation, and water-productivity products at global, national, and scheme level. <https://www.fao.org/in-action/remote-sensing-for-water-productivity/wapor-data/en>; <https://www.fao.org/aquastat/en/geospatial-information/wapor/>

<sup>76</sup>FAO, *d-iap* — *Drought Impact Assessment Platform on Water Productivity* — evaluates drought impacts on crop and water productivity; computes net irrigation requirements, yield-loss probabilities, and income impacts under current and future climate scenarios at approximately 9 km resolution using AquaCrop. <https://www.fao.org/in-action/drought-portal/d-iap/en>

**KPIs:** Water applied per unit yield (target 5–15% reduction vs baseline); number of avoidable stress events prevented; delivery timing error; advisory adoption rate (target >30% in engaged districts).

### 11.3 Phase 3 — Basin-scale and finance-linked deployment (24–60 months)

**Goal:** Establish  $\tau$  water intelligence as a planning and investment infrastructure layer for development banks and government programs.

**Uses:** - Basin-level drought planning and allocation pre-agreements - Investment screening for irrigation modernization programs - Insurance and credit products using water-state intelligence as trigger index - Public accountability dashboards for irrigation service performance monitoring - Climate-resilient agricultural planning linked to World Bank, GCF, and IFAD programs

**KPIs:** B:C ratio in pilot schemes (target >2:1); area under verifiable water-productivity monitoring; number of financial products using  $\tau$  water-state as input; transboundary coordination episodes using  $\tau$  as shared technical basis.

### 11.4 Phase 4 — Full agrifood integration (36–96 months)

**Goal:** Connect irrigation intelligence with the broader  $\tau$  agrifood twin.

The full integration would link Water for Food (this paper) with operational agro-weather (Paper 1), pest and disease warning (Paper 3), seasonal planning and food-system resilience (Paper 4), and crop-biology and breeding intelligence (Paper 5). The coupling is natural: water state is a common state variable across all five domains, and the  $\tau$  framework's scalability claim (Assumption 6) means that field-level water intelligence can be coherently aggregated into seasonal and system-level analysis.

**KPIs:** Cross-paper model integration milestones; coverage of the agriculture portfolio's combined opportunity map.

## 12 Stakeholder Map and Change Management

### 12.1 Primary institutional stakeholders

**Ministries of agriculture and water resources** are the natural anchor for national deployment. They control the institutional mandates, the irrigation authority structures, and the extension systems through which advisory services reach farmers. Their primary interest is in food security, productivity, and water allocation — exactly what  $\tau$  serves.

**Irrigation district authorities and basin agencies** are the operational layer. They manage canal releases, pump schedules, rotation planning, and water-user association relationships. They are the immediate beneficiaries of better scheme-operational intelligence and the most likely early adopters if the advisory layer provides genuinely actionable improvement over existing tools.

**National meteorological and hydrological services (NMHSs)** provide the weather and hydrology data inputs that  $\tau$  would integrate. They are natural infrastructure partners rather than competitors, and in many countries already serve as the institutional host for agricultural weather advisory programs.

**Development banks (World Bank, ADB, AfDB, IFAD)** are the primary finance channel. Their project design teams, results-measurement units, and country offices are the institutional gateway to deployment at national scale.

**FAO and CGIAR** are both institutional partners and potential validators. Their existing tool

stacks (WaPOR, d-iap, AquaCrop, IWMI water-productivity databases) are the most natural interoperability targets for  $\tau$  integration.

## 12.2 Secondary stakeholders

**Farmer cooperatives and water-user associations** are the last-mile delivery point in most scheme contexts. Their trust in advisory services — established through consistent accuracy and actionable guidance — is a prerequisite for behavioral change at the field level.

**NGOs and extension services** provide the field presence and language capability to translate digital advisories into farm-level action, particularly for smallholders with limited digital access.

**Agricultural insurers and lenders** are emerging institutional stakeholders with growing interest in better water-state data for product design and risk pricing.

## 12.3 Change management priorities

The primary change management challenge is not technical adoption but **institutional trust**. Irrigation operators and farmers are often skeptical of new advisory tools, especially those that deviate from established rules and calendars. The deployment ladder's shadow-mode phase is specifically designed to build trust through demonstrated accuracy before requesting behavioral change.

A second challenge is **data sovereignty**: transboundary deployments (Nile Basin, Indus) require formal data-sharing agreements and confidence that the model's physical state does not give any party an informational advantage that could be weaponized in allocation negotiations. Shared governance structures for the model state are a prerequisite for transboundary uptake.

# 13 Gender, Equity, and Labor Dimensions

## 13.1 Women's land and water rights

Women farmers manage a substantial share of smallholder plots in sub-Saharan Africa, South Asia, and Southeast Asia — regions that overlap substantially with the high-priority deployment geographies for  $\tau$  irrigation intelligence. However, women face systematic disadvantages in access to irrigation infrastructure, water rights, extension services, and digital advisory platforms. FAO and IFAD have both documented the gender gap in irrigation access and its productivity consequences.<sup>77</sup>

A  $\tau$  deployment that does not explicitly address the gender dimension risks replicating the access inequalities of existing advisory services. Design requirements include: delivery channels that reach women farmers (mobile advisory through women's extension networks; community radio; cooperative channels with women's membership); advisory languages and formats appropriate to women's literacy levels and decision-making contexts; and water-productivity metrics that capture the crops and plots most commonly managed by women (often vegetable gardens and secondary plots rather than main staple fields).

---

<sup>77</sup>IFAD, *Rural Water Management and Climate Resilience* programme documentation — smallholder water access, gender equity, and climate resilience in agricultural water management. <https://www.ifad.org/en/web/knowledge/-/publication/water-and-food-security>

## 13.2 Groundwater equity

Groundwater access is deeply unequal in many high-priority geographies. In Punjab (Pakistan and India), access to tube wells correlates strongly with landholding size, credit access, and energy subsidies that favor larger farms. A  $\tau$  advisory layer that improves irrigation scheduling for large tube-well operators without addressing smallholder access dynamics would widen, not narrow, the productivity gap.

Deployment designs should include: public advisory channels that provide  $\tau$ -grounded irrigation guidance to smallholders who share access to community wells or water-user association systems; mobile-first interfaces that do not require private sensor installation; and integration with existing publicly funded extension and cooperative channels.

## 13.3 Smallholder access and the digital divide

The deployment scenarios in Section 10 explicitly include mobile delivery as a primary last-mile channel for Phase 2 pilot sites. Design principles for smallholder-appropriate advisory include: low-bandwidth delivery (SMS or USSD rather than data-intensive apps); locally calibrated outputs in regional languages; simple actionable formats (“irrigate today / delay 2 days / reduce by 30%”) rather than complex dashboards; and offline or cached delivery for areas with intermittent connectivity.

FAO’s digital services portfolio provides an institutional template for this class of delivery at national scale.<sup>78</sup>

# 14 Benchmark Suite and Success Metrics

A credible  $\tau$  irrigation program must be judged against metrics that irrigation operators, agronomists, and development financiers already use and trust.

## 14.1 Physical and agronomic metrics

Metric	Target	Measurement basis
Root-zone soil-moisture forecast RMSE	$\leq 0.03 \text{ m}^3/\text{m}^3$ (10 cm layer) vs in-situ or calibrated proxy	In-situ sensors or NASA-USDA product comparison <sup>7980</sup>
Net irrigation requirement error	$\leq 10\%$ vs AquaCrop/d-iap estimate	FAO d-iap as benchmark <sup>8182</sup>

<sup>78</sup>FAO Digital Services Portfolio — digital advisory service infrastructure at national and global scale. <https://www.fao.org/digital-services/about/en>

<sup>79</sup>NASA Goddard Space Flight Center, *NASA-USDA Global Soil Moisture Data* — global soil-moisture product at  $0.25^\circ \times 0.25^\circ$  resolution for agricultural monitoring, weather prediction, drought and flood early warning, and water-supply management. <https://earth.gsfc.nasa.gov/hydro/data/nasa-usda-global-soil-moisture-data>

<sup>80</sup>Drought.gov, *Drought and Soil Moisture Data* — operational soil-moisture products for agricultural drought monitoring and early warning. <https://www.drought.gov/topics/soil-moisture>

<sup>81</sup>FAO, *d-iap — Drought Impact Assessment Platform on Water Productivity* — evaluates drought impacts on crop and water productivity; computes net irrigation requirements, yield-loss probabilities, and income impacts under current and future climate scenarios at approximately 9 km resolution using AquaCrop. <https://www.fao.org/in-action/drought-portal/d-iap/en>

<sup>82</sup>FAO, *AquaCrop — Crop-Water Productivity Model of FAO* — simulates yield response to water for a wide range of crops; designed for balance between simplicity, robustness, and applicability where water is the key limiting factor. <https://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/category/detail>

Metric	Target	Measurement basis
Water applied per unit harvested yield	5–15% reduction vs baseline	Plot-level tracking, WaPOR comparison <sup>83</sup>
Physical water productivity (kg/m <sup>3</sup> )	≥upper quartile of regional CGIAR benchmark range	CGIAR/IWMI water-productivity database <sup>84</sup>
Avoidable stress days at critical crop stages	≥30% reduction vs control group	Crop model validation
Delivery timing deviation within scheme	Reduction in variance vs prior-season baseline	Scheme operator records
Salinity risk indicator (EC trend)	Early detection ≥12 months before yield damage threshold	Soil EC monitoring

## 14.2 Operational metrics

Metric	Target
Advisory adoption rate	≥30% of target farmers by end of Phase 2
Irrigation-window execution rate	≥70% of recommended windows acted upon within ±12 hours
Pumping-hour reduction	≥10% reduction per unit yield in groundwater-dependent pilots
Emergency watering events prevented	≥20% reduction vs baseline
Time from forecast update to advisory delivery	≤6 hours for short-range decisions

## 14.3 Economic and public-good metrics

Metric	Target
Pilot scheme B:C ratio	≥2.0:1 at 5-year horizon
Net farm income effect (enrolled farms)	≥5% improvement vs control group
Scheme water-service cost per m <sup>3</sup> delivered	≥5% reduction
Smallholder reach	≥50% of enrolled farmers holding ≤2 ha
Area with active salinity protection monitoring	100% of Phase 3 enrolled ha

s/en/c/1026354/

<sup>83</sup>FAO, *WaPOR database* — open-access remote sensing platform for water productivity monitoring including actual ET, reference ET, relative soil moisture, biomass, precipitation, and water-productivity products at global, national, and scheme level. <https://www.fao.org/in-action/remote-sensing-for-water-productivity/wapor-data/en>; <https://www.fao.org/aquastat/en/geospatial-information/wapor/>

<sup>84</sup>CGIAR/IWMI, *Water Productivity Studies* — benchmark ranges for physical water productivity by crop and system type: wheat 0.8–1.2 kg/m<sup>3</sup>, rice 0.5–0.9 kg/m<sup>3</sup>, vegetables 2–6 kg/m<sup>3</sup>. See: Zwart, S.J. and Bastiaanssen, W.G.M. (2004). “Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize.” *Agricultural Water Management* 69(2), pp. 115–133. doi:10.1016/j.agwat.2004.04.007

## 15 Governance Guardrails

Six structural safeguards are necessary to ensure that  $\tau$  irrigation intelligence serves public good rather than reinforcing existing inequalities or enabling perverse incentives.

**Guardrail 1 — No rebound authorization.**  $\tau$ -enabled water savings must not be automatically reallocated to irrigation area expansion. The governance framework for any deployment must include explicit provisions that efficiency gains are applied first to reducing extraction from stressed aquifers, then to ecosystem flow maintenance, before being available for production expansion. This must be a legal or contractual provision in national deployment agreements, not merely a programmatic aspiration.

**Guardrail 2 — Equity-first access design.** Deployment architectures must prioritize smallholder and women-farmer access through public delivery channels. No national or scheme-level deployment should be approved without a smallholder-access component that reaches at least 40% of enrolled farmers holding 2 ha or less.

**Guardrail 3 — Uncertainty always visible.** Every advisory output must display confidence bounds and the basis for the estimate. Operators and farmers should never receive a black-box recommendation without the ability to inspect the underlying physical-state estimate and its uncertainty range. This is both a scientific integrity requirement and a trust-building mechanism.

**Guardrail 4 — Salinity and drainage co-monitoring required.** All deployment contexts with known or possible salinity risk must include salinity and drainage monitoring as a standard advisory output — not as an optional add-on. The USD 27.3B/yr salinity cost<sup>85</sup> represents accumulated failure to monitor this dimension;  $\tau$  deployments must not replicate this failure.

**Guardrail 5 — Public-sector interoperability by design.** All  $\tau$  irrigation advisory infrastructure must be designed for interoperability with FAO, national NMHSs, and existing irrigation-authority systems. Proprietary lock-in that prevents national governments from transitioning to open-access or alternative platforms after initial deployment is a disqualifying design choice for any publicly funded component.

**Guardrail 6 — Transboundary data governance protocols.** In transboundary river-basin deployments, the  $\tau$  physical-state model must operate under a jointly agreed governance framework that prevents any party from using model outputs as private informational advantage in allocation negotiations. Shared oversight structures, jointly published state data, and formal dispute-resolution provisions for disagreements about model outputs are prerequisites.

**Guardrail 7 — No false precision in energy-water trade-offs.** In contexts where  $\tau$  reduces irrigation demand and thereby reduces pumping energy, the energy savings must not be represented as additionality for carbon credit schemes unless full verification against a credible counterfactual can be demonstrated. Premature carbon crediting of water-efficiency gains is a governance risk in the current voluntary carbon market environment.

**Guardrail 8 — Long-run soil condition tracked, not overridden.** Advisory outputs that maximize short-run yield at the cost of long-run soil productivity — through accelerated depletion, salinity accumulation, or compaction — must be flagged, not presented as optimal. The  $\tau$  twin must include explicit soil-condition tracking as a binding constraint on advisory output, not merely a monitoring variable.

## 16 SDG Mapping and Bottom Line

---

<sup>85</sup>FAO Global Soil Partnership, *Soil Salinity* — soil salinization takes up to 1.5 million hectares of farmland per year out of production; global annual cost in irrigated areas from salt-induced land degradation approximately USD 27.3 billion in lost crop production. <https://www.fao.org/global-soil-partnership/areas-of-work/soil-salinity/en/>

## 16.1 SDG alignment

$\tau$  irrigation intelligence maps directly onto four Sustainable Development Goals:

**SDG 2 — Zero Hunger.** Improving water productivity on irrigated land — which produces 48% of global crop value<sup>86</sup> — directly supports food security and agricultural productivity. The World Bank’s “doubles productivity vs rainfed” anchor<sup>87</sup> quantifies the productivity potential;  $\tau$  advisory would contribute to capturing this potential at scale without requiring proportional increases in water extraction.

**SDG 6 — Clean Water and Sanitation.** Target 6.4 calls for substantial increases in water-use efficiency and ensuring sustainable freshwater withdrawals. A 5–15% improvement in irrigation scheduling efficiency across major irrigated systems would constitute a measurable contribution to 6.4 progress. Target 6.5 on integrated water resources management is directly served by the basin-scale coordination capabilities described in Section 7C and Case Study 1.

**SDG 13 — Climate Action.** Improved drought resilience, anticipatory allocation management, and adaptation of irrigation to shifting precipitation patterns are core climate adaptation outcomes.  $\tau$  irrigation intelligence supports NDC implementation for countries where agricultural water stress is a primary climate vulnerability.

**SDG 17 — Partnerships for the Goals.** The institutional architecture of  $\tau$  deployment — built on FAO open-access tools, World Bank and GCF finance, CGIAR research partnerships, and national government institutional embedding — exemplifies the partnership model SDG 17 envisions for technology transfer and capacity building in support of the broader agenda.

## 16.2 Bottom line

Climate-smart irrigation, soil-moisture intelligence, and water-productivity improvement represent one of the clearest, most institutionally grounded, and most immediately deployable public-good opportunities in the  $\tau$  programme.

The demand already exists. Institutional partners — FAO, World Bank, CGIAR, GCF — are already active in this space with well-developed tool stacks and finance pipelines. The public data infrastructure is already in place. The gap is fidelity, coupling, and bounded decision confidence: the step change from a stitched advisory system to a law-faithful water-state twin.

If  $\tau$  delivers on its core assumptions, this paper’s domain could generate some of the fastest and most broadly distributed public-good gains in the entire agriculture portfolio — feeding more people from less water, protecting the productive base from salinization and depletion, and building the institutional capacity for adaptive water governance under a more variable climate.

## 17 References

*Source: Full manuscript text integrated from Public-Good Briefing draft.*

<sup>86</sup>FAO, *State of the World’s Land and Water Resources for Food and Agriculture 2025 — Executive Summary and Status-Trends* — irrigated croplands represent approximately 22.5% of croplands and produce approximately 48% of crops in value terms. <https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/executive-summary.html>

<sup>87</sup>World Bank Group, *Transforming Lives Through Climate-resilient Irrigation* (2026) — climate-resilient irrigation more than doubles productivity compared with rainfed agriculture; could feed 1.4 billion additional people. <https://shorthand.worldbankgroup.org/transforming-lives-through-climate-resilient-irrigation/>

## 18 Dossier accountability addendum

The following addendum records the release-facing accountability layer for this dossier: claim boundaries, baseline evidence, upstream dependencies, translation assumptions, scenario bands, scorecard rationales, benchmark requirements, governance guardrails, and related Panta Rhei surfaces. It is intentionally downstream of the full source argument above.

### Impact thesis

A Public-Good Briefing showing how a law-faithful tau water-soil-crop twin could transform irrigation scheduling, water productivity, and drought-adaptive farming across the sector that uses 72% of global freshwater. The v3 impact thesis is conditional: a Tau-grade weather-soil-water-crop irrigation advisory twin would become valuable if it improves benchmarked public decisions while preserving transparent uncertainty, reviewability, and governance control.

### 18.1 Public-good burden and baseline evidence

A Public-Good Briefing showing how a law-faithful tau water-soil-crop twin could transform irrigation scheduling, water productivity, and drought-adaptive farming across the sector that uses 72% of global freshwater. The public-good burden is treated here as an institutional decision problem: existing agencies already monitor parts of the domain, but the operational handoff from data to timely, auditable action remains incomplete.

#### 18.1.1 External evidence baseline

- **FAO**, State of the World's Land and Water Resources for Food and Agriculture 2025 (SOLAW 2025) [5]: agriculture represented 72% of total freshwater withdrawals in 2020.
- **FAO**, State of the World's Land and Water Resources for Food and Agriculture 2025 [4]: Executive Summary and Status-Trends - irrigated croplands represent approximately 22.5% of croplands and produce approximately 48% of crops in value terms.
- **World Bank Group**, Transforming Lives Through Climate-resilient Irrigation (2026) [10]: climate-resilient irrigation more than doubles productivity compared with rainfed agriculture; could feed 1.4 billion additional people.
- **World Bank Group**, Water for Food results page [11]: TRIMING in Nigeria expanded irrigation across 43,400 hectares; food produced enough for 1 million people.
- **World Bank Group**, World Bank Supports Resilient and Sustainable Agriculture in Morocco (2022) [12]: 23,500+ farmers connected to advisory services focused on climate resilience and water productivity.
- **FAO**, WaPOR database [6]: open-access remote sensing platform for water productivity monitoring including actual ET, reference ET, relative soil moisture, biomass, precipitation, and water-productivity products at global, national, and scheme lev.
- **FAO**, d-iap [3]: Drought Impact Assessment Platform on Water Productivity - evaluates drought impacts on crop and water productivity; computes net irrigation requirements, yield-loss probabilities, and income impacts under current and fu.
- **FAO**, AquaCrop [2]: Crop-Water Productivity Model of FAO - simulates yield response to water for a wide range of crops; designed for balance between simplicity, robustness, and applicability where water is the key limiting factor.

- **NASA Goddard Space Flight Center**, NASA-USDA Global Soil Moisture Data [8]: global soil-moisture product at  $0.25^\circ \times 0.25^\circ$  resolution for agricultural monitoring, weather prediction, drought and flood early warning, and water-supply management.
- **Drought.gov**, Drought and Soil Moisture Data [1]: operational soil-moisture products for agricultural drought monitoring and early warning.

## 18.2 Current institutional landscape

The relevant landscape includes public agencies, research infrastructures, standards bodies, development-finance channels, and domain review communities represented in the evidence base, including FAO, World Bank Group. These references are evidence and adoption surfaces, not endorsements or deployment partners.

## 18.3 Capability gap

The practical gap is a benchmarkable translation gap: current systems expose useful data or partial models, but they do not yet provide a single law-faithful, bounded-error decision layer for weather-soil-water-crop irrigation advisory twin.

## 18.4 Tau framework dependency map

Surface	Role in this dossier
<a href="#">Build the Tau-Kernel</a>	finite address and scalar foundation
<a href="#">Recover Core Mathematics</a>	mathematical bridge and model interface
<a href="#">Derive Physics</a>	physical readout and domain translation candidate
<a href="#">Results lane</a>	upstream consequences to be mapped precisely during release preparation
direct-registry-mapping-withheld	no direct Registry object is asserted until a substantive Corpus mapping is available
public-docs-mapping-withheld	TauLib module links are asserted only where public documentation exposes a clear surface
<a href="#">Release Manifest</a>	release baseline
<a href="#">Predictions and Falsification</a>	empirical accountability route

## 18.5 Translation assumptions and missing engineering

Required domain model: **weather-soil-water-crop irrigation advisory twin**.

First benchmarkable test: irrigation timing, net irrigation requirement, and water-productivity guidance against WaPOR, AquaCrop, and incumbent extension advisories.

- domain-specific model construction
- data ingestion and validation
- benchmark harness
- pilot protocol
- independent review workflow







### 18.6 Impact mechanism chain

Public-good burden → external evidence baseline →  $\tau$  capability hypothesis → upstream Results / Corpus / Verify dependency → translation assumptions → benchmarked pilot → governed adoption pathway.

### 18.7 Scenario bands

Band	Scenario summary	Confidence
<b>Conservative</b>	A narrow shadow-mode pilot improves one bounded decision task for Climate-Smart Irrigation, Soil Moisture, and Water Productivity without operational authority.	medium
<b>Realistic</b>	A reviewed prototype strengthens several public-sector workflows for Climate-Smart Irrigation, Soil Moisture, and Water Productivity after benchmark comparison with incumbent systems.	medium-low
<b>Optimistic</b>	A reusable public-good intelligence layer becomes plausible for Climate-Smart Irrigation, Soil Moisture, and Water Productivity after external validation and transparent governance review.	low

### 18.8 Impact scorecard

<b>Public-good scale</b>	 5/5	The affected public-good burden is large or institutionally significant within the portfolio.
<b>Tau fit</b>	 4/5	The proposed pathway depends on coupled state, bounded uncertainty, and compositional modelling rather than isolated prediction alone.
<b>Evidence proximity</b>	 5/5	The evidence base is anchored in public institutions, official monitoring systems, or established scientific reviews.
<b>Measurability</b>	 5/5	A first benchmark can be framed against incumbent public datasets, institutional records, or operational decision metrics.
<b>Adoption readiness</b>	 3/5	Adoption remains conditional on domain review, governance fit, data access, and institutional integration.
<b>Equity leverage</b>	 5/5	The pathway can prioritize underserved or vulnerable populations where public access and safeguards are built in.

### 18.9 Candidate pilot pathways

shadow-mode irrigation advisory pilot with an irrigation authority, national agrometeorological service, and extension partner

### 18.10 Benchmark suite and success metrics

Type	Incumbent line	base-	Required benchmark	Tau	Success metric	Validator
translation benchmark	current public or institutional systems in the domain		irrigation net irrigation requirement, water-productivity guidance against WaPOR, AquaCrop, and incumbent extension advisories	timing, pre-registered racy, latency, uncertainty, or decision-quality metric	pre-registered accuracy, latency, uncertainty, or decision-quality metric	independent domain reviewers
governance benchmark	existing audit, disclosure, and reporting practice		transparent assumption, data, model, and failure-mode disclosure	reviewable evidence pack and adverse-outcome protocol	reviewable evidence pack and adverse-outcome protocol	public-sector or expert governance panel
equity benchmark	current service-quality, or exposure disparities	access, or	documented way for underserved or vulnerable without exclusion	path- and risk hidden	distributional benefit and risk review before pilot expansion	equity, community, or public-interest review process

### 18.11 Governance and risk guardrails

- Human oversight for any operational use.
- Public benchmark disclosure before institutional adoption.
- Equity access review for underserved or vulnerable communities.
- Data-rights and privacy controls for operational datasets.
- Misuse-prevention and adverse-outcome monitoring.
- Adverse-outcome monitoring with a documented escalation path.
- External domain review before pilot expansion.

### 18.12 Related Results / Corpus / Verify / Publications

This dossier is downstream of Results, Corpus, Verify, and Publications surfaces. It is not a Registry object. Direct Registry or TauLib links are asserted only where the mapping is substantive rather than decorative.

### 18.13 Bibliography and external evidence

## References

[1] Drought.gov. Drought and soil moisture data. <https://www.drought.gov/topics/soil-moisture>, 2026. operational soil-moisture products for agricultural drought monitoring and early warning.

[2] FAO. Aquacrop. <https://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/category/details/en/c/1026354/>, 2026. Crop-Water Productivity

Model of FAO - simulates yield response to water for a wide range of crops; designed for balance between simplicity, robustness, and applicability where water is the key limiting factor.

- [3] FAO. d-iap. <https://www.fao.org/in-action/drought-portal/d-iap/en>, 2026. Drought Impact Assessment Platform on Water Productivity - evaluates drought impacts on crop and water productivity; computes net irrigation requirements, yield-loss probabilities, and income impacts under current and fu.
- [4] FAO. State of the world's land and water resources for food and agriculture 2025. <https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/executive-summary.html>, 2026. Executive Summary and Status-Trends - irrigated croplands represent approximately 22.5% of croplands and produce approximately 48% of crops in value terms.
- [5] FAO. State of the world's land and water resources for food and agriculture 2025 (solaw 2025). <https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/scenarios-offer-insights-assumptions.html>, 2026. agriculture represented 72% of total freshwater withdrawals in 2020.
- [6] FAO. Wapor database. <https://www.fao.org/in-action/remote-sensing-for-water-productivity/wapor-data/en>, 2026. open-access remote sensing platform for water productivity monitoring including actual ET, reference ET, relative soil moisture, biomass, precipitation, and water-productivity products at global, national, and scheme lev.
- [7] Thorsten Fuchs and Anna-Sophie Fuchs. Tau for climate-smart irrigation, soil moisture, and water productivity. <https://panta-rhei.site/impact/papers/climate-smart-irrigation-soil-moisture-water-productivity/>, 2026. Current public full-text source for dossier climate-smart-irrigation-soil-moisture-water-productivity.
- [8] NASA Goddard Space Flight Center. Nasa-usda global soil moisture data. <https://earth.gsfc.nasa.gov/hydro/data/nasa-usda-global-soil-moisture-data>, 2026. global soil-moisture product at  $0.25^\circ \times 0.25^\circ$  resolution for agricultural monitoring, weather prediction, drought and flood early warning, and water-supply management.
- [9] Panta Rhei Research Program. Public-good briefing landing page. <https://panta-rhei.site/publications/research-briefings/public-good/climate-smart-irrigation-soil-moisture-water-productivity/>, 2026.
- [10] World Bank Group. Transforming lives through climate-resilient irrigation (2026). <https://shorthand.worldbankgroup.org/transforming-lives-through-climate-resilient-irrigation/>, 2026. climate-resilient irrigation more than doubles productivity compared with rainfed agriculture; could feed 1.4 billion additional people.
- [11] World Bank Group. Water for food results page. <https://www.worldbank.org/ext/en/topic/water/water-for-food>, 2026. TRIMING in Nigeria expanded irrigation across 43,400 hectares; food produced enough for 1 million people.
- [12] World Bank Group. World bank supports resilient and sustainable agriculture in morocco (2022). <https://www.worldbank.org/en/news/press-release/2022/03/25/world-bank-supports-resilient-and-sustainable-agriculture-in-morocco>, 2026. 23,500+ farmers connected to advisory services focused on climate resilience and water productivity.



# Panta Rhei Research Program

Public-Good Impact Dossier

## Tau for Climate-Smart Irrigation, Soil Moisture, and Water Productivity

Dossier ID: PGID-AGRI-01 Portfolio: Agriculture Release: May 2026  
publication-ready release

Conditional scenario map. Domain review pending. Deployment, product, validation, certified-impact, and policy-commitment claims are not made.

### Public contact and review routes

Website: [panta-rhei.site](https://panta-rhei.site)

Contact: [panta-rhei.site/engage/contact/](https://panta-rhei.site/engage/contact/)

Public discussion: [github.com/orgs/Panta-Rhei-Research/discussions](https://github.com/orgs/Panta-Rhei-Research/discussions)

General: [hello@panta-rhei.site](mailto:hello@panta-rhei.site)

Corrections: [errata@panta-rhei.site](mailto:errata@panta-rhei.site)

Media: [press@panta-rhei.site](mailto:press@panta-rhei.site)