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Valuing ecosystem services from climate-smart irrigation practices

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Climate-smart irrigation offers a pathway to improve agricultural productivity, water-use efficiency and resilience while strengthening ecosystem services. Precision and micro-irrigation, IoT-based scheduling, alternate wetting and drying, deficit irrigation, rainwater harvesting and water reuse reduce water consumption, energy use, nutrient losses and greenhouse gas emissions. Water footprint assessment provides the key indicators for evaluating these benefits, while the TEEB framework supports their recognition, demonstration and economic valuation, guiding sustainable irrigation investment, policy and climate-resilient water management.

Keywords: Ecosystem services, Sensor based irrigation, TEEB framework, Water footprint

WATER resources underpin human well-being, agricultural production and ecosystem functioning. India holds about 4% of the world's freshwater but faces rising water stress from uneven distribution, groundwater overexploitation, pollution and climate change. Average annual rainfall of 1,170 mm is irregularly distributed, and of an estimated 4,000 billion cubic metres (BCM) of water resources, only 1,123 BCM is utilisable including about 433 BCM of groundwater. As agriculture is the largest freshwater-consuming sector, efficient and climate-resilient irrigation is essential. Effective water management also advances Sustainable Developmental Goal (SDG) 6 through sustainable water use, SDG 2 through improved water productivity and food security, and SDG 7 through reduced pumping energy.

Climate-smart irrigation integrates precision irrigation, real-time monitoring, remote sensing, weather information and resource-conserving practices to improve productivity and resilience, delivering groundwater conservation, energy efficiency, improved water quality, carbon regulation, soil health and biodiversity benefits. Water footprint assessment and ecosystem-service valuation can therefore support irrigation decisions that balance productivity, resource conservation and ecosystem resilience.

Climate-smart irrigation practices: Ecosystem services benefits

Climate-smart irrigation refers to strategies that raise crop productivity and water-use efficiency, strengthen resilience to climate variability and minimise environmental impacts, integrating efficient technologies, crop water-demand assessment, real-time monitoring and resource conservation. Their benefits extend beyond water saving to food and freshwater provisioning, groundwater regulation, water purification, climate regulation, soil-health maintenance and nutrient cycling. The major practices and their ecosystem-service benefits are described below.

***Precision and micro-irrigation*:** Precision irrigation applies water in the right amount, at the right time and place according to crop requirement. Drip, sprinkler and subsurface drip systems improve root-zone delivery while reducing evaporation, runoff and deep percolation, raising productivity per unit of water and stabilising production under variable climate, strengthening food and freshwater provisioning. Reduced groundwater abstraction and pumping contribute to water and energy regulation, while minimised nutrient movement improves water quality and supports purification. Suitable soil moisture also promotes soil structure, microbial activity and nutrient cycling.

***Sensor- and IoT-based irrigation*:** Real-time information on soil moisture, crop condition and atmospheric demand optimises irrigation scheduling. Soil moisture sensors, weather stations, tensiometers and remote sensing enable site-specific application, while IoT integration allows automated irrigation, reducing over-irrigation and improving water productivity. Better synchronisation enhances food and freshwater provisioning, reduced abstraction and pumping support water and energy regulation, and improved control minimises nutrient leaching, supporting water purification, soil regulation and nutrient cycling.

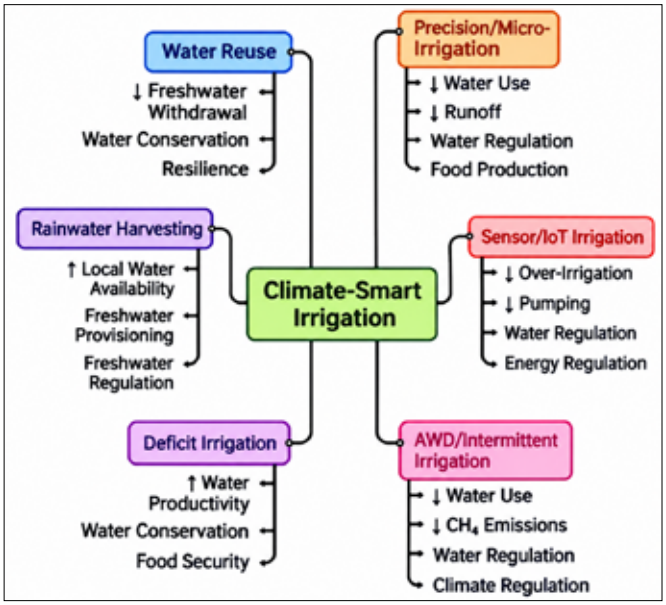
***Alternate wetting and drying*:** Alternate wetting and drying (AWD) replace continuous flooding of rice with periodic irrigation and drying cycles. By maintaining adequate soil moisture without prolonged standing water, it reduces irrigation requirement and improves water productivity, supporting freshwater provisioning and water regulation. Changes in soil redox conditions suppress methane (CH_4) production relative to continuous flooding, providing an important climate-regulation service while maintaining productivity. Appropriate wetting and drying cycles also influence soil microbial activity and nutrient cycling.

***Deficit and demand-based irrigation*:** Deficit irrigation applies water below full crop requirement at selected growth stages while ensuring adequate moisture at critical periods. Regulated deficit irrigation and evapotranspiration-based scheduling match irrigation to growth stage, atmospheric demand and available water. Managed appropriately, these practices improve water productivity with limited yield reduction, supporting food provisioning while conserving freshwater; reduced pumping contributes to water and energy regulation, and adequate soil moisture supports soil biological activity and nutrient cycling.

***Rainwater harvesting and water reuse*:** Rainwater harvesting stores rainfall for agricultural use, increasing local availability and reducing dependence on groundwater and surface water. This mitigates runoff, soil erosion and associated nutrient losses, supporting freshwater provisioning, water regulation and purification. Appropriately treated wastewater can be reused for irrigation and other non-potable purposes, reducing freshwater withdrawal and providing an alternative source during scarcity.

Water footprint as an indicator of irrigation sustainability

Water footprint (WF) assessment quantifies freshwater consumption and pollution associated with climate-smart irrigation and links these to ecosystem service benefits. It comprises blue WF (surface- and groundwater consumption), green WF (rainwater use) and grey WF (freshwater required to assimilate pollutants to acceptable standards). Blue WF is particularly useful for assessing reductions in water use through precision irrigation, sensor-based scheduling, AWD and deficit irrigation; a lower blue WF eases pressure on freshwater resources and supports provisioning and regulation. Green WF reflects effective rainfall use, relevant to rainwater harvesting and demand-based irrigation, while grey WF indicates pollution from nutrient and chemical losses, its reduction enhancing water-purification services.



Ecosystem service benefits of climate-smart irrigation

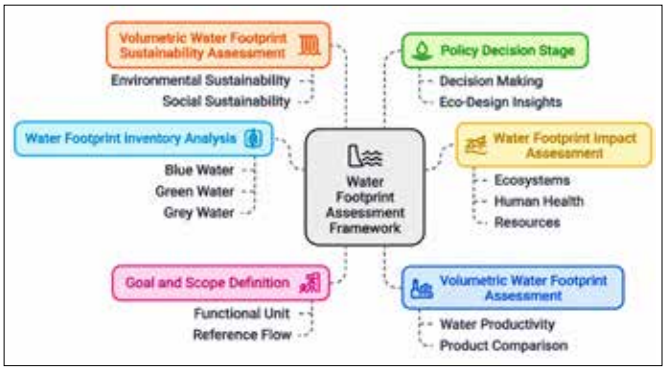
The WF assessment framework covers goal and scope definition, inventory analysis and impact assessment, and should consider water availability, environmental flows, groundwater conditions and ecosystem service outcomes alongside volumetric accounting and sustainability evaluation. Higher water productivity and lower blue and grey WF generally indicate more sustainable irrigation, but WF should be evaluated together with crop productivity, energy use, GHG emissions and nutrient losses, providing the basis for quantifying and economically valuing ecosystem services.

Framework for valuing ecosystem services

Valuing the ecosystem services generated by



Climate-smart irrigation practices



Water footprints assessment framework

Table 1. Ecosystem services, indicators and potential valuation approaches under climate-smart irrigation

Ecosystem service	Key biophysical indicator	Potential valuation approach
Food provisioning	Crop yield, water productivity	Market price/production function
Freshwater provisioning	Water saved, blue water footprint reduction	Market price/avoided cost
Water regulation	Groundwater abstraction avoided, water saved	Avoided or replacement cost
Climate regulation	GHG reduction (CO_2-eq)	Carbon price/social cost of carbon
Water purification	Nutrient losses or grey WF reduced	Avoided treatment/remediation cost
Energy conservation	Electricity/fuel saved	Market price
Soil regulation	Soil organic carbon, soil-quality indicators	Replacement of cost/production function
Nutrient cycling	Nutrient-use efficiency, nutrient losses avoided	Replacement of cost/production function
Biodiversity support	Habitat and ecological indicators	Contingent valuation/benefit transfer

climate-smart irrigation requires integrated assessment of water use, resource efficiency, ecosystem functions and economic benefits. The WF assessment provides a starting point by quantifying changes in blue, green and grey WF, while complementary indicators capture changes in energy consumption, GHG emissions, nutrient losses, soil quality, groundwater conditions and crop productivity.

The assessment first quantifies water savings and changes in resource use under different practices. Reduced blue WF indicates lower pressure on freshwater resources; reduced grey WF reflects lower nutrient pollution and improved purification; reduced pumping energy and GHG emissions indicate energy-conservation and climate-regulation benefits; and changes in soil properties and productivity indicate improvements in soil regulation and food provisioning. These benefits can then be valued using appropriate market and non-market methods, enabling comparison of irrigation practices on productivity, resource conservation, ecosystem service benefits and overall economic value.

The economic value of individual ecosystem services can be estimated as:

$$V_i = Q_i \times P_i$$

Where Economic value of ecosystem service, P_i: Quantified change in the relevant biophysical indicator, and is its corresponding unit value or price. The aggregate value can subsequently be expressed as:

$$TEV = \sum_{i=1}^{n} V_i$$

Where TEV: Total economic value of the ecosystem service benefits generated by a climate-smart irrigation practice, providing a common basis for comparing irrigation alternatives and for decisions balancing crop production, water security, energy efficiency, climate mitigation and ecosystem resilience.

Economic valuation of ecosystem services

The Economics of Ecosystems and Biodiversity (TEEB) framework helps recognise, demonstrate and incorporate the economic importance of ecosystem services in decision-making. For climate-smart irrigation, it links changes in water footprint, energy use, nutrient losses, GHG emissions and soil condition with changes in ecosystem function and the benefits received by society, extending valuation beyond direct returns to both tangible and intangible ecosystem benefits. The approach is structured as:

- ***Recognise*:** Identify the ecosystem functions and services influenced by climate-smart irrigation i.e. food and freshwater provisioning, water regulation and purification, climate regulation, soil regulation and nutrient cycling.
- ***Demonstrate*:** Quantify changes using indicators such as water saved, blue and grey WF reduction, energy saved, additional yield, GHG emissions avoided, nutrient losses reduced and soil quality improvement.
- ***Capture*:** Where appropriate, translate these benefits into monetary values using market-based and non-market valuation methods to support investment, resource allocation and policy decisions.

For the economic valuation stage, the Total Economic Value (TEV) framework can complement TEEB:

$$TEV = DUV + IUV + OV + NV$$

Where DUV: Direct-use value, IUV: Indirect-use value, OV: Option value: NV: Non-use value. Direct-use values may include additional crop or fodder production, water and energy savings, while indirect-use values include groundwater regulation, water purification, climate regulation and soil conservation. Option and non-use values reflect the importance of conserving ecosystem functions and resources for future use and for future generations. For example, the value of irrigation water saved can be estimated as:

$$V_w = W_s \times C_w$$

Where W_s: Water saved (m^3/ha), C_w: Unit value of water. Similarly,

$$V_e = E_s \times C_e$$

Where E_s: Energy saved, C_e: Unit energy cost.

The value of avoided GHG emissions can be estimated as:

$$V_{GHG} = GHG_r \times P_c$$

Where GHG_r: avoided CO_2-equivalent emissions, P_c: Applicable carbon price or social cost of carbon. The overall measurable benefit can therefore be expressed as:

$$V_{total} = V_w + V_e + V_{GHG} + V_n + V_y + \ldots$$

Where V_n: Value of reduced nutrient pollution, V_y: Additional production value.

Challenges and barriers to adoption

- ***High initial investment*:** Drip, sprinkler, sensors, IoT systems and automation require substantial upfront capital.
- ***Technical limitations*:** Lack of technical knowledge, maintenance facilities and skilled personnel can restrict effective operation.
- ***Small and fragmented holdings*:** Small farm sizes may reduce the economic feasibility of advanced irrigation technologies.
- ***Limited awareness*:** Farmers may lack information on water-saving technologies and their long-term ecosystem and economic benefits.
- ***Energy–water trade-offs*:** Pressurised irrigation systems require energy, creating trade-offs between water saving and energy use.
- ***Uncertainty in valuation*:** Many ecosystem services, particularly biodiversity, soil health and non-use values, lack direct market prices and are difficult to monetize.
- ***Behavioural and socioeconomic barriers*:** Risk perception, traditional irrigation practices and uncertainty about returns may slow adoption.
- ***Climate variability*:** Shifting rainfall and temperature patterns complicate irrigation scheduling and long-term assessment of ecosystem-service benefits.



Implications of climate-smart irrigation

Future directions

- ***Integrate water footprint assessment*:** Include blue, green and grey WF in irrigation and watershed planning.
- ***Value ecosystem services*:** Develop standardised methods to quantify and monetise ecosystem service benefits.
- ***Adopt TEEB framework*:** Apply the Recognise–Demonstrate–Capture approach in irrigation policies and investments.
- ***Link water–energy–climate*:** Assess water savings alongside energy use and GHG emissions.
- ***Promote payment for ecosystem services* (*PES*):** Develop mechanisms to reward farmers for water conservation, pollution reduction and carbon benefits.
- ***Develop decision-support tools*:** Compare irrigation options on water productivity, ecosystem services, economic returns and environmental impact.

Policy implications and mainstreaming of the TEEBAgriFood framework

The TEEBAgriFood framework can mainstream ecosystem service considerations into irrigation and agri-food policy by moving beyond yield and water-use efficiency. Climate-smart irrigation should be assessed through its impacts on natural, produced, human and social capital, linking changes in water footprint, energy use, GHG emissions, soil health and productivity with ecosystem service flows and wider outcomes. Integrating these indicators into irrigation planning, investment appraisal and agricultural programmes reveals hidden environmental benefits and trade-offs, while the Recognise–Demonstrate–Capture approach supports targeted incentives.

SUMMARY

Climate-smart irrigation enhances agricultural productivity, water-use efficiency and climate resilience while generating substantial ecosystem service benefits like food and freshwater provisioning, groundwater and water regulation, water purification, climate regulation, soil regulation and nutrient cycling. Precision and micro-irrigation, sensor- and IoT-based scheduling, AWD, deficit irrigation, rainwater harvesting and water reuse reduce water consumption, energy use, nutrient losses and greenhouse gas emissions. Water footprint assessment supplies the biophysical indicators, and the TEEBAgriFood Recognise – Demonstrate – Capture approach allows these benefits to be identified, quantified and, where appropriate, valued in monetary terms across natural, produced, human and social capital. Mainstreaming this framework into irrigation policy, investment appraisal and payment for ecosystem services can support efficient resource use, reduced environmental impact and balanced water–energy–climate outcomes for sustainable, resilient agri-food systems.

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