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Water bankruptcy in the 21st century: climate pressure, groundwater and surface water depletion and the macroeconomics of water scarcity in northwest Bangladesh

Duti, Bushra Monowar

Independent University, Bangladesh (IUB)

Independent University, Bangladesh

Water Bankruptcy in the 21st Century

Climate Pressure, Groundwater and Surface Water Depletion and the Macroeconomics of Water Scarcity in Northwest Bangladesh

A research paper presented in partial fulfillment of the requirements for the degree

Master of Science in Economics

Submitted by

Bushra Monowar Duti
ID: 2312656
Department of Economics
School of Business and Entrepreneurship (SBE)
Independent University, Bangladesh.

Supervisor

Dr. Md. Khaled Saifullah
Assistant Professor and Head
Department of Economics
School of Business and Entrepreneurship (SBE)
Independent University, Bangladesh.

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Bushra Monowar Duti
ID: 2312656

has been approved

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Dr. Md. Khaled Saifullah
Assistant Professor and Head
Department of Economics
School of Business and Entrepreneurship (SBE)
Independent University, Bangladesh

DECLARATION

This research paper has been done under the supervision of Dr. Md. Khaled Saifullah. The topic has been approved by my supervisor. This paper contains no material published elsewhere or extracted in whole or in part from a research project, thesis or article by which I have qualified for or been awarded another degree or diploma. No other person's work has been used without due acknowledgment in the main text of the research paper. This research paper has been undertaken to fulfil the requirement of ECN 599.

Bushra Monowar Duti
ID: 2312656
Date: August 30, 2026

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Bushra Monowar Duti
2312656
MSc. Economics (IUB)

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ABSTRACT

Bangladesh is usually described as a country of water abundance, yet its northwest is quietly moving in the opposite direction. This thesis asks whether water bankruptcy is emerging in the High Barind Tract, how climate and human pressures produce it, how it is linked to the dry-season decline of the Teesta River, and what governance and financing responses are required. Water bankruptcy is understood here as a condition in which a region can no longer meet its water commitments without drawing down its stored reserves faster than they recover. Rather than treating drought, groundwater, river flow, irrigation, energy and agriculture as separate problems, the study examines them as one connected system.

The analysis draws on observed climate records, a reconstructed long-term groundwater series, river water-level and discharge data, satellite imagery, energy accounting and economic valuation, using standard trend tests (Mann–Kendall and Theil–Sen) and clearly stated assumptions. Findings from each strand are kept traceable, uncertainty is reported openly, and estimates are given as ranges rather than single points.

The climate record shows that the dry season is changing in ways that raise water demand. Night-time temperatures have risen significantly at Rajshahi, Rangpur and Bogra while daytime maxima have been stable or falling, narrowing the day–night temperature range. Rainless spells are long, about 55 to 59 days on average, and are lengthening at Rajshahi by roughly 1.35 days per year. Published projections suggest dry-season (Boro) irrigation demand could rise by about 5 to 15 percent by mid-century even before any change in cultivated area.

The groundwater evidence is the clearest sign of bankruptcy in the land-based system. Pre-monsoon groundwater depth in the Barind fell from about 2.5 metres below ground in 1985 to about 15.2 metres in 2020 (Mann–Kendall $\tau = 0.98$, $p < 0.001$), and the aquifer's ability to recover during the monsoon is weakening. Under business as usual the 40-metre economic pumping limit for deep tube wells is projected to be reached around 2086, and around 2074 under a high-stress pathway; managed aquifer recharge could push it beyond 2100. The outcome is not fixed, but every year of delay narrows the margin.

The Teesta shows the same pattern for surface water. Four independent records (water level at Kaunia, measured discharge at Dalia, published long-period flow, and satellite open-water extent) all point to a large contraction of the river in its Bangladesh reach, roughly a three-quarter reduction from the 1979 baseline and a sustained breach of the environmental-flow reserve since the mid-1990s. Because these different records agree, the finding holds despite the limits of any single dataset.

These systems are connected. The Teesta Barrage Irrigation Project was designed around about 4,500 cusec, but a typical recent February flow is closer to 1,000 cusec, leaving a seasonal

delivery gap of roughly 1.03 billion cubic metres. Much of this shortfall is met by pumping more groundwater, which deepens the aquifer and raises the energy needed to lift water. The extra energy cost created by this surface-to-groundwater substitution is estimated at about USD 46 to 96 million a year, alongside higher diesel use and emissions. The Teesta dispute is therefore not only about sharing a river; it is a linked water–energy–food–climate problem.

To turn these physical findings into a governance rule, the thesis develops the Basin Bankruptcy-Adjusted Allocation (BBAA) framework. Using a total available discharge of about 200 m^3/s, an environmental-flow reserve of 142 m^3/s and a historical mean flow of 541 m^3/s, the Basin Bankruptcy Index for the Teesta is about 0.107, well inside the bankruptcy range, where a fixed percentage-sharing agreement cannot resolve the shortage. BBAA instead protects the ecological reserve first, measures what remains against the historical baseline, and then shares any deficit through a flow-contingent rule, with compensation or benefit-sharing where water physically cannot be delivered.

The costs are already large. The direct annual cost of water bankruptcy is estimated at about USD 456 to 773 million for northwest Bangladesh (central estimate around USD 604 million) and USD 403 to 653 million for the Barind alone (central estimate USD 517 million). Once wider economy-wide effects are added separately, the total footprint is roughly USD 0.9 to 1.2 billion a year. If the loss of the aquifer is valued as the depreciation of natural capital rather than as a free input, the implied annual loss rises to about USD 2.3 to 7.5 billion, a cost that conventional accounts largely ignore.

Intervention is cheaper than continued depletion. A managed aquifer recharge pathway could save on the order of USD 24.6 billion by 2060 compared with business as usual, far exceeding the proposed climate-finance pipeline of about USD 598 million to 1.8 billion. That pipeline centres on recharge, soil restoration, drought-tolerant crops, transboundary diplomacy, shared monitoring and safeguarded solar irrigation.

The thesis concludes that water bankruptcy in northwest Bangladesh is a measurable, connected condition rather than a set of separate shortages, and that the appropriate response is to govern scarcity directly: recognise ecological limits first, manage surface water and groundwater as one resource, restore storage while restraining demand, share transboundary shortage explicitly, and finance the transition before depletion reaches its most costly thresholds.

CHAPTER 1: Introduction

1.1 Background

Water is at the centre of Bangladesh's development story. For most of the country, the dominant narrative has historically been one of abundance. The Ganges–Brahmaputra–Meghna delta produces annual river flows of more than 1,200 billion cubic metres and receives a national average of approximately 2,500 millimetres of rainfall per year, making Bangladesh one of the wettest populated countries on Earth (Mirza, 2004; BBS, 2024). Yet this national-scale abundance conceals deep sub-national inequality in water availability. The High Barind Tract of northwestern Bangladesh, an elevated Pleistocene landform covering approximately 7,770 km^2 across the districts of Rajshahi, Chapai Nawabganj and Naogaon, receives only 1,100–1,500 mm of annual rainfall, has a thick impermeable red-clay surface that converts much of that rainfall into runoff, and depends for its dry-season cultivation almost entirely on groundwater abstraction (Mongabay, 2024; BMDA, 2023; Hasan et al., 2018). It is, in a country known for water, a region known for drought.

Over the past four decades, two transformations have converged to push the Barind water system toward what the international hydro-economic literature terms water bankruptcy: a condition in which committed consumptive water demand structurally exceeds renewable supply, maintained only by the drawdown of non-renewable storage (Madani et al., 2016; AghaKouchak et al., 2015). The first is the intensification of dry-season Boro rice cultivation, which expanded through the Green Revolution of the 1980s–1990s and now accounts for approximately 54% of national rice output (Ministry of Agriculture, 2023). Boro cultivation is nearly 80% groundwater-irrigated (New Age, 2025). The second is climate change: rainfall variability has increased, dry-season rainfall has declined, mean temperatures have risen by approximately 0.5°C per decade in the region (Shahid, 2010; Rahman & Lateh, 2017), and both the frequency and severity of drought episodes have intensified. The resulting groundwater decline is approximately 2.1 metres per year in the High Barind between 1985 and 2012 (Hasan et al., 2018b), with cumulative drawdown exceeding six metres in many areas. This is sufficient that standard number-6 hand tubewells and shallow pumps routinely fail during the Boro season (The Business Standard, 2025).

The crisis is not purely subterranean. The Barind is also the downstream recipient of the Teesta River, the fourth-largest transboundary river in Bangladesh, whose dry-season flow has fallen from approximately 200 cumec (before India's 1985 Gajoldoba barrage) to below 40 cumec in recent decades and, in the most extreme months, to as low as 10 cumec (Mullick et al., 2010; Afroz & Rahman, 2018; The Daily Star, 2023). Bangladesh's Teesta Barrage Irrigation Project (TIP) at Doani, engineered in 1990 to deliver 4,500 cusec of surface irrigation water to 60,500 hectares of northwest cropland, typically receives between 500 and 1,500 cusec during peak Boro months, between 11% and 33% of design capacity (Dhaka Tribune, 2020). The deficit in surface-water supply drives farmers to substitute groundwater abstraction, intensifying the aquifer depletion already induced by climate and agricultural pressure. The Teesta surface-water crisis and the Barind groundwater crisis are therefore not independent phenomena; they are coupled, and they must be analysed together.

Together, these pressures amount to what this thesis frames as a **condition of water bankruptcy in the Barind Tract, driven simultaneously by climate change** (rainfall decline, temperature rise, evapotranspiration increase, drought intensification), **by human factors** (unsustainable groundwater abstraction, land-use intensification, soil fertility degradation), **and by the transboundary under-delivery of the Teesta's dry-season flow.** The consequences are distributed across farmers (income loss, livelihood displacement), national economy (food security, GDP, fiscal costs), energy system (increased pumping burden), ecosystem (environmental flow deficit, loss of fisheries and navigation), and intergenerational welfare (depletion of aquifer storage that will be unavailable to future generations). No single disciplinary lens (hydrology, agronomy, economics, or diplomacy) captures the full problem. A unified analytical framework is required.

1.2 Statement of the Problem

Bangladesh's existing water governance architecture treats groundwater and surface water as institutionally separate domains: groundwater is managed by the Barind Multipurpose Development Authority (BMDA), the Department of Public Health Engineering, and the Water Resources Planning Organisation (WARPO) under the Ministry of Water Resources; transboundary surface water is the remit of the Joint Rivers Commission under the Ministry of Foreign Affairs. Climate adaptation is coordinated by the Ministry of Environment, Forest and Climate Change through the Bangladesh Climate Change Strategy and Action Plan (BCCSAP) and the National Adaptation Plan (NAP). These institutions operate with overlapping mandates but without a unified quantitative framework for assessing water bankruptcy as a single composite condition.

The 2025 Gazette Notification declaring 4,911 villages across 25 upazilas of the High Barind Tract as water-stressed, issued under the Bangladesh Water Act 2013, represents the first formal institutional acknowledgement of the scale of the groundwater crisis (The Daily Star, 2025). But the notification is not accompanied by a published economic impact assessment, by an explicit linkage to Teesta flow restoration diplomacy, by a climate-finance sourcing plan for the interventions it implies, or by a proportional framework that matches the severity of local restrictions to the severity of local bankruptcy. The present thesis responds directly to these gaps.

1.3 Research Questions

Central Research Question

How is water bankruptcy emerging as a measurable composite condition in the High Barind Tract of northwestern Bangladesh, what are the relative contributions of climate drivers and human drivers to this condition, how does it interact with the transboundary under-delivery of the Teesta River, and what governance and climate-finance responses are required to prevent its further deterioration?

Sub-Questions

- **SQ1 (Climate drivers):** What are the documented and projected changes in rainfall, temperature, evapotranspiration, and drought frequency in the Barind Tract under CMIP6 RCP and SSP scenarios, and what are their projected impacts on agricultural yield and national GDP?
- **SQ2 (Groundwater bankruptcy):** Do hydrological, agronomic, and economic evidence jointly support a classification of the High Barind as being in a state of water bankruptcy, and what are the per-hectare, per-household, and national-scale economic consequences of this condition?
- **SQ3 (Surface water dimension):** What is the scale of Teesta dry-season flow reduction since 1985, what are the economic costs to Bangladesh across environmental flow, fisheries, navigation and irrigation domains, and what allocation framework could integrate environmental flow and water-bankruptcy indicators into bilateral river-sharing agreements?
- **SQ4 (Energy–water nexus):** How does reduced Teesta surface-water delivery translate into additional groundwater pumping energy demand in the TIP command area and the broader Barind, and what is the economic and emissions cost of this induced substitution?
- **SQ5 (Transboundary allocation framework):** Can a bankruptcy-theoretic allocation rule that embeds a first-priority environmental-flow reserve and a quantified Basin Bankruptcy Index offer a more equitable and more negotiable basis for sharing the Teesta's dry-season flow than the fixed-percentage formulas of conventional river treaties, and what share does such a rule imply for Bangladesh under present bankruptcy conditions?
- **SQ6 (Macroeconomic transmission):** What is the aggregate economic cost of water bankruptcy in the Barind and the wider northwest, and through which macroeconomic channels (agricultural GDP, food-price inflation, input–output multipliers, the trade and foreign-exchange balance, public finances, and the labour market) is that cost transmitted to the national economy once aquifer drawdown and soil-fertility loss are accounted for as depreciation of natural capital in a water-adjusted measure of GDP?

- **SQ7 (Climate finance):** What finance is required, from which international and domestic sources (GCF, Loss and Damage Fund, CCTF, bilateral donors), to fund the priority interventions (Managed Aquifer Recharge, topsoil restoration, drought-tolerant variety adoption, transboundary diplomacy, and dry-season flow monitoring) that this thesis identifies?

1.4 Study Area

1.4.1 Geographic Focus

The primary study area is the High Barind Tract (HBT) of northwestern Bangladesh, comprising the districts of Rajshahi, Chapai Nawabganj and Naogaon. The HBT covers approximately 7,770 km² (Mongabay, 2024), lying between approximately 24°07' and 25°15' N latitude and 88°01' and 88°57' E longitude (BMDA, 2023). It is bounded on the west and north by the Indian state of West Bengal, on the south by the Padma (Ganges) river, and on the east by the floodplains of the Atrai and Jamuna. Its elevation of 20–40 metres above surrounding floodplains, formed from Pleistocene Older Alluvium, gives it a characteristic red-clay surface and an absence of the seasonal flooding that dominates the hydrology of most of Bangladesh (Rahman et al., 2015). The three districts together support a population of approximately 5.6–6.5 million people, the overwhelming majority of whom are engaged directly or indirectly in agriculture (IMED, 2019; BBS, 2022 Census).

A secondary study area, linked hydrologically and institutionally to the Barind, is the Teesta Basin command area of the districts of Nilphamari, Rangpur and Lalmonirhat. Although this area is distinct from the Barind Tract proper, its hydrological behaviour during the dry season is tightly coupled to Barind groundwater dynamics because of the induced-substitution mechanism described above. The Teesta basin within Bangladesh covers approximately 9,667 km² of catchment area and supports approximately 9.15 million people (Afroz & Rahman, 2018).

Table 1.1 Key characteristics of the study area

Characteristic	High Barind Tract (primary)	TIP / Teesta basin (secondary)
Districts	Rajshahi, Chapai Nawabganj, Naogaon	Nilphamari, Rangpur, Lalmonirhat
Area	~7,770 km²	9,667 km² (catchment)
Population	~5.6–6.5 million	~9.15 million
Mean annual rainfall	1,100–1,500 mm	~2,000–2,500 mm

Dominant water source	Groundwater (~75%)	Teesta surface water + groundwater
Elevation	20–40 m asl (Pleistocene upland)	Alluvial floodplain
Surface soil	Red-clay, low permeability	Alluvial silt-loam
Dominant crop (dry season)	HYV Boro rice	HYV Boro rice
Key governance authority	BMDA	BWDB (TIP) + JRC (transboundary)

1.4.2 Climatic Character

The Barind has a humid subtropical climate (Köppen Cwa) with four distinct seasons: winter (December–February, cool and dry), pre-monsoon (March–May, hot and dry), monsoon (June–September, hot and wet), and post-monsoon (October–November, cooling and drying). Over 75% of annual rainfall occurs in the four monsoon months, leaving an eight-month dry season during which crop cultivation requires irrigation (Shahid, 2010; Rahman & Lateh, 2017). Dry-season maximum temperatures regularly exceed 38–40°C, and the 2023 heatwave registered values above 43°C in Rajshahi (BMD, 2023). These thermal conditions drive high reference evapotranspiration (ET_0), typically 5–7 mm/day in the pre-monsoon period, and correspondingly high Boro rice water requirements of approximately 800–1,000 mm per season (Maniruzzaman et al., 2015; Mainuddin et al., 2021).

1.4.3 Agricultural and Economic Significance

The three High Barind districts together produce approximately 4.0 million tonnes of Boro rice per year, roughly 18–22% of national Boro output (BBS district data, 2023). Chapai Nawabganj is also Bangladesh's leading mango producer, with 2025 output of approximately 458,000 tonnes from over 100,000 hectares of orchards (Grokipedia/Chapai Nawabganj, 2026). The region's agricultural GDP contribution, and its role in national food-security reserves, place it at the centre of Bangladesh's rural economy.

1.5 Significance of the Study

This study is positioned at the intersection of four currents that make it timely:

- **The 2026 expiry of the Ganges Water Treaty** creates a diplomatic window for reframing Bangladesh–India transboundary river governance. A thesis that offers a scientifically grounded framework for integrating environmental flow and water-bankruptcy indicators into such reframing is therefore immediately policy-relevant.

- **The 2025 WARPO gazette on Barind water-stressed villages** has created an explicit policy instrument without an accompanying economic impact assessment. The present thesis fills this gap.
- **The scaling of international climate finance** (particularly the post-COP28 operationalisation of the Loss and Damage Fund and the expanded Green Climate Fund pipeline) makes clear, evidence-based proposal development a priority for Bangladesh. This thesis provides the quantitative basis for several such proposals.
- **The acceleration of climate change in South Asia** , with monsoon variability, heatwave frequency, and drought risk all projected to intensify under RCP 4.5 and higher emissions pathways (IPCC AR6 WGII, 2022), makes the cost of delayed action high and rising.
- **No Water sharing treaty for Teesta** : unlike the Ganges, whose dry-season flow is governed by the 1996 Ganges Water Treaty, the Teesta, the fourth-largest transboundary river shared by Bangladesh and India, remains without any bilateral water-sharing agreement. A draft interim arrangement negotiated in 2011 was not concluded, and in its absence the river's dry-season discharge is allocated by no agreed formula, carries no guaranteed environmental-flow reserve, and is subject to no joint dispute-resolution mechanism. This absence is not merely a diplomatic shortcoming but an analytical opening: a basin with no treaty baseline is precisely the setting in which a transparent, bankruptcy-adjusted allocation rule can be introduced without displacing an entrenched legal regime. By quantifying the Teesta's flow decline and proposing the Basin Bankruptcy-Adjusted Allocation (BBAA) framework, this thesis offers a scientifically grounded starting point for an allocation architecture where none currently exists.

1.6 Overarching Aim

The overall aim of this research is to characterise, quantify, and propose governance and climate-finance responses to the emerging condition of water bankruptcy in the High Barind Tract of northwestern Bangladesh, examined as a composite phenomenon driven jointly by climate change, unsustainable groundwater abstraction, soil fertility degradation, and the structural under-delivery of Teesta River dry-season flow. The research applies an integrated hydrological, agronomic, economic, and policy framework, and produces both empirical findings and methodological contributions, in particular the Basin Bankruptcy-Adjusted Allocation (BBAA) framework for transboundary river sharing, intended to inform Bangladeshi water governance and South Asian river diplomacy over the 2026–2035 horizon.

1.7 Primary Objective

To develop and apply an **integrated analytical framework for assessing water bankruptcy in the High Barind Tract, combining the hydrological, climate, agricultural, economic, energy and transboundary dimensions, and to translate the resulting evidence into actionable governance and climate-finance recommendations for Bangladesh.**

1.8 Secondary Objectives

The primary objective is operationalised through six secondary objectives, spanning the empirical analysis of the thesis:

1. Climate driver characterisation

To document and project the climate drivers of water stress in the Barind Tract (rainfall change, temperature rise, reference evapotranspiration increase, and drought frequency and severity) using observational records and CMIP6 projections under RCP 4.5, RCP 8.5 and corresponding SSP scenarios, and to quantify their implications for Boro rice yield and for national agricultural GDP.

2. Groundwater bankruptcy quantification

To assess, using long-term monitoring well data, satellite-derived storage anomalies, and recharge-abstraction balance analysis, whether the High Barind satisfies the definitional criteria of water bankruptcy, and to quantify the economic consequences of this condition across four interdependent channels: farmer-level income, national food security and GDP, energy-system pumping costs, and crop output.

3. Teesta transboundary analysis

To document the magnitude of dry-season flow reduction in the Teesta River at the Bangladesh border since the 1985 Gajoldoba barrage, to quantify the associated economic costs to Bangladesh across environmental flow, fisheries, navigation, and irrigation domains, and to develop the Basin Bankruptcy-Adjusted Allocation (BBAA) framework as an original governance contribution.

4. Energy–water nexus analysis

To quantify how Teesta surface-water deficit translates into induced groundwater pumping in the TIP command area and the broader northwestern Bangladesh, and to estimate the resulting incremental energy cost, subsidy burden, and greenhouse-gas externality.

5. BBAA framework development

To formalise the Basin Bankruptcy-Adjusted Allocation (BBAA) framework as an original governance contribution: computing the Basin Bankruptcy Index for the Teesta, testing its sensitivity to the definition of total available discharge, and deriving a sequential proportional (SSR-PRO) allocation rule compatible with the 1997 UN Watercourses Convention and the Kunming–Montreal Global Biodiversity Framework.

6. Macroeconomic quantification

To consolidate the sectoral and basin-level loss estimates into a national macroeconomic account of water bankruptcy: tracing the transmission channels to GDP, inflation, trade, and fiscal accounts, valuing the destruction of physical and natural capital (stranded irrigation infrastructure, aquifer depletion, soil-fertility loss), and expressing the result as a water-adjusted GDP measure with its distributional incidence and implications for the Bangladesh Delta Plan 2100.

7. Climate finance analysis

To identify and evaluate the international and domestic climate-finance instruments, among them the Green Climate Fund (GCF), Loss and Damage Fund, Adaptation Fund, Bangladesh Climate Change Trust Fund (CCTF), multilateral development banks, and bilateral donors, through which the priority Barind and Teesta-related interventions can be financed, with particular attention to Managed Aquifer Recharge, topsoil restoration, drought-tolerant variety adoption, transboundary diplomacy, and integrated monitoring.

1.9 Expected Contributions

The thesis is designed to produce four distinct categories of contribution:

Table 1.2 Intended contributions of the thesis

Type	Specific contribution
Conceptual	Extending the water-bankruptcy framework (Madani et al., 2016; AghaKouchak et al., 2015), developed for arid economies, to a humid monsoonal deltaic context with an explicit coupled groundwater–surface-water–climate framing.
Empirical	A unified quantitative account of Barind groundwater bankruptcy and Teesta surface-water bankruptcy, with internally consistent loss estimates at farmer, sectoral, national, and basin levels.
Methodological	The Basin Bankruptcy-Adjusted Allocation (BBAA) framework, an original allocation rule integrating environmental flow requirements and basin

	bankruptcy indices into transboundary river-sharing agreements, compatible with the 1997 UN Watercourses Convention and the Kunming–Montreal Global Biodiversity Framework.
Policy	Concrete, quantified recommendations for Bangladesh's Ministry of Water Resources, WARPO, BMDA, Ministry of Environment (CCTF), and the Joint Rivers Commission; and a fundable pipeline of climate-finance project concepts aligned with GCF, Loss and Damage Fund, and bilateral donor windows.

1.10 Scope and Limitations of the Study

In the interest of analytical transparency, the scope boundaries and limitations of the research are stated explicitly below. These are not weaknesses to be concealed but choices that make the research tractable within the time and resources available to a single doctoral-level study.

1.10.1 Geographic Scope

The research focuses on the High Barind Tract (Rajshahi, Chapai Nawabganj, Naogaon) as the primary study area, with the Teesta Barrage Irrigation Project (TIP) command area (Nilphamari, Rangpur, Lalmonirhat) as a hydrologically linked secondary study area. Other portions of the broader Barind Tract (Dinajpur, Thakurgaon, Panchagarh, Bogra, Joypurhat, Gaibandha, Kurigram, Pabna, Natore, Sirajganj) are referenced where relevant national statistics require it, but are not examined in the same depth. The Ganges and Brahmaputra basins are discussed comparatively; they are not the subjects of primary analysis. Areas outside Bangladesh are treated as context (the Sikkim–West Bengal upstream reach of the Teesta) rather than as primary subjects. These geographic boundaries are deliberate and follow from the research focus; they do not preclude the extension of the methods to other settings in future work.

1.10.2 Temporal Scope

Quantitative analyses use the following time windows, determined primarily by data availability:

- Groundwater monitoring well records: 1985–2023 (Bangladesh Water Development Board, BWDB, and BMDA).
- Teesta flow records: 1985–2023 at Dalia gauging station (BWDB).
- Climate records: 1981–2020 baseline (Bangladesh Meteorological Department) and 2021–2100 projection horizon (CMIP6 under RCP 4.5, RCP 8.5 and corresponding SSP scenarios).
- Agricultural statistics: 2000–2024 (Bangladesh Bureau of Statistics, Department of Agricultural Extension, Ministry of Agriculture).

- Economic analyses: 2024 price base, with present values computed over 25-year horizons at 3%, 6% and 10% discount rates.

Projections beyond 2100 are not undertaken. Historical analyses of the pre-Green-Revolution, pre-irrigation-expansion hydrology of the Barind (prior to 1980) are discussed qualitatively but are not quantitatively reconstructed in this thesis; they are an appropriate subject for future palaeohydrological work.

1.10.3 Data Limitations

Several data limitations condition the quantitative findings of the thesis:

- **Groundwater monitoring well density.** BWDB and BMDA maintain approximately 30–40 monitoring wells across the High Barind, yielding a sampling density lower than that of more intensively studied basins elsewhere in South Asia. Uncertainty in spatial interpolation of water-table declines is correspondingly higher.
- **Teesta flow data.** Flow records at Gajoldoba (on the Indian side of the border) are not publicly released; the analysis relies on flow measured at Dalia (Bangladesh side) and on reconstructed values from secondary literature (Mullick et al., 2010, 2013; Afroz & Rahman, 2018). This asymmetry itself is a finding, not just a limitation.
- **Climate projections.** CMIP6 downscaling for Bangladesh remains at a coarser resolution (typically 25–50 km grid) than ideal for district-scale impact assessment. The thesis uses bias-corrected downscaled outputs from published sources (e.g. CORDEX South Asia, Mohsenipour et al., 2018; Nashwan et al., 2019) rather than running its own regional climate model.
- **Farm-level economic data.** Farmer income, cost of cultivation, and livelihood data are drawn from published BRRI, BBS, DAE, and BIDS sources, not from primary survey work by the present author. Distributional findings are therefore based on representative rather than statistically sampled household-level inference.
- **Soil fertility data.** Long-term soil organic carbon (SOC) time series for the Barind are fragmented. Analyses draw on SRDI, BARI, and BAU datasets plus peer-reviewed case-study literature (Ali et al., 2010; Islam et al., 2021).

1.10.4 Methodological Scope and Limitations

The thesis is a mixed-methods synthesis analysis; it does not undertake original hydrogeological numerical modelling, original regional climate modelling, original econometric panel estimation, or primary household survey work. Its methodological contribution is in the integrated application and extension of published tools, and in the development of the BBAA framework. Specifically:

- Hydrology is treated through synthesis of published monitoring and modelling (Hasan et al., 2018; Mainuddin et al., 2021; Mullick et al., 2010; BWDB records) rather than through new groundwater-flow model runs.

- Crop-water productivity analyses draw on published AquaCrop model applications (Maniruzzaman et al., 2015, 2018; FAO AquaCrop manuals) rather than on new AquaCrop simulations by the present author, though the author's professional familiarity with AquaCrop is used in interpretation.
- Economic analyses use standard cost–benefit, shadow-pricing, and Total Economic Value (TEV) frameworks (Pearce et al., 2006; Brouwer, 2000; Costanza et al., 2014) applied to published and aggregated data.
- Policy analysis is qualitative and comparative, drawing on published treaty texts, gazette notifications, parliamentary records, and the peer-reviewed political-economy literature on South Asian water governance.

The research is not primarily experimental or predictive; it is an evidence-based synthesis whose contribution is conceptual, empirical, methodological, and policy-oriented rather than laboratory or field-experimental. This choice is appropriate to the research question but should be understood when interpreting the findings.

1.10.5 Sectoral Scope

Within the water sector, the thesis focuses on irrigation (Boro rice as reference crop), environmental flow, inland capture fisheries, small-scale navigation, and rural domestic water. Large-scale industrial water use, municipal water supply in major urban centres, coastal and estuarine systems, and marine fisheries are outside the primary scope. Within the energy sector, the focus is on agricultural pumping (diesel and electric tubewells); other energy demand sectors are not analysed. Within the climate-finance sector, the focus is on instruments accessible to Bangladesh for adaptation and loss-and-damage purposes; mitigation finance is discussed only where it complements adaptation work.

1.10.6 Limitations Arising from Political and Diplomatic Sensitivity

The Teesta and Ganges cases involve politically sensitive material concerning Bangladesh–India bilateral relations, and within India the relationship between the central government, the state government of West Bengal, and the state government of Sikkim. The thesis takes a balanced, evidence-based approach, acknowledging legitimate water-security interests on both sides, documenting federal-political constraints, and proposing a framework (BBAA) specifically designed to be politically negotiable rather than maximalist. However, access to certain Indian hydrological datasets and internal government documents is constrained by political sensitivity, and this thesis does not attempt to obtain such materials; it relies on publicly available sources and peer-reviewed literature. Readers should interpret the transboundary findings in this light.

1.11 Ethical Considerations

The research does not involve primary human-subject data collection and therefore does not require institutional review board clearance for fieldwork. Where secondary household-level data are used (e.g., from BBS HIES, BIDS surveys, or published case-study interviews), original authors' ethical approvals are recorded and cited. In discussing transboundary questions, the thesis is committed to balanced treatment of all riparians' legitimate interests, to avoidance of inflammatory or pejorative language, and to the accurate representation of cited positions. Where the analysis supports a normative conclusion (for example, that environmental flow should be a first-priority allocation), the conclusion is distinguished from the quantitative findings and is supported by cited evidence.

1.12 Key Assumptions

The analyses of this thesis rest on the following assumptions, each of which is examined in sensitivity analysis in the relevant empirical chapter:

- That the last four decades of groundwater monitoring (1985–2023) provide a representative basis for characterising the Barind aquifer system, allowing for the instrumentation gaps noted in Section 1.10.3.
- That CMIP6 ensemble mean projections under the examined RCP/SSP scenarios provide a reasonable central estimate of future climate conditions, with extreme-scenario results used to bound uncertainty.
- That the Teesta flow records at Dalia are representative of downstream-boundary conditions in the absence of Gajoldoba data.
- That exchange rates, price levels, and discount rates used in economic analyses are approximately stable within the sensitivity ranges reported; currency or macroeconomic shocks are outside the scope of the analysis.
- That the institutional framework (BMDA, WARPO, JRC, MoEFCC) continues to function approximately as currently structured over the project horizon; major institutional restructuring is outside the scope of the analysis and is flagged as a source of policy risk.

1.13 Structure of the Thesis

The thesis is organised in eleven chapters:

- Chapter 1 (present chapter) introduces the problem, research questions, and study area (Sections 1.1–1.5); sets out the research aim, objectives, and expected contributions (Sections 1.6–1.9); and states the scope, limitations, ethical considerations, and key assumptions that condition the analysis (Sections 1.10–1.12).
- Chapter 2 provides a detailed literature review covering water-bankruptcy theory and its analytical neighbours, the global groundwater-depletion literature, climate-drought science for South Asia and the Barind, Barind-specific hydrogeology and agronomy, transboundary river-sharing and the Teesta hydro-economic literature, the energy–water nexus, the macroeconomics of water scarcity, and the climate-finance architecture available to Bangladesh.

- Chapter 3 sets out the data and methodology: the data sources and confidence tiers on which the empirical chapters rest, and the analytical methods (trend detection, reconstruction, regression, remote sensing, bankruptcy-theoretic allocation, and cost accounting) applied in each.
- Chapter 4 analyses the climate drivers of water stress in the Barind (rainfall, temperature, reference evapotranspiration, and drought) through an original station-level analysis and CMIP6 SSP projections, with their agricultural and economic implications.
- Chapter 5 presents the Barind groundwater-bankruptcy analysis: the reconstructed depth series, Mann–Kendall trend and OLS driver analysis, the bankruptcy-threshold projections, and the associated soil-fertility and energy dimensions.
- Chapter 6 documents the hydrological decline of the Teesta in its Bangladesh reach, through gauge water level, measured discharge, published long-period series, and satellite open-water extent, and values the ecosystem services that its flow sustains.
- Chapter 7 examines the energy–water nexus in northwest Bangladesh, showing how reduced Teesta surface-water delivery drives induced groundwater pumping, and quantifying the resulting energy burden, subsidy cost, and greenhouse-gas externality in the TIP command area and the wider Barind.
- Chapter 8 develops the Basin Bankruptcy-Adjusted Allocation (BBAA) framework as an original methodological contribution, computing the Basin Bankruptcy Index for the Teesta and recommending a sequential proportional (SSR-PRO) allocation rule.
- Chapter 9 consolidates the economic evidence into a macroeconomic account of water bankruptcy: a four-component direct-cost framework for the Barind, its consolidation with the Teesta losses, the macroeconomic transmission channels to national GDP, inflation, trade and fiscal accounts, and the concept of water-adjusted GDP.
- Chapter 10 analyses the climate-finance options for the priority interventions this thesis identifies (Managed Aquifer Recharge, topsoil restoration, drought-tolerant variety adoption, transboundary-diplomacy capacity, and integrated monitoring), drawing on GCF, the Loss and Damage Fund, the CCTF, and bilateral instruments.
- Chapter 11 presents the conclusions and recommendations of the thesis.

CHAPTER 2: Literature Review

2.1 Introduction to the Review

This chapter reviews the literature in eight thematic streams that together form the conceptual and empirical foundation of the thesis: (i) the concept of water bankruptcy and closely related hydro-economic frameworks; (ii) the global groundwater depletion literature, situating Bangladesh within a planetary pattern; (iii) climate-drought science for South Asia and the Barind Tract, with particular reference to CMIP5/6 projections under RCP and SSP scenarios; (iv) Barind-specific hydrogeological, agronomic and land-degradation research; (v) transboundary river-sharing theory and the specific hydro-economic literature on the Teesta, Ganges and Brahmaputra; (vi) the energy–water nexus in groundwater irrigation and its emissions dimension; (vii) the macroeconomics of water scarcity, including its transmission channels and natural-capital accounting; and (viii) the climate finance architecture available to Bangladesh for drought and water-sector adaptation. Each section identifies both what is known and what remains unresolved, and concludes by flagging the specific knowledge gap that the present thesis addresses.

The review draws on approximately 170 sources, with emphasis on peer-reviewed journal publications, IPCC assessment reports, and institutional reports from BMDA, BWDB, WARPO, IWM, BRRI, FAO, UNESCO, World Bank, GCF, and UNFCCC. Grey literature and investigative journalism are used where they provide original quantitative evidence (for example, 2022 and 2026 reporting on the diesel-price shocks affecting Barind irrigation) and are flagged as such. The review is organised thematically rather than chronologically, because the phenomenon under study is inherently cross-disciplinary and the insights required are not sequential.

2.2 The Concept of Water Bankruptcy

2.2.1 Origins and Definition

The formal use of 'water bankruptcy' as an analytical category is associated principally with Madani, AghaKouchak and Mirchi (2016), whose Iranian Studies paper applied the concept to Iran's hydro-economy. In Madani et al.'s formulation, water bankruptcy is a condition in which (i) total consumptive water commitments exceed sustainable renewable supply over a multi-year horizon; (ii) the deficit is closed by persistent drawdown of non-renewable or slow-recharging storage (typically groundwater or deep fossil aquifers); and (iii) institutional arrangements are unable, within a reasonable adjustment horizon, to reconcile commitments with availability. The framing is explicitly analogous to financial bankruptcy: future obligations cannot be met from current and projected assets, and continued operation depends on unsustainable 'borrowing' from stored water that functions as a multi-decadal or multi-century capital stock.

AghaKouchak et al. (2015) extended the concept to California during the 2012–2016 drought, coining the related term 'anthropogenic drought' to capture drought conditions whose severity is partly attributable to human water-demand rather than to climate forcing alone. Madani (2014) had earlier argued that water conflicts are in this sense 'problems of choice' rather than purely 'problems of scarcity': where total committed demand exceeds available supply, the question is not whether someone will be denied water but who will be denied, and under what decision rule.

In January 2026, the United Nations University Institute for Water, Environment and Health (UNU-INWEH) released its flagship report, ***Global Water Bankruptcy: Living Beyond Our Hydrological Means in the Post-Crisis Era***, marking the formal adoption of the water-bankruptcy concept within the United Nations system (Madani, 2026). The report characterises water bankruptcy as a condition in which the sustained overdraft of renewable flows and long-term storage pushes river basins and aquifers beyond their historical baselines, such that recurrent shortage hardens from a temporary crisis into a chronic and effectively irreversible state. Two conditions are held to define this transition: **hydrological insolvency, in which withdrawals exceed renewable inflows and safe depletion limits; and irreversibility, in which the resulting damage cannot be undone without disproportionate economic, social or environmental cost.** In place of the reactive management of successive emergencies, the report calls for a shift towards "bankruptcy management", founded on transparent water accounting, enforceable abstraction limits, the protection of water-related natural capital, and explicitly equity-oriented transitions.

This diagnosis leads directly to our thesis research: the non-recovering pre-monsoon decline of the Barind aquifer and the collapsing dry-season flow of the Teesta are precisely the basin- and aquifer-scale insolvency the report describes, while the Basin Bankruptcy Index and BBAA allocation framework advanced in this study operationalise, at the scale of a single transboundary basin, the accounting-and-limits approach that the report advocates globally.

2.2.2 Related Frameworks

Several adjacent frameworks in the literature overlap with water bankruptcy and are integrated in the present thesis:

- **Water stress and water scarcity indices.** The Falkenmark Index (per capita availability), the Water Stress Index (WSI = withdrawal / availability), and the Water Exploitation Index (WEI) are classical metrics (Falkenmark, 1989; Raskin et al., 1997; Smakhtin et al., 2004). Recent basin-scale applications in Chile (HESS, 2025) indicate WSI values approaching or exceeding 100% in stressed basins, signalling, in the vocabulary of the present thesis, water bankruptcy. The WSI is a useful diagnostic but does not by itself capture the institutional and inter-temporal dimensions that water bankruptcy foregrounds.
- **Virtual water and water footprint.** Hoekstra and Chapagain (2008) and Mekonnen and Hoekstra (2011) developed the water-footprint framework, which accounts for direct and indirect (embedded) water use in products and trade flows. The framework is informative

for the present thesis's treatment of Boro rice (for which the BRRI-CSIRO studies of Mainuddin et al., 2021 estimate approximately 1,300–1,800 L/kg).

- **Integrated Water Resources Management (IWRM).** The Global Water Partnership's (2000) IWRM framework provides the institutional template within which water-bankruptcy indicators should be embedded. The 1992 Dublin Principles and the 2000 EU Water Framework Directive are the foundational instruments (GWP, 2000; EU, 2000). Bangladesh's 1999 National Water Policy and 2013 Water Act are broadly IWRM-compatible in design but, as the present thesis argues, lack the quantitative bankruptcy-triggered allocation rules that the framework requires in stressed basins.
- **Planetary boundaries.** Rockström et al. (2009, 2023) include freshwater use as one of the nine planetary boundaries. The 2023 update separates blue-water and green-water boundaries, both of which the authors assess as already transgressed. This framing motivates the present thesis's treatment of water bankruptcy not only as a local economic concern but also as part of a global pattern of over-appropriation of freshwater systems.

2.2.3 Hydro-Economic Models

Hydro-Economic Models (HEMs) integrate hydrological constraints with economic optimisation and are the primary quantitative tool used in the water-bankruptcy literature. Harou et al. (2009) review the methodological foundations. Jalilov et al. (2024) apply an HEM to the Teesta basin (reviewed in Section 2.6 below). Mullick et al. (2013, 2014) present a related marginal-benefit-based allocation model for the Bangladesh segment of the Teesta. The key methodological contribution of HEMs is the demonstration that apparent water-scarcity problems are often, at bottom, water-allocation problems: basin-wide welfare can be improved by reallocating water from low-marginal-benefit to high-marginal-benefit uses without changing the total quantity available. The BBAA framework developed in Chapter 8 of this thesis is a direct extension of this tradition.

2.2.4 Gap Addressed by This Thesis

Despite the theoretical development of the water-bankruptcy concept, its empirical application has been concentrated in arid and semi-arid economies (Iran, California, Spain, Australia). It has not, to the author's knowledge, been applied as a unified analytical frame to a humid deltaic economy such as Bangladesh, nor has it been integrated with transboundary river-sharing analysis. The present thesis makes both extensions.

2.3 Global Groundwater Depletion: The Planetary Pattern

2.3.1 The Evidence Base

The transformation of global understanding of groundwater depletion over the last two decades has been driven principally by the Gravity Recovery and Climate Experiment (GRACE, 2002–2017) and its successor GRACE-Follow-On (2018–present) satellite missions. By measuring time-varying components of Earth's gravity field, these missions yield monthly estimates of terrestrial water storage anomalies at ~150,000 km^2 resolution (Tapley et al., 2004; Landerer & Swenson, 2012). Rodell, Famiglietti and colleagues have used GRACE data to document large-scale groundwater depletion across northern India and Bangladesh (Rodell et al., 2009), the Central Valley of California (Famiglietti et al., 2011), and the North China Plain (Feng et al., 2013). Their synthesis for 2002–2016 (Rodell et al., 2018) identifies anthropogenic groundwater abstraction as the largest single human driver of global changes in terrestrial water storage.

The most comprehensive synthesis to date is Jasechko et al. (2024), who analysed approximately 170,000 groundwater monitoring wells globally and found that groundwater levels are declining in 71% of aquifer systems examined, with the rate of decline accelerating in the 21st century relative to the late 20th. Critically for the present thesis, Bangladesh, and specifically the Barind Tract and the greater Dhaka region, are among the aquifers they identify as experiencing accelerated decline. Richey et al. (2015) earlier identified 21 of the world's 37 largest aquifer systems as being depleted at rates exceeding natural recharge, a finding consistent with Jasechko et al.'s later well-level analysis. Famiglietti (2014) provided the influential Nature Climate Change commentary framing global groundwater depletion as a quiet but significant component of the broader global water crisis.

2.3.2 South Asian Specifics

For South Asia, the foundational empirical contributions include Tiwari, Wahr and Swenson (2009), who used GRACE to document approximately 54 km^3/year of groundwater depletion across northern India, and Rodell et al. (2009), which localised that depletion to the Indus–Ganges Plain. MacDonald et al. (2016) provide a complementary well-based analysis showing that groundwater storage in the Indo-Gangetic Basin had begun to recover in some parts of Bangladesh even as it continued to deplete across northern India, a finding consistent with Shamsudduha et al.'s (2011, 2022) 'Bengal Water Machine' hypothesis (Section 2.5 below). Taylor et al. (2013) published an influential Nature Climate Change review synthesising the relationship between groundwater and climate change globally, and Cuthbert et al. (2019) extended this to quantify the dependence of groundwater recharge on climate variability.

The policy implications of this literature are captured in UN Water (2022) and World Bank (2020, 2023): unsustainable groundwater abstraction is one of the least-regulated but most consequential human pressures on freshwater systems globally, with the poorest and most rural populations disproportionately exposed to the consequences of aquifer decline. The framework is also relevant to the emerging Kunming–Montreal Global Biodiversity Framework (CBD, 2022), which for the first time explicitly includes freshwater ecosystem targets, Target 2 commits signatories to restore at least 30% of degraded inland water ecosystems by 2030.

2.3.3 Gap Addressed

Global groundwater depletion is now well documented, but integrated economic analyses that translate hydrological decline into farmer-level, sectoral, and national monetary costs, and into climate-finance proposal figures, remain rare for South Asia. The Barind-specific hydrogeological literature (Section 2.5) is strong on hydrology and weak on economics; this thesis provides the missing economic layer.

2.4 Climate-Drought Science for South Asia and the Barind

2.4.1 IPCC Assessment Reports

The IPCC assessment reports are the authoritative synthesis of climate-change science relevant to the Barind context. AR5 WGII Chapter 24 (IPCC, 2014) identified South Asia as one of the world's most vulnerable regions to climate-induced changes in water availability, agricultural productivity, and food security. AR6 WGI (IPCC, 2021) confirmed with high confidence that the South Asian monsoon is intensifying in wet-extreme terms and becoming more variable on sub-seasonal timescales, with both trends attributable in part to anthropogenic forcing. AR6 WGII Chapter 10 (Asia) and Chapter 4 (Water) (IPCC, 2022) detail the projected impacts on crop yield, water availability, and rural livelihoods, with explicit assessment of Bangladesh as a high-vulnerability country. The IPCC Special Report on 1.5°C (IPCC, 2018) and the Special Report on Climate Change and Land (IPCC, 2019) provide additional focused analyses relevant to agricultural drought.

2.4.2 CMIP5, CMIP6, and CORDEX Downscaling

Global climate model projections under the Representative Concentration Pathways (RCPs) of CMIP5 and the Shared Socioeconomic Pathways (SSPs) of CMIP6 provide the quantitative basis for impact assessment. Eyring et al. (2016) describe the CMIP6 framework; O'Neill et al. (2016) and Riahi et al. (2017) document the SSP scenarios. For Bangladesh specifically, key regional applications include:

- **Kirby et al. (2015, 2016)**: the CSIRO-BRRI analysis of climate change impacts on regional water balances in Bangladesh under CMIP5, with emphasis on the northwest and the Barind.
- **Nashwan, Shahid and Abd Rahim (2019)**: high-resolution (0.25°) CMIP5 projections for Bangladesh, identifying statistically significant warming trends and increased rainfall variability.
- **Mohsenipour, Shahid, Chung and Wang (2018)**: drought-focused projection analysis using bias-corrected CMIP5 outputs, with explicit SPI/SPEI computations for Bangladesh.
- **Islam, Almazroui and Islam (2021)**: CMIP6 projections showing accelerated warming under SSP3-7.0 and SSP5-8.5, with mean warming of 2.5–4.5°C over Bangladesh by 2100.
- **Shahid (2010, 2011) and Rahman & Lateh (2017)**: foundational observational analyses documenting historical rainfall and temperature trends in Bangladesh, including the northwestern region.

The CORDEX South Asia programme (Sanjay et al., 2017; Mishra et al., 2020) provides regionally downscaled climate projections at approximately 25 km resolution, used extensively in Bangladeshi adaptation planning including the National Adaptation Plan (MoEFCC, 2022). CORDEX-SA results broadly confirm the global-model pattern: wetter wet seasons, drier dry seasons, higher temperatures, and increased extreme-event frequency.

2.4.3 Drought Indices and Agricultural Drought

Agricultural drought differs from meteorological drought in that it incorporates soil moisture, evapotranspiration demand, and crop-specific water requirements. The key indices in the literature are: the Standardized Precipitation Index (SPI; McKee et al., 1993) for meteorological drought; the Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010) which incorporates temperature-driven demand; the Palmer Drought Severity Index (PDSI; Palmer, 1965) and its self-calibrated version (scPDSI; Wells et al., 2004); and the FAO Reference Evapotranspiration (Penman-Monteith) method (Allen et al., 1998) used in crop-water analysis. For Bangladesh, applications include Rahman and Lateh (2017), Mohsenipour et al. (2018), and Sarker et al. (2021). These studies consistently identify the northwestern region, including the Barind, as the most drought-prone part of the country under both historical and projected conditions.

2.4.4 Evapotranspiration and Climate Warming

Reference evapotranspiration (ET_0) rises with temperature, solar radiation and wind speed, and declines with humidity. Under warming scenarios, ET_0 for Bangladesh is projected to rise by approximately 5–15% by 2050 and 10–25% by 2100 under RCP 4.5 and RCP 8.5 respectively (Acharjee et al., 2019; Salam et al., 2020). For Boro rice specifically, the net effect is a likely increase in irrigation water requirement of a similar percentage range, holding other factors constant, a finding of direct relevance to the groundwater-bankruptcy analysis of Chapter 5. The AquaCrop simulations of Maniruzzaman et al. (2015, 2018) and the Hossain et al. (2017) combined heat-drought impact study quantify the yield implications.

2.4.5 Gap Addressed

Climate projections for Bangladesh are well-developed at the national level and reasonably well-developed for the northwestern region. The gap lies in integrating these projections with groundwater, energy and economic loss functions into a single water-bankruptcy accounting, which is the ambition of Chapters 4 and 5 of this thesis.

2.5 Barind-Specific Hydrogeology, Agronomy and Land Degradation

2.5.1 Hydrogeological Characterisation

The Barind Tract was first systematically characterised as a distinct hydrogeological unit by Morgan and McIntire (1959) and the subsequent UNDP–WHO (1982) Master Plan for Bangladesh water resources. Subsequent peer-reviewed work has built a now-substantial body of knowledge:

- **Hoque, Hoque and Ahmed (2007)**: a seminal Hydrogeology Journal paper on declining groundwater levels in Dhaka and the Barind, documenting 2–3 m/year declines in central Dhaka and comparable rates in the High Barind.
- **Shamsudduha, Taylor, Ahmed and Zahid (2011)**: a Hydrogeology Journal analysis of the impact of intensive groundwater abstraction on shallow aquifer recharge in Bangladesh, introducing the 'induced recharge' concept that became foundational for later Bengal Water Machine analyses.
- **Shamsudduha et al. (2022)**: a GRACE-based study formalising the Bengal Water Machine concept: the idea that dry-season abstraction induces monsoon recharge in much of Bangladesh, though not in the aquitard-dominated High Barind.
- **Rahman, Jahan, Arefin and Mazumder (2015)**: a Barind-specific analysis of groundwater depletion linked to Boro expansion in Rajshahi district.
- **Hasan, Ahmed, Sultana, Rahman, Ghosh and Ravenscroft (2018a, 2018b)**: two companion papers providing the 2.1 m/year decline statistic for 1985–2012 and the long-term trend analysis via MAKESENS modelling.
- **Jahan, Mazumder, Islam and Adham (2010)**: pre-2010 characterisation of Barind aquifer lithology and recharge potential.
- **Mainuddin, Maniruzzaman, Alam, Mojid, Schmidt, Islam and Scobie (2021)**: the CSIRO–BRRI Agricultural Water Management paper that is the most comprehensive recent integrated hydrological and agricultural analysis for the NW region.

2.5.2 Agronomy and Boro Rice

The agronomic literature on Boro rice and Barind conditions is extensive. Key contributions include the BRRI annual reports and technical bulletins; the Banglapedia (2023) overview of irrigation; the AquaCrop validation and projection work of Maniruzzaman, Talukder, Khan, Biswas and Nemes (2015) and Maniruzzaman, Biswas, Hossain, Haque, Kabir and Kalra (2018); the high-temperature–drought combined stress analyses of Hossain, Teixeira da Silva, Lozovskaya and Zvolinsky (2017); and the Ali, Johansen and Musa (2018) book-length analysis of the evolution of agriculture in the High Barind. The crop-water productivity analyses of Mainuddin et al. (2021) are particularly important because they refute the widely held assumption that Bangladeshi rice is exceptionally water-intensive: their field measurements show that Bangladeshi Boro rice uses approximately 1,300–1,800 L per kg of paddy, comparable to or better than rice systems in India and China despite the dry-season cultivation context.

2.5.3 Soil Fertility and Land Degradation

The literature on Barind soil degradation is less developed than the hydrological literature but growing. Key contributions:

- **Ali (2008, 2010)**: analyses of soil organic matter decline and micronutrient depletion in Barind Boro–fallow rotations, showing that continuous Boro monoculture degrades soil carbon stocks over multi-decadal horizons.

- **Islam et al. (2021)**: a detailed analysis of soil quality indicators in High Barind upazilas showing significant declines in organic carbon, cation exchange capacity, and aggregate stability over 1990–2020.
- **Sarker, Biswas and Maniruzzaman (2015)**: Bangladesh Rice Journal analysis of the climate change adaptation and economic profitability of shifting from rice to mango orchards in Rajshahi, implicitly documenting the effects of water-stress-driven land-use change on soil fertility trajectories.
- **SRDI (Soil Resource Development Institute) reports,** which provide the national framework for soil-quality monitoring; coverage in the Barind is less intensive than the agro-ecological zones of the coastal belt and Ganges floodplain.

The desertification framing, most visibly advanced in the ICCES (2025) geospatial-remote-sensing study, is contested but increasingly accepted. Islam, Ali, Amin and Zaman (2010) in their Springer chapter on climatic variations, farming systems and livelihoods in the High Barind provided an early warning of structural land-use change driven by water and climate stress.

2.5.4 Gap Addressed

The Barind literature is strong on hydrology, moderate on agronomy, and relatively weak on soil-fertility economics and on the integration of these strands into a unified water-bankruptcy assessment. The present thesis draws these strands together.

2.6 Transboundary River Sharing and the Teesta Basin

2.6.1 The International Law Framework

The foundational instrument is the 1997 UN Convention on the Law of the Non-Navigational Uses of International Watercourses (entered into force 2014), whose Articles 5, 6, 7 and 10 establish the principles of equitable and reasonable utilisation, the obligation not to cause significant harm, and the priority of vital human needs. McCaffrey (2007) provides the authoritative legal commentary. The Helsinki Rules (1966), the Berlin Rules (2004) of the International Law Association, and the New York Draft Articles (1994) provide complementary legal infrastructure. The 1992 UNECE Water Convention, originally a regional instrument, has since been opened to global accession and is becoming an increasingly important framework.

For the Bangladesh–India context specifically, the Joint Rivers Commission (established 1972) is the principal bilateral institution. Rahaman (2009, 2012) and Hossain (2013) provide the most comprehensive analyses of the 1996 Ganges Water Treaty and the broader Bangladesh–India water-sharing framework. Crow, Lindquist and Wilson (1995) published the foundational historical analysis in their book 'Sharing the Ganges'.

2.6.2 The Teesta-Specific Literature

The Teesta River has received sustained scholarly attention since the 2011 near-miss of the draft agreement. The principal contributions include:

- **Mullick, Babel and Perret (2010, 2013, 2014)**: a foundational three-paper series on flow characteristics, environmental flow requirements, marginal-benefit-based optimal allocation, and benefit functions for instream water uses in the Teesta. These papers establish the quantitative baseline used in Chapter 6.
- **Afroz and Rahman (2013, 2018)**: transboundary flow analysis for the Ganges and Teesta, and a follow-up paper in the Journal of Water and Climate Change on chronological trends in Teesta water flows.
- **Jalilov, Amer and Ward (2024)**: the most recent hydro-economic model (THEM) for the Teesta, quantifying current water-use values at USD 41.5 million for India and USD 77 million for Bangladesh, and identifying potential for cross-border trade-off between upstream hydropower and downstream environmental uses.
- **Rudra (2012)**: the West Bengal government-commissioned report on the Teesta dispute, important for its diagnosis that a share of the downstream shortage is attributable to upstream hydropower development in Sikkim.
- **Noolkar-Oak (2017)**: Observer Research Foundation issue brief on the geopolitics of water conflicts in the Teesta Basin.
- **The Asia Foundation (2013)**: political economy analysis of the Teesta River basin, a comprehensive qualitative account.
- **Islam and Higano (2002)**: an early University of Tsukuba working paper on equitable sharing of international waters, using the Teesta as case.
- **Haque (2017)**: BUET M.Sc. thesis on the Teesta water dispute and hydro-economic modelling.
- **Sztulwark and Lehuedé (2025)**: though focused on Chile, this work demonstrates the broader relevance of water-conflict hydro-political analysis and is methodologically suggestive.

2.6.3 Environmental Flow Science

The environmental flow literature is now substantial. The Brisbane Declaration (2007), the Tennant/Montana method (Tennant, 1976), the Building Block Methodology (King & Louw, 1998), IFIM/PHABSIM (Bovee, 1982), and the ELOHA framework (Poff et al., 2010) are the principal methodological references. Arthington, Bunn, Poff and Naiman (2006) and Arthington et al. (2018) argue for the primacy of the natural flow regime; Acreman and Ferguson (2010) survey implementation under the EU Water Framework Directive. The recent synthesis by Anderson, Higgins, Pringle and Thieme et al. (2024), published in Environmental Reviews, provides the current state-of-the-art guidance on accelerating environmental flow implementation to bend the curve of global freshwater biodiversity loss. The recent review by Babel et al. (2021) specifically addresses environmental flow status in Southeast Asian rivers.

For Bangladesh specifically, the Mullick, Babel and Perret (2010) Teesta analysis is the principal reference, supplemented by the more recent Jalilov et al. (2024) HEM. The estimate of 90–120 cumec as the dry-season EFR for the Teesta (Mullick et al., 2010) is the basis for the numerical application of the BBAA framework in Chapter 8.

2.6.4 Benefit-Sharing Theory

Sadoff and Grey (2002), in their classic Water Policy paper 'Beyond the River', articulated the case for benefit-sharing, as opposed to water-sharing, frameworks in transboundary rivers. The central argument is that reallocation of benefits is often easier to negotiate than reallocation of water, because benefits are more fungible (can be compensated in alternative forms such as electricity, finance, or infrastructure). Dombrowsky (2009) extended this with a critical review. Giordano, Drieschova, Duncan, Sayama, De Stefano and Wolf (2014) provided a comprehensive review of transboundary water agreements. These works underpin Step 4 of the BBAA framework developed in Chapter 8.

2.6.5 Gap Addressed

The Teesta literature is hydrologically strong and politically well-documented, but no existing work provides an integrated, negotiable treaty-design framework that explicitly integrates environmental flow and water-bankruptcy indicators. The BBAA framework developed in Chapter 8 is intended to fill this gap.

2.7 The Energy–Water Nexus in Groundwater Irrigation

The coupling between water and energy is a distinct literature stream, and one that is central to the mechanism examined in Chapter 7 of this thesis: the substitution of pumped groundwater for undelivered surface water, and the energy burden that substitution imposes. Where the preceding sections treat water quantity and its allocation, this section reviews the literature that treats the energy required to move that water, and the emissions that follow. The stream is important because a food-production system that compensates for a surface-water deficit by pumping groundwater converts a hydrological problem into an energy problem, and thereby exposes itself simultaneously to hydrological and to energy-market risk.

2.7.1 The Energy–Groundwater Nexus in South Asia

The foundational body of work on the energy–groundwater nexus in South Asia is associated principally with Tushaar Shah and colleagues at the International Water Management Institute. Shah, Scott, Kishore and Sharma (2004) and Shah (2009) established that in the subsidised-electricity economies of India, the price of energy for pumping is the effective price of groundwater, so that flat-rate or subsidised power severs the link between abstraction and its marginal cost and drives over-extraction. Mukherji (2007) demonstrated, for the eastern Indo-Gangetic basin that includes Bangladesh, that the structure of energy markets (diesel versus electricity, metered versus flat-rate) shapes the intensity and equity of groundwater use through informal pump-rental and water-selling markets. Shah, Giordano and Mukherji (2012) synthesised these findings into a political-economy account of the nexus, arguing that reform of the energy–groundwater relationship, rather than direct water regulation, is often the more tractable lever for managing abstraction. Mukherji, Shah and Banerjee (2020) extended the analysis to the governance challenges of the nexus across South Asia. This literature underpins the treatment in Chapter 7 of diesel and electricity as the operative cost of Barind groundwater, and its warning that lowering the marginal cost of pumping, whether through subsidy or through solar power, accelerates depletion absent complementary abstraction controls (Shah, Giordano and Mukherji, 2012; Mukherji et al., 2020).

2.7.2 Pumping Energy, Lift and the Depletion Penalty

A second strand quantifies the physical relationship between water-table depth and pumping energy. Because the hydraulic power required to lift water is linear in the total dynamic head, each additional metre of drawdown raises the energy (and, for diesel pumps, the fuel and emissions) required to deliver a given volume to the field. This 'depletion penalty' is documented for the north-west of Bangladesh in the CSIRO–BRRI work of Mainuddin et al. (2021), which links field-level Boro water use to the sustainability of groundwater irrigation, and in the long-term water-table trend analysis of Hasan, Rahman and Shamsudduha (2018b). The emissions consequence of energy use in the water sector more broadly was framed by Rothausen and Conway (2011) in their review of greenhouse-gas emissions from water-sector energy use, which established the accounting logic (energy intensity per unit water, multiplied by an emission factor) that Chapter 7 applies to Barind irrigation. Siddiqi and Anadón (2011) provided an influential regional treatment of the water–energy nexus in arid economies, demonstrating that the nexus is most acute precisely where surface water is scarce and pumping lifts are large, the condition that characterises the Barind.

2.7.3 Diesel Dependence, Solar Irrigation and Rebound

A third strand concerns the fuel base of the pump fleet and the prospects for its decarbonisation. The dependence of Boro irrigation on diesel, and its exposure to fuel-price shocks, is documented in Bangladeshi reporting and in the IDCOL (2023) solar-irrigation programme assessment, which estimates the diesel and emissions savings available from full substitution of the national diesel-pump fleet. The greenhouse-gas footprint of dry-season rice irrigation specifically is quantified by Maniruzzaman et al. (2025), who report national groundwater-pump emissions on the order of two million tonnes of carbon dioxide equivalent per dry season, the figure on which the Barind apportionment in Chapter 7 rests. The critical caveat in this literature is the rebound risk: Shah, Giordano and Mukherji (2012) and Mukherji et al. (2020) both warn that when the marginal cost of pumping falls toward zero, as with solar power, farmers have an incentive to pump more, so that solar irrigation deployed without metering or tariff safeguards can trade diesel savings for accelerated aquifer decline. This is the tension that Chapter 7 carries into its policy discussion.

2.7.4 Gap Addressed

The energy–groundwater nexus is well theorised for the subsidised-electricity economies of north-west India, but its downstream, transboundary form, in which a surface-water deficit created by upstream diversion is transmitted into additional pumping energy borne entirely by the downstream country, has not been quantified for the Teesta command area. Nor has the energy cost of induced substitution been priced and placed alongside the volumetric water claim in a transboundary negotiation frame. Chapter 7 addresses both gaps.

2.8 The Macroeconomics of Water Scarcity

The final analytical stream concerns the macroeconomics of water scarcity, the channels through which a localised water deficit propagates into national economic aggregates, and the accounting conventions that determine whether aquifer depletion is recorded as a cost at all. This literature is the foundation for the macroeconomic consolidation of Chapter 9, which traces the Barind and Teesta losses through to national GDP, inflation, the trade balance, and the fiscal accounts, and which advances the concept of a water-adjusted national product.

2.8.1 Water Scarcity and Macroeconomic Performance

The proposition that water scarcity is a macroeconomic and not merely a sectoral concern has moved from assertion to measurement over the last decade. The World Bank's 'High and Dry' report (2016) provided the first influential global statement, estimating that water-scarce regions could see GDP growth decline by as much as six percent by 2050, while noting that reallocation of even a modest share of water to higher-value uses could neutralise much of the loss. Damania, Desbureaux, Rodella, Russ and Zaveri (2017), in the World Bank study 'Uncharted Waters', extended this to the effects of water variability and rainfall shocks on growth, health and migration, establishing that the economic damage of scarcity operates as much through variability as through mean availability. The most rigorous cross-country treatment to date is the Bank for International Settlements working paper on the economics of water scarcity (BIS, 2025), which finds across a large country panel that increased water scarcity depresses GDP growth and investment and raises consumer-price inflation, with the effect operating primarily through food prices, the transmission channel most relevant to a rice economy such as Bangladesh's. These works provide the elasticities and the transmission logic applied in Chapter 9.

2.8.2 Sectoral Transmission and General-Equilibrium Modelling

A parallel strand models how a shock in one water-dependent sector propagates through an economy's structure. Computable general equilibrium (CGE) and input–output methods are the standard tools. For Bangladesh specifically, Islam, Hossain, Murshed, Islam and Molla (2022) applied a dynamic CGE model and found that climate change reduces national GDP and investment by mid-century while raising rice prices, with the agricultural shock amplified through inter-sectoral linkages. The broader case that basin-scale water shortages can produce abrupt, non-linear economic impacts, tipping points beyond which losses shift from manageable to severe, is made in the linked human–earth-system modelling literature, and the Global Commission on the Economics of Water (2024) has argued for valuing the hydrological cycle as a global common good whose neglect systematically understates economic risk. This literature supplies the multiplier logic through which Chapter 9 amplifies the direct Barind and Teesta losses to an economy-wide footprint, and the caution, observed in that chapter, that such amplification must be counted once, and not double-counted across the direct and the general-equilibrium accounts.

2.8.3 Natural-Capital Accounting and Aquifer Depreciation

A third strand concerns whether the depletion of a stored resource is recorded as a cost in national accounts. The standard System of National Accounts does not treat aquifer depletion as capital consumption, so that water pumped from a declining aquifer appears as a costless input and the permanent loss of storage goes unrecorded. The foundational critique is Repetto, Magrath, Wells, Beer and Rossini (1989), whose World Resources Institute study 'Wasting Assets' argued that natural-resource depletion should be charged as depreciation against national income; Konikow and Kendy (2005) applied the argument specifically to groundwater as a globally significant and largely unrecorded loss. The United Nations System of Environmental-Economic Accounting, and its water account (SEEA-Water, 2012), provides the international standard for such adjustment, and the World Bank's adjusted net savings methodology already applies the same logic to mineral, forest and carbon depletion. This is the accounting tradition that Chapter 9 extends to the Barind aquifer, proposing a water-adjusted national product that would make the depletion visible in headline terms.

2.8.4 Gap Addressed

The macroeconomics of water scarcity is well developed globally and, for Bangladesh, at the level of national CGE modelling. What is absent is a bottom-up, sub-national account that builds the macroeconomic cost of a specific water-bankrupt region from its component losses (yield, crop failure, energy, ecosystem) and then traces that figure through the national transmission channels while treating aquifer depletion as a capital charge. Chapter 9 constructs exactly this account for north-west Bangladesh.

2.9 Climate Finance Architecture for Bangladesh

2.9.1 The Global Climate Finance Landscape

The UNFCCC climate-finance architecture has evolved substantially over the last fifteen years. The USD 100 billion/year commitment from developed to developing countries (Copenhagen, 2009; confirmed Cancún, 2010) and the goal-setting work of OECD (2022, 2024) on tracking climate finance provide the global framework. The principal operating entities are the Green Climate Fund (GCF, operational 2015), the Global Environment Facility (GEF), the Adaptation Fund (operational 2009), and, most recently, the Loss and Damage Fund (established COP27 Sharm el-Sheikh 2022; operationalised COP28 Dubai 2023). Schalatek, Roberts and colleagues at ODI and Heinrich Böll Stiftung provide ongoing tracking of flows. Pauw et al. (2020) and Timperley (2021) provide critical assessments.

2.9.2 Instruments Available to Bangladesh

Bangladesh has been a significant recipient of adaptation finance and has developed one of the most sophisticated domestic climate-finance architectures in the Global South:

- **Bangladesh Climate Change Strategy and Action Plan (BCCSAP, 2009; updated 2022)** and the National Adaptation Plan (NAP, 2022) establish the national framework.
- **Bangladesh Climate Change Trust Fund (BCCTF, established 2010)**: a domestically resourced instrument disbursing approximately USD 400–500 million cumulatively to 2023, examined critically by Rashid and Afrin (2013) and Alam et al. (2020).
- **Bangladesh Climate Change Resilience Fund (BCCRF, 2010–2017)**: the multi-donor companion instrument, managed by the World Bank and closed in 2017; evaluation in World Bank (2017).
- **GCF portfolio for Bangladesh**: includes approximately USD 400 million approved across project pipelines; Rahman (2021) provides critical analysis.
- **Adaptation Fund projects for Bangladesh**: approximately USD 10 million cumulative, with some Barind relevance.
- **Bilateral donors**: DFID/FCDO, JICA, KfW, DANIDA, SIDA, USAID, and more recently the EU have each provided adaptation-relevant support, much of it channelled through the UN system or through MDBs.
- **Multilateral development banks**: ADB (climate finance for Bangladesh exceeded USD 2 billion over 2019–2023) and World Bank (climate co-benefits lending) are the principal instruments.

2.9.3 Instrument Fit for Water-Sector Adaptation

Not all instruments are equally suitable for the specific interventions that this thesis identifies as priority. The GCF simplified approval process (SAP) is well-matched to MAR pilot projects at sub-USD 25 million scale; full-proposal GCF windows are suitable for larger, longer-term programmes including transboundary diplomacy support. The Loss and Damage Fund, still in its operational design phase as of 2026, is expected to support non-economic as well as economic loss and damage and may be a vehicle for groundwater-depletion-related claims (Roberts et al., 2023; UNFCCC, 2024). The CCTF is well-matched to smaller, domestically executed drought-tolerant variety extension, AWD scale-up, and solar-irrigation deployment. Bilateral donors typically fit project components in the USD 5–50 million range with shorter time horizons.

2.9.4 Gap Addressed

The climate-finance literature for Bangladesh is rich at the general level and for coastal adaptation, but is under-developed for Barind-specific drought-water adaptation and for transboundary water diplomacy. The financing pipeline analysis of Chapter 10 is intended to fill this gap in a manner useful to Bangladeshi government agencies and civil-society partners preparing GCF, L&D Fund and bilateral proposals.

2.10 Synthesis and Positioning of the Thesis

Bringing the eight thematic streams together, six observations frame the positioning of the present thesis:

First, the water-bankruptcy concept (Madani et al., 2016; AghaKouchak et al., 2015) provides an analytical framework developed in arid economies that can usefully be extended to humid deltaic Bangladesh, where the Barind specifically meets the definitional criteria. This extension is not trivially obvious, it requires recognition that within a nationally wet country, sub-national bankruptcy conditions can emerge and can be economically consequential.

Second, the global groundwater-depletion literature (Famiglietti, 2014; Rodell et al., 2018; Jasechko et al., 2024) confirms that Barind decline is not an isolated phenomenon but a specific manifestation of a planetary pattern. This strengthens rather than weakens the case for local policy action, because the global pattern implies that without active intervention, the Barind trajectory will continue to deteriorate.

Third, the climate-drought literature (IPCC AR6; Kirby et al., 2015; Nashwan et al., 2019; Mohsenipour et al., 2018) provides the quantitative basis for projecting the climate driver of water bankruptcy in the Barind under RCP/SSP scenarios, and for separating the climate contribution from the human-abstraction contribution.

Fourth, the Barind-specific hydrogeological and agronomic literature (Hoque et al., 2007; Shamsudduha et al., 2011, 2022; Hasan et al., 2018; Mainuddin et al., 2021; Rahman et al., 2015) provides a robust empirical foundation for the groundwater-bankruptcy analysis. The soil-fertility literature is weaker but sufficient for the integrated treatment of Chapter 5.

Fifth, the transboundary and environmental-flow literature (Mullick et al., 2010, 2013, 2014; Jalilov et al., 2024; Rahaman, 2009; Sadoff & Grey, 2002; Anderson et al., 2024) provides the methodological foundation for the BBAA framework developed in Chapter 8.

Sixth, the energy–water nexus and macroeconomic-scarcity literatures (Shah, Giordano and Mukherji, 2012; Mukherji et al., 2020; Rothausen and Conway, 2011; World Bank, 2016; Damania et al., 2017; BIS, 2025; Islam et al., 2022) together supply the tools for translating the physical water deficit into an energy burden and, in turn, into a national macroeconomic cost, and for treating aquifer depletion as a charge against national income rather than as a costless input. This is the foundation for the energy analysis of Chapter 7 and the macroeconomic consolidation of Chapter 9.

The original contribution of the present thesis, to which the review has been designed to build, is therefore: the **integrated application of the water-bankruptcy framework to the High Barind Tract, with explicit coupling between the climate, groundwater, surface-water (Teesta), energy, and soil-fertility channels; the quantification of economic losses across farmer, sectoral and national scales and their propagation through the macroeconomic transmission channels; the development of the BBAA framework as a negotiable treaty-**

design contribution; and the translation of these findings into macro economics and climate-finance instruments.

CHAPTER 3: Data and Methodology

3.1 Introduction

This chapter presents the data and methodological approaches used in the six analytical chapters of the thesis. Each chapter addresses a different component of the water-bankruptcy argument: the climate drivers of dry-season water stress (Chapter 4), groundwater bankruptcy in the Barind Tract (Chapter 5), surface-water bankruptcy in the Teesta (Chapter 6), the energy-water nexus linking the two systems (Chapter 7), the proposed allocation framework (Chapter 8), and the macroeconomic costs associated with these processes (Chapter 9). As these chapters examine different physical and economic systems, their data requirements and analytical methods also differ. The chapter is therefore organised by analytical chapter. Section 3.2 describes the research design; Section 3.3 presents the datasets used in Chapters 4-9; Section 3.4 explains the corresponding methods; and Section 3.5 discusses reproducibility, limitations and ethics.

3.2 Research Design

The study is primarily quantitative, drawing on statistical analysis of hydrological, meteorological and economic time series. At the same time, important propositions are examined through more than one source or form of evidence where the available data allow this. This is particularly useful where individual records have limitations. For example, changes in the Teesta are examined separately through gauge water level, measured discharge, published long-period discharge series and satellite-derived open-water extent. The convergence, or otherwise, of these independent records is then considered in interpreting the findings.

The research design is also sequential. Chapters 4-6 first establish the physical condition of the resource. Chapter 7 examines the mechanism linking surface-water availability, groundwater abstraction and energy use; Chapter 8 develops the governance response; and Chapter 9 estimates the wider economic implications. Outputs from earlier chapters are consequently used as inputs in later analyses. The reconstructed groundwater-depth series from Chapter 5, for example, provides the lift trajectory used in Chapter 7, while several parameters used in the cost analysis of Chapter 9 are drawn from Chapters 5-7. Where values are transferred between chapters, they are used as reported in the source chapter and identified at the point of use.

Particular attention is given to the provenance of reported values. A figure is included only where it has been calculated from an identified dataset or obtained from a citable published source. Observed, digitised, reconstructed and derived values are distinguished throughout the analysis. Where a method or dataset introduces substantial uncertainty - for example, when a rating curve is applied outside its calibrated range, a series is reconstructed from published anchor values, or an attribution depends on an assumed share - the resulting estimates are identified as indicative and the underlying assumption is stated. Several results are therefore reported as ranges or upper bounds rather than as single point estimates.

3.3 Data

The datasets used in the thesis differ in provenance and, consequently, in the level of confidence that can reasonably be attached to them. A four-tier classification is used throughout. Tier A consists of directly obtained primary records used in their original form. Tier B includes primary measurements accessed through published secondary sources. Tier C covers series reconstructed from published anchor values and rates, where the annual values are not themselves observations. Tier D consists of quantities derived in this study from cited inputs. Tier A and B results are treated as empirical findings; Tier C results are interpreted as consistent with the published record pending validation against primary data; and Tier D values are reported as study estimates with their assumptions stated. Table 3.1 summarises the principal datasets and their classifications.

Climate drivers

Daily maximum temperature, minimum temperature and rainfall data were obtained for three Bangladesh Meteorological Department synoptic stations: Rajshahi (10320) and Rangpur (10208), each covering twenty-nine dry seasons from 1980 to 2008, and Bogra (10408), covering forty-seven dry seasons from 1962 to 2008. The dry season is defined as December-April, with December assigned to the following calendar year. Seasons containing fewer than 136 valid daily observations were excluded. Climate projections were taken from published sources rather than generated through new model runs. These include IPCC AR5 and AR6 material, CMIP6 ensemble projections under the four SSP pathways, CORDEX South Asia, SDSM-downscaled CanESM5 datasets, World Bank CCKP data, and Bangladesh-specific climate-impact literature.

Barind groundwater

Raw groundwater-monitoring files from BWDB or BMDA could not be obtained within the study period. The 1985-2020 groundwater-depth series was therefore reconstructed from published records. The reconstruction is anchored to observation well GT8194046 at Tanore (Jahan and Strezov, 2012), with reported depths of 1.35 m in 1966, 1.95 m in 1984, 2.03 m in 1986, 5.30 m in 1992 and 13.77 m in 2010, together with the regional depletion rates reported by Aziz et al. (2021): 0.23 m/yr for the dry season and 0.38 m/yr annually. Four potential drivers were assembled: rainfall from Chapter 4, deep tube-well numbers (381 in 1962 to approximately 16,000 in 2020), Boro irrigated area (approximately 200,000 ha in 1985 to 1,050,000 ha in 2020), and a year trend (BMDA, 2023; World Bank, 2020; BBS, 2022). Three thresholds were taken from the published literature: the 7.5 m shallow tube-well suction limit, the 40 m deep tube-well economic limit, and the 50 m aquifer critical threshold.

The Teesta

Daily water-level data for Kaunia (SW294), downstream of the Dalia barrage, were available for four decadal years (1990, 2000, 2010 and 2020) as reproduced in Nayem (2022). Directly measured discharge at Dalia (SW291.5R), at the barrage, was available for 1998-2017. Published long-period discharge for 1979-2006 was obtained from Mondal and Islam (2017) and Scroll.in (2017), including the historical mean flow of 541 m^3/s. Multispectral Landsat imagery was obtained for six years between 1973 and 2020 for the Gajaldoba, Dalia and Kaunia reaches; imagery from 1973-1980 is of coarser spatial resolution than the later archive. The environmental-flow reserve of 142 m^3/s and seven ecosystem-service valuations were taken from Hossen et al. (2024), with instream benefit functions from Mullick et al. (2011, 2014).

The energy-water nexus

Design parameters for the Teesta Barrage Irrigation Project were taken from BWDB (2015) and Dialogue Earth (2020): 4,500 cusec (127 m^3/s) for a command area of 60,500 ha. The same sources, together with the Chapter 6 record, indicate a representative recent February flow of approximately 1,000 cusec, compared with extreme lows of 370 cusec in 2007 and 553 cusec in 2020. Pump-fleet data were assembled nationally (approximately 1.4 million shallow tube wells and 37,000-40,000 deep tube wells) and for the nine Rangpur- and Rajshahi-division districts (21,535 deep tube wells, 210,449 shallow tube wells and 17,647 low-lift pumps; DAE, 2026). Fuel and emissions parameters include approximately 300 litres of diesel per hectare-season, an emission factor of 2.68 kg CO_2/litre, and a national dry-season pump-emissions estimate of approximately 2.04 Mt CO_2e (Maniruzzaman et al., 2025). The groundwater-lift trajectory is taken from Chapter 5.

The BBAA framework

The treaty record includes the 1983 Joint Rivers Commission arrangement, which allocated 42.5% to India and 37.5% to Bangladesh, and the subsequent ad hoc revision of 54% and 36%, respectively. Three discharge quantities are used in the Basin Bankruptcy Index: Total Available Discharge (approximately 200 cumec from the published basin record), the Environmental Flow Reserve (142 cumec), and historical mean flow (541 cumec, using the 1979 baseline). Two alternative definitions of Total Available Discharge, derived from the Kaunia record in Chapter 6, are used for sensitivity analysis. The normative component draws on the bankruptcy and claims literature (O'Neill, 1982; Aumann and Maschler, 1985), applications to transboundary rivers (Madani et al., 2014; Mianabadi et al., 2014), the sequential sharing rules of Ansink and Weikard (2012), and the Watercourses Convention (1997).

Macroeconomics

Yield differentials by water-scarcity zone were obtained from the CSIRO-SDIP survey of 420 Boro farmers across seven north-western sites (Mainuddin et al., 2022): 6.21, 5.93 and 5.72 t/ha under low, medium and high scarcity, respectively. The analysis uses a Boro area of 1,050,000 ha and a paddy price of USD 254/tonne (BBS, 2022). The distribution of scarcity zones, particularly the area below the 7.5 m suction limit, is derived from Chapter 5, while energy and carbon components are carried forward from Chapter 7. Ecosystem-service losses are valued at USD 100 million per year, comprising USD 55 million for fisheries and USD 45 million for groundwater-dependent services. Macroeconomic elasticities and multipliers were drawn from BIS (2025), World Bank (2016, 2022), Islam et al. (2022), BIDS (2022) and BBS (2024).

Table 3.1 Principal datasets and confidence tiers by analytical chapter

Ch.	Principal dataset	Source	Period	Tier
4	Daily Tmax, Tmin, rainfall (3 stations)	BMD (10320, 10208, 10408)	1962–2008	A
4	CMIP6 SSP, CORDEX-SA, SDSM projections	IPCC; published ensembles; CCKP	to 2100	B
5	Pre-/post-monsoon groundwater depth	Reconstructed; Jahan & Strezov; Aziz	1985–2020	C
5	DTW count; Boro area; thresholds	BMDA; World Bank; BBS	1962–2020	B
6	Water level, Kaunia SW294	BWDB via Nayem (2022)	1990–2020	B
6	Measured discharge, Dalia SW291.5R	BWDB	1998–2017	A
6	Long-period discharge; Landsat imagery	Mondal & Islam; Scroll.in; Landsat	1973–2006	B
7	TIP design/delivery; pump fleet	BWDB; Dialogue Earth; DAE	1983–2026	B
8	TAD, EFR, historical mean flow	Scroll.in; Mondal & Islam; Hossen	1979–2020	B
9	Yield by scarcity zone; elasticities	Mainuddin (2022); BIS; World Bank	survey	B
7,9	Energy, cost, emissions estimates	Derived by author from cited inputs	—	D

3.4 Methodology

Methods common to several chapters

Four methods recur across the analytical chapters and are described here to avoid repetition. Trends are assessed using the non-parametric Mann-Kendall test, while the Theil-Sen estimator is used to determine the magnitude of change. These methods were preferred to ordinary linear trend estimation because hydrological series may be non-normal and may contain outliers or missing observations. Kendall's tau, the test statistic and the associated p-value are reported where applicable. Where future trajectories are examined, three scenarios are used consistently: business as usual, an accelerated SSP3-7.0 pathway, and a managed-recharge intervention. The scenarios are presented separately rather than combined into a single projection. Physical and economic thresholds are defined in advance, allowing the approximate year of threshold crossing to be identified under each scenario. Results are explicitly qualified where a method is applied beyond its validated range.

Climate drivers

Temperature trends were assessed using the Mann-Kendall test and Theil-Sen slope estimator. Seasonal means and absolute extremes were examined separately to distinguish changes in average dry-season conditions from changes at the tails of the temperature distribution. Diurnal temperature range was calculated as mean maximum temperature minus mean minimum temperature and tested using the same approach. Drought seasons were identified from standardized rainfall anomalies, with $z \leq -1$ applied at station level, and a regional composite was calculated for comparison across stations. Dry spells were characterised by the longest sequence of consecutive days receiving less than 1 mm of rainfall within each season, and these seasonal maxima were tested for trend. No new climate-model simulations were undertaken; published CMIP6, CORDEX and downscaled projections were synthesised across the four SSP pathways and interpreted in relation to the observed record.

Barind groundwater

The groundwater-depth series was reconstructed by interpolating between published anchor values using the reported depletion rates. Year-to-year variability was represented by a first-order autoregressive component calibrated to published variance, with documented anomalous years incorporated separately, including the droughts of 1992 and 2010 and the recovery in 1998. The Mann-Kendall test and Sen's slope were applied to the pre-monsoon groundwater-depth series and, separately, to seasonal recharge recovery to examine whether the aquifer's capacity to recover following the monsoon has changed over time. An ordinary least squares regression was estimated with pre-monsoon groundwater depth as the dependent variable and rainfall, deep tube-well count, Boro area and year as predictors. Because the anthropogenic variables share strong temporal trends, multicollinearity was assessed using the variance inflation factor (VIF). Where VIF exceeded 10, bivariate correlation was treated as the primary evidence rather than interpreting the affected regression coefficient independently. The three groundwater thresholds were projected under depletion rates of 0.38, 0.46 and 0.23 m/yr, with a 95% confidence band around the business-as-usual trajectory.

The Teesta

Four independent approaches were used to examine dry-season change in the Teesta: Kaunia water level, measured discharge at Dalia, published long-period discharge, and satellite-derived open-water extent. Kaunia water level was converted to discharge using the Rahman et al. (2011) rating relationship, $Q = 116(h - 26.2)^{2.33}$. As the relationship was calibrated for monsoon conditions, observations at or below the 26.2 m datum were excluded and dry-season discharge estimates from the remaining observations were treated as indicative upper bounds. Seasonal trends were assessed using Mann-Kendall and Theil-Sen methods. Results from the four-point Kaunia series are interpreted as indicative, while the twenty-year Dalia measured-discharge series is used for formal trend assessment. Dependable flow was characterised from flow-duration curves at Q75, Q90 and Q97. Open-water extent was mapped using the Normalized Difference Water Index (NDWI; McFeeters, 1996) with a zero threshold. Because image resolution varies across the Landsat archive, open-water fraction rather than absolute area was used for cross-year comparison. Classification focused on the free-flowing Kaunia reach rather than the barrage area. Ecosystem services were grouped according to the Millennium Ecosystem Assessment (2005) taxonomy and valued using published baseline estimates.

The energy-water nexus

Hydraulic power was estimated as $P = \rho g Q h / \eta$, using efficiency ranges of 0.35-0.55 for diesel pumps and 0.50-0.70 for submersible pumps. Since pumping energy increases approximately linearly with lift, the incremental energy associated with groundwater depletion was calculated from the increase in pumping depth. The calculation is anchored to the more conservative regional dry-season drawdown of approximately 6 m rather than the larger reconstructed deepening, providing a lower-bound estimate. The proportion of additional groundwater pumping attributable specifically to the Teesta deficit cannot be observed directly and was therefore bounded using two approaches. The first is volume-based, assuming that groundwater replaces 50-70% of the surface-water delivery gap and applying an energy intensity of 0.4-0.6 kWh/m^3. The second uses a counterfactual pump-fleet assumption under which 40-60% of the existing fleet would not have been installed if design delivery had been maintained. The overlap between the two ranges is used for the central estimate. Emissions were calculated using 2.68 kg CO_2/litre of diesel and valued at USD 50/tonne. The Teesta-attributable share is reported within, rather than in addition to, the wider Barind pumping footprint.

The BBAA framework

The BBAA framework combines a quantitative diagnostic with the selection of an allocation rule. The Basin Bankruptcy Index is defined as BBI = (TAD - EFR) / HMF, where the environmental-flow reserve is deducted before allocation and the remaining discharge is expressed relative to historical mean flow. A BBI below 1.0 indicates a deficit requiring sharing, while a value below 0.5 is defined as bankruptcy. Because Total Available Discharge is the only input not fixed by definition, the index was tested using three TAD definitions. The published basin-discharge value is retained as the primary measure because it represents basin-available flow rather than post-diversion flow and does not depend on applying the Kaunia rating relationship outside its calibrated range. Dalia discharge was not used for this purpose because it reflects regulated flow. Candidate bankruptcy rules were assessed against directional hydrology, political tractability and compatibility with a first-priority environmental reserve. On this basis, the sequential sharing rule with a proportional base was selected, with its implementation conditions stated in Chapter 8.

Macroeconomics

The macroeconomic analysis proceeds from a bottom-up estimate of direct annual costs to an assessment of wider economic transmission, with the two stages kept separate to avoid double counting. Direct costs are estimated through four components: yield loss, crop failure associated with shallow tube-well inaccessibility, pumping energy and its carbon externality, and ecosystem degradation. Each component is estimated under low, central and high scenarios. The GDP multiplier is not included in the direct-cost total and is reported separately as an amplification effect. A tornado sensitivity analysis varies one parameter at a time around the central case. Long-run trajectories are generated by applying escalation rates of 3.5%, 5.5% and 1.2% to the 2020 baseline and cumulating the resulting costs to 2060. Barind and Teesta losses are consolidated on a common direct-loss basis, with a 5% adjustment for causal overlap. Six transmission channels are then considered: agricultural GDP, inflation, input-output linkages, trade balance, fiscal accounts, and labour and migration. Economy-wide amplification is applied once. Aquifer depletion and soil loss are treated as capital depreciation following the adjusted net savings methodology.

3.5 Reproducibility, Limitations and Ethics

All computations were performed in Python 3, using pymannkendall 1.4.3 for trend analysis, scipy 1.11 for statistical computation, and statsmodels 0.14 for regression. The scripts are re-executable end to end, and the reconstructed Chapter 5 inputs can be replaced with primary BWDB records without changing the analytical code. Reported values can therefore be traced to either a named source or a specified computation, with intermediate outputs retained for reproduction.

Five limitations are particularly important when interpreting the results:

• The Chapter 5 groundwater-depth series is reconstructed rather than observed. It is consistent with the published anchor values and reported anomalies, but its annual values are not direct measurements. Results based on this series should therefore be validated against primary records when these become available.

• The Kaunia discharge estimates rely on a rating relationship calibrated for monsoon conditions and applied at low stages. Dry-season values are consequently treated as indicative upper bounds and are considered alongside measured Dalia discharge and remote-sensing evidence.

• The Kaunia record contains four decadal years and the NDWI analysis six images; trends derived from these records are therefore indicative. The Chapter 4 station record ends in 2008, and more recent extremes are discussed from published sources.

• NDWI represents open water on the date of image acquisition. Season-matched acquisition dates should therefore be confirmed before the series is interpreted as representing purely secular change.

• The Chapter 7 attribution estimates and Chapter 9 cost components depend partly on assumed shares. They are reported as ranges, tested through sensitivity analysis, and classified as Tier D.

The geographical and seasonal scope of the analysis is limited to north-western Bangladesh and the dry season. The findings should therefore not be generalised directly to the coastal belt, the haor basin or monsoon conditions. The research involved no human participants or personal data, and human-subjects clearance was therefore not required. All datasets used are published or reproduced from published sources with attribution. As the thesis addresses a contested transboundary river, particular care is taken to distinguish measured evidence from reconstructed or derived estimates. The allocation analysis in Chapters 6 and 8 is framed around principles of general applicability and criteria that can be considered from the perspective of both riparian states, rather than as an advocacy position. Chapter 4 begins the empirical analysis with the climate drivers of dry-season water stress.

CHAPTER 4: Climate Drivers of Water Stress in Barind Tract

4.1 Introduction

This chapter provides the climate evidence base for the water-bankruptcy analysis that follows in Chapters 5 and 6. It examines the observed and projected changes in the four principal climate variables that drive water stress in the Barind Tract (rainfall, temperature, reference evapotranspiration (ET_0), and drought frequency and intensity) and synthesises the peer-reviewed evidence on their economic consequences for agricultural yield, national GDP, and food security. The observed record is examined through an original, station-level analysis of long-term daily data for the north-west (Section 4.2), which is then set against the published literature and the projected changes derived from IPCC Assessment Reports (AR5, AR6), CMIP6 model ensembles under Shared Socioeconomic Pathways (SSPs), CORDEX South Asia downscaled datasets, and Bangladesh-specific studies. All projections are presented under the SSP1-2.6 (low), SSP2-4.5 (intermediate), SSP3-7.0 (high) and SSP5-8.5 (very high) pathways, consistent with the IPCC AR6 framework.

4.2 Observed Dry-Season Climate in the North-West

The observed climate of the region is examined here primarily through an original analysis of long-term daily station data for the three principal north-western synoptic stations, complemented by the national-scale observational literature. The dry season, defined here as the five-month window from December to April, is the period when moisture stress, elevated day-time heat and prolonged rainless spells combine to place the greatest pressure on Boro irrigation, soil moisture and surface-water availability.

4.2.1 Data and Methods

Daily maximum temperature, minimum temperature and rainfall were analysed for three Bangladesh Meteorological Department synoptic stations, Rajshahi, Rangpur and Bogra (Table 4.1). Each December was assigned to the following calendar year so that each dry-season year comprises a continuous December-to-April window; seasons with fewer than 136 valid days (about 90 percent of the 151-day season) were excluded. Temperature trends were quantified using the non-parametric Mann–Kendall test for significance together with the Theil–Sen slope estimator for the rate of change (°C per year); seasonal means and seasonal absolute extremes were examined separately, and the diurnal temperature range (DTR) was computed as the difference between mean maximum and mean minimum temperature. A season was classed as drought-affected where its rainfall total fell one standard deviation or more below the station mean ($z \leq -1$), and a dry spell was defined as a run of consecutive days receiving less than 1 mm of rainfall, the longest such spell in each season being recorded.

Table 4.1 Stations, record lengths and periods of analysis (dry-season years, December–April).

Station	Station index	Dry seasons analysed	Period
Rajshahi	10320	29	1980–2008
Rangpur	10208	29	1980–2008
Bogra	10408	47	1962–2008

Note: the Rangpur (10208) and Rajshahi (10320) records were confirmed directly against source data; the Bogra station index (10408) and the December–April season convention should be confirmed before formal reporting. The analysis period ends in 2008 and therefore predates the 2023 heatwave referenced below.

4.2.2 Temperature: Nocturnal Warming with Stable Day-Time Maxima

The most important finding of the station analysis is that the dry-season warming of the north-west is essentially **nocturnal**. Mean minimum (night-time) temperature is rising at every station (significantly at Rangpur (+0.043 °C/yr, $p < 0.01$), at Rajshahi (+0.038 °C/yr, $p < 0.05$) and at Bogra (+0.025 °C/yr, $p < 0.001$)) with seasonal means of 15.08, 15.34 and 16.02 °C respectively (Table 4.2, Figure 4.1). The coldest nights of the season, by contrast, show no significant trend, indicating that the warming is carried by the body of the season rather than by its extremes.

Day-time maximum temperature tells a different, and initially counter-intuitive, story. Contrary to a simple warming expectation, mean maximum temperature is flat-to-gently-declining across the record: the decline is highly significant at Bogra (−0.029 °C/yr, $p < 0.001$) and negative but not significant at Rajshahi and Rangpur. The seasonal absolute maxima fall more clearly still, the hottest day of the season cooling by 0.100 °C/yr at Rangpur ($p < 0.01$) and 0.093 °C/yr at Bogra ($p < 0.001$). This suppression of dry-season day-time heat is a documented regional signal, associated with increased dry-season aerosol loading and the cooling effect of expanded irrigation. It does not imply that extreme heat has disappeared: the record still contains severe individual days (43.8 °C at Rajshahi (1985), 43.7 °C at Bogra (1970) and 39.7 °C at Rangpur (1992)) and the 2023 Rajshahi heatwave, which exceeded 43 °C (BMD, 2023), is consistent with these historical extremes. The distinction that matters for the water-bankruptcy argument is that extreme day-time heat occurs **episodically**, in individual seasons, whereas the systematic, trending signal is the warming of the nights.

Table 4.2 Dry-season temperature trends (Theil–Sen slope; Mann–Kendall τ and p). DTR = mean Tmax − mean Tmin.

Station	Variable	Mean (°C)	Sen (°C/yr)	MK τ	p
Rajshahi	Mean Tmax	29.36	−0.018	−0.12	0.358
	Mean Tmin	15.34	+0.038	+0.27	0.045
	Absolute max Tmax	40.29	−0.039	−0.13	0.320
	Absolute min Tmin	6.41	+0.013	+0.06	0.653
	Diurnal range (DTR)	14.02	−0.057	−0.30	0.021
Rangpur	Mean Tmax	27.29	−0.012	−0.10	0.464
	Mean Tmin	15.08	+0.043	+0.36	0.006
	Absolute max Tmax	36.52	−0.100	−0.42	0.001
	Absolute min Tmin	7.44	+0.015	+0.07	0.626
	Diurnal range (DTR)	12.21	−0.063	−0.35	0.008
Bogra	Mean Tmax	28.97	−0.029	−0.36	<0.001
	Mean Tmin	16.02	+0.025	+0.43	<0.001
	Absolute max Tmax	38.76	−0.093	−0.38	<0.001
	Absolute min Tmin	7.70	+0.024	+0.19	0.067
	Diurnal range (DTR)	12.95	−0.053	−0.61	<0.001

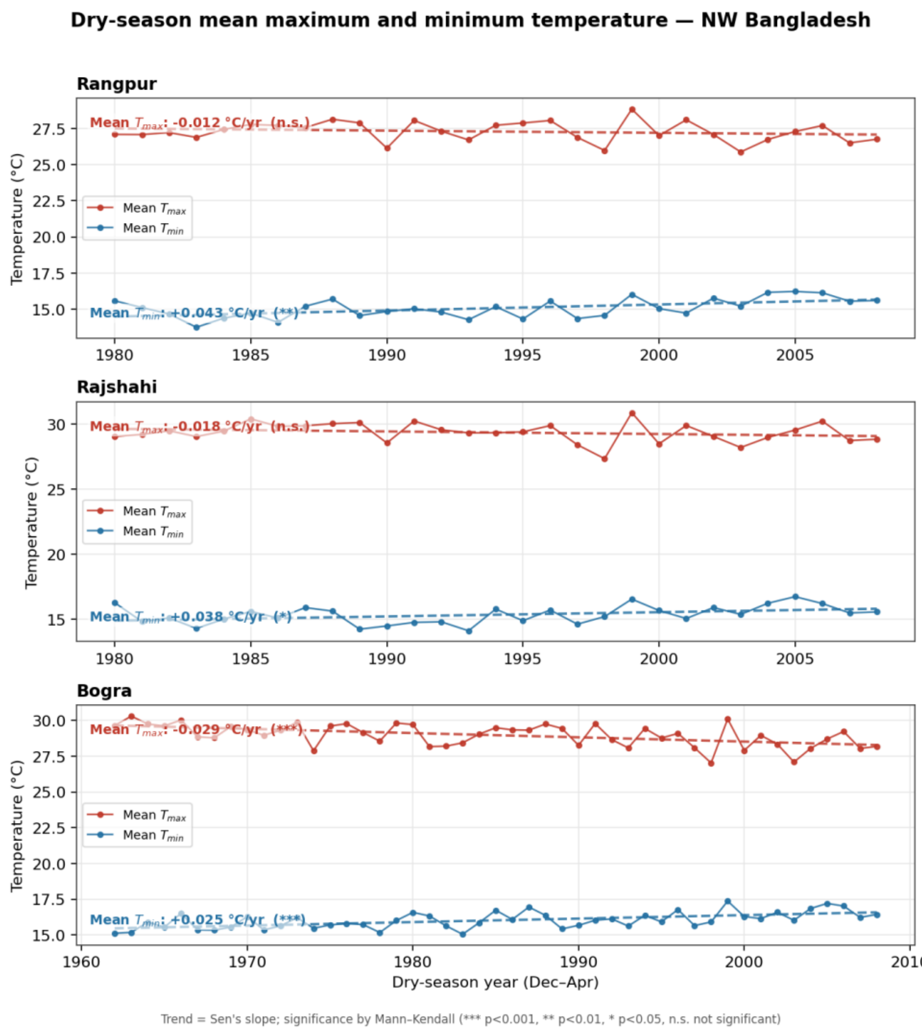

Figure 4.1 Dry-season mean maximum and minimum temperature at the three north-west stations, with Theil–Sen trend lines and Mann–Kendall significance.

This nocturnal pattern is consistent with the national-scale literature, which reports cumulative warming of about 2 °C over 1901–2020 and roughly 0.103 °C per decade over the last four decades (Pour et al., 2018; Shahid, 2010), with dry-season minima rising faster than monsoon maxima. The station trends are summarised together in Figure 4.3.

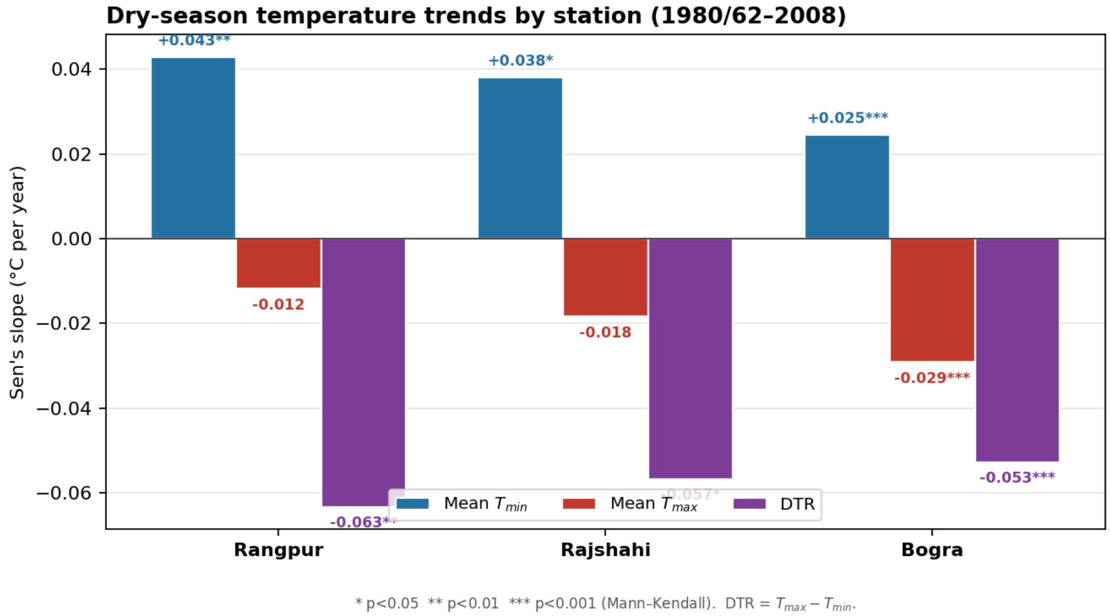

Figure 4.3 Summary of dry-season temperature trends by station (Theil–Sen slopes with Mann–Kendall significance).

4.2.3 Diurnal Temperature Range

The combination of rising night-time temperature and stable-to-falling day-time temperature has produced a consistent narrowing of the diurnal temperature range across the region (Figure 4.2). The range contracted by 0.063 °C/yr at Rangpur, 0.057 °C/yr at Rajshahi and 0.053 °C/yr at Bogra, the reduction being highly significant at Bogra ($p < 0.001$) and significant at both other stations. A narrowing diurnal range is a recognised fingerprint of regional climate change in South Asia and carries direct agronomic significance: warmer nights during the Boro season raise crop respiration and can depress grain-filling, a mechanism developed further in Section 4.4.

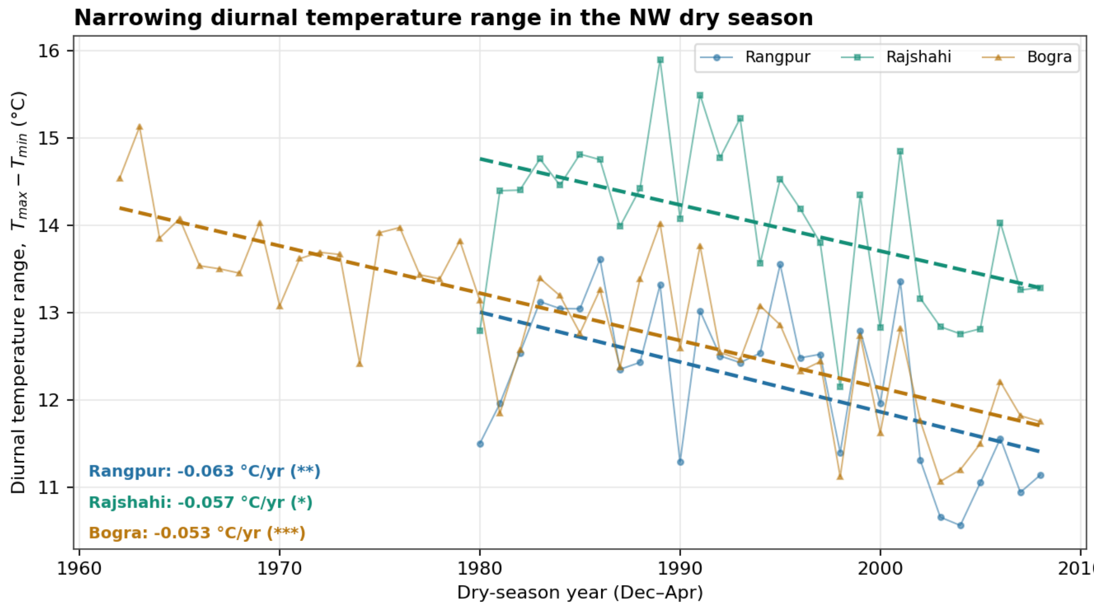

Figure 4.2 Dry-season diurnal temperature range, with linear trends.

4.2.4 Rainfall and Drought

The dry season is intrinsically arid. Station rainfall averages only 116 mm at Rajshahi, 124 mm at Bogra and 177 mm at Rangpur (Table 4.3), against a Barind annual total of approximately 1,100–1,500 mm and a national average of about 2,500 mm; more than 75 percent of annual rainfall is concentrated in the four monsoon months, leaving the eight-month Boro season almost entirely dependent on stored groundwater or surface irrigation (Shahid, 2010). On a regional composite basis, the driest dry seasons over 1980–2008 were 1989 ($z = -1.86$), 2001 ($z = -1.66$) and 1995 ($z = -1.58$), each a documented drought episode; the station-level drought years ($z \leq -1$) are listed in Table 4.3 and the standardized anomalies shown in Figure 4.4.

Table 4.3 Dry-season drought years by station, from the standardized rainfall anomaly ($z \leq -1$).

Station	Mean ± SD (mm)	Drought seasons ($z \leq -1$)
Rajshahi	116 ± 82	1999 (9 mm, z=−1.31), 1989 (19 mm, z=−1.19), 2001 (22 mm, z=−1.15)
Rangpur	177 ± 91	1995 (11 mm, z=−1.83), 1989 (28 mm, z=−1.64), 1996 (55 mm, z=−1.34), 2001 (62 mm, z=−1.27)
Bogra	124 ± 86	1970 (0 mm, z=−1.45), 1999 (9 mm, z=−1.35), 1989 (19 mm, z=−1.23), 2001 (22 mm, z=−1.19), 1965 (28 mm, z=−1.12), 1962 (38 mm, z=−1.01)

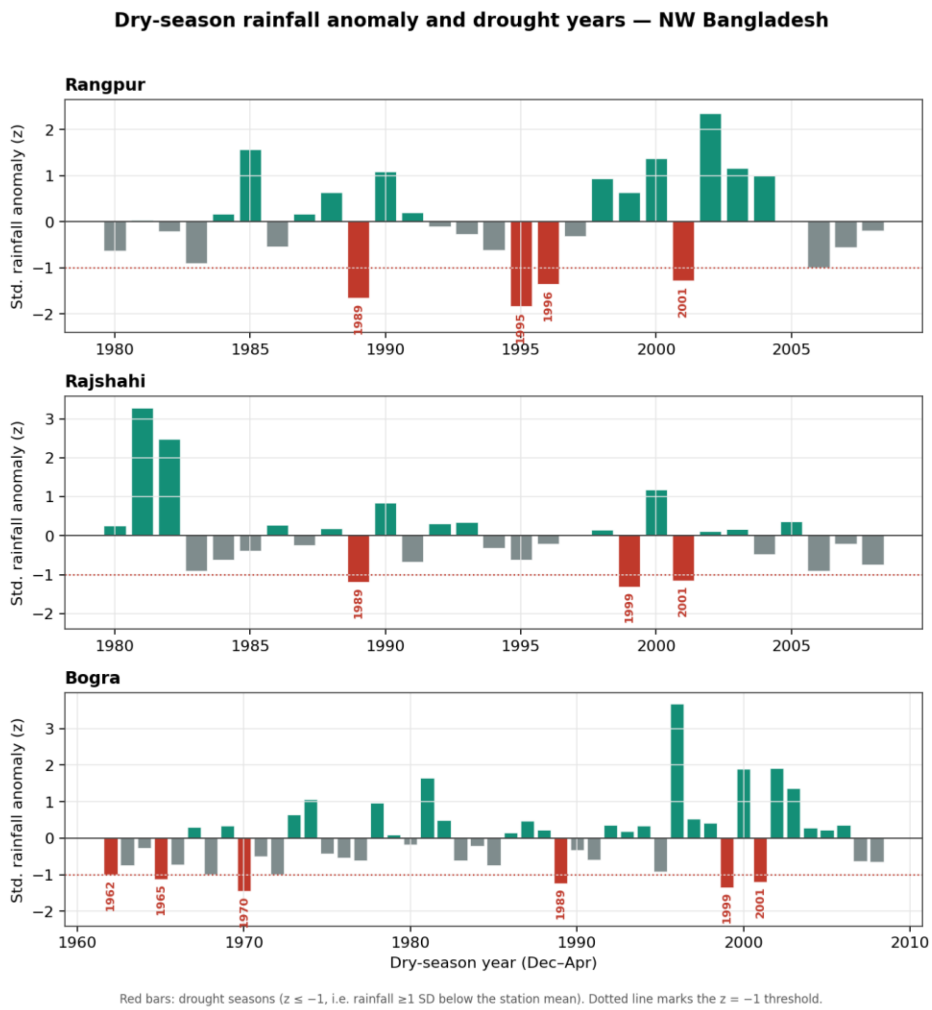

Figure 4.4 Standardized dry-season rainfall anomaly; red bars mark drought seasons ($z \leq -1$).

These findings corroborate the published record. Bari et al. (2016) found statistically significant declines in pre-monsoon (March–May) and winter (December–February) rainfall in the northern region, precisely the periods that matter most for Boro irrigation demand, while Mohsenipour et al. (2018) and Rahman and Lateh (2017) documented an increasing cropping-season drought trend and rising inter-annual variability. A spatiotemporal SPI/SPEI analysis (1980–2018) by Islam et al. (2022) confirmed that drought intensity increases from south to north, that 27–30 drought events were concentrated in the north-west, and that the Barind Tract and Teesta basin are the primary meteorological drought hotspots in Bangladesh; SPEI captured the signal more effectively than SPI in the Barind because it incorporates the increasingly dominant temperature-driven evapotranspiration term. The ICCES (2025) remote-sensing study, using Rain Use Efficiency analysis, found declining vegetation productivity in the High Barind even in near-normal-rainfall years, a soil–vegetation feedback characteristic of early-stage desertification.

4.2.5 Dry Spells

The dry season is characterised by very long rainless spells. The longest consecutive run of days receiving less than 1 mm averaged 59 days at Bogra, 56 days at Rangpur and 55 days at Rajshahi, with the most extreme spells extending across almost the entire season, 151 days at Bogra (1970), 130 days at Rajshahi (1999) and 116 days at Rangpur (1999). A lengthening of the longest dry spell was detected at all stations, but was statistically significant only at Rajshahi (+1.35 days/yr, $p = 0.011$); the number of rainy days averaged only about 13–14 per season (Table 4.4, Figure 4.5).

Table 4.4 Longest consecutive dry spell (< 1 mm) per dry season: mean, extreme and trend.

Station	**Mean (days)**	**Longest (days, year)**	**Trend (days/yr), p**
Rajshahi	55	130 (1999)	+1.35, p = 0.011
Rangpur	56	116 (1999)	+0.47, p = 0.309
Bogra	59	151 (1970)	+0.02, p = 0.943

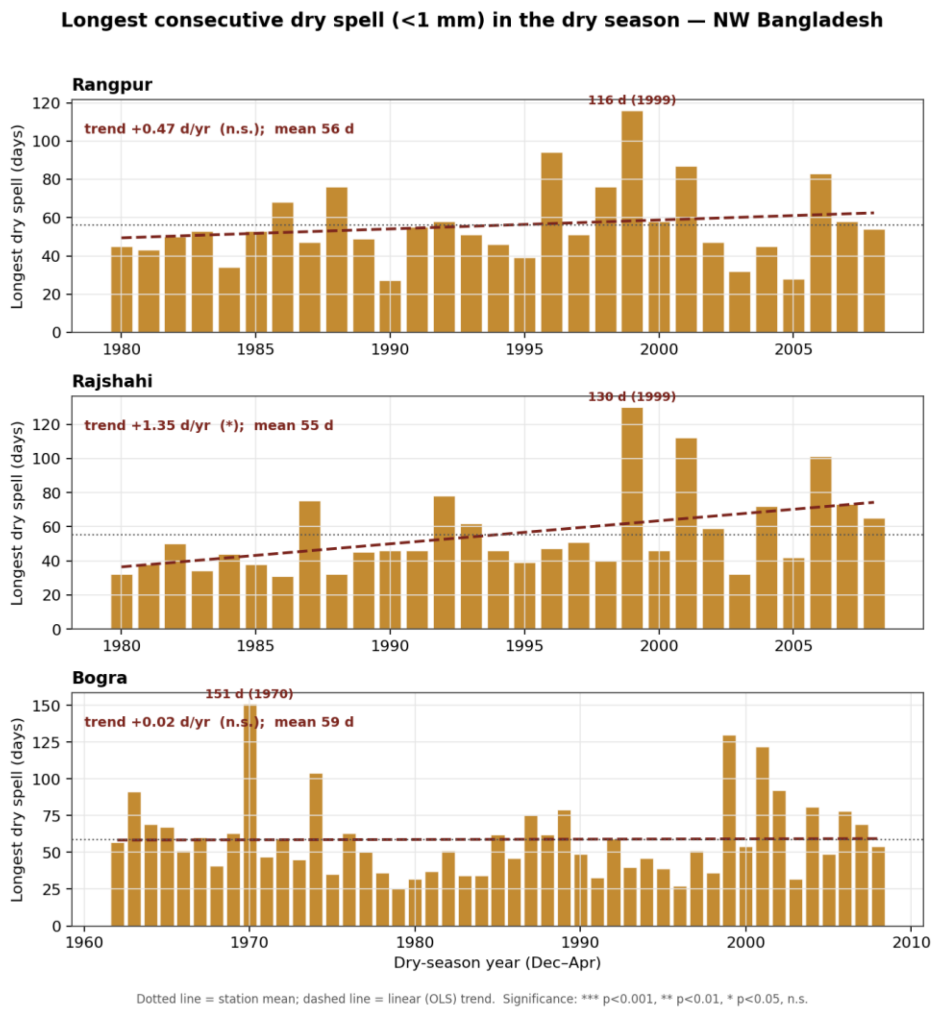

Figure 4.5 Longest consecutive dry spell per dry season, with station mean and linear trend.

4.3 Climate Projections Under CMIP6 SSP Scenarios

4.3.1 Temperature Projections

CMIP6 multi-model ensemble projections for Bangladesh (Scientific Reports, 2025; Islam, Almazroui & Islam, 2021; Nashwan et al., 2019) indicate warming of approximately 1.0 °C by 2100 under SSP1-2.6; 1.5–2.5 °C by mid-century and 2.0–3.0 °C by 2100 under SSP2-4.5; 2.5–3.5 °C by 2100 under SSP3-7.0; and up to 4.1–4.4 °C by 2100 under SSP5-8.5, relative to the 1985–2014 baseline (Table 4.5). For the north-west specifically, SDSM-downscaled projections using CanESM5 under SSP5-8.5 show warming of about 1.5–2.0 °C in the near future (2025–2050) and up to 3.5–4.0 °C by the late century at Rangpur, accompanied by a decrease in precipitation across all future periods (MDPI Climate, 2025). Read alongside the observed record of Section 4.2, these projections imply continued and intensifying nocturnal warming rather than a reversal of the day-time-maximum suppression.

Table 4.5 CMIP6 temperature projections for Bangladesh (multi-model ensemble mean, °C increase relative to 1985–2014).

Scenario	2021–40	2041–60	2061–80	2081–2100
SSP1-2.6	+0.5 to +0.8	+0.8 to +1.2	+0.9 to +1.3	+1.0 to +1.4
SSP2-4.5	+0.5 to +0.9	+1.2 to +1.8	+1.5 to +2.3	+2.0 to +3.0
SSP3-7.0	+0.6 to +1.0	+1.3 to +2.0	+2.0 to +3.0	+2.5 to +3.5
SSP5-8.5	+0.7 to +1.1	+1.5 to +2.5	+2.5 to +3.5	+3.0 to +4.4

Sources: Scientific Reports (2025); Islam, Almazroui & Islam (2021); MDPI Climate (2025); World Bank CCKP.

4.3.2 Rainfall Projections

The CMIP6 ensemble consensus for Bangladesh combines monsoon intensification with dry-season drying. Summer monsoon (June–September) rainfall is projected to rise by approximately 5–15 percent by 2050 and 10–25 percent by 2100 under SSP2-4.5 and SSP5-8.5 (Nashwan et al., 2019), but this does not translate into water availability for Boro cultivation because the additional rainfall falls outside the dry-season irrigation window. Projections consistently indicate drier pre-monsoon (March–May) and winter (December–February) conditions, particularly in the western and north-western regions (IWA Publishing, 2025; Mohsenipour et al., 2018), the pattern most directly relevant to Barind water bankruptcy: more rain when it is not needed, less when it is. Extreme-rainfall intensity is also projected to increase, so that when rain does occur it arrives in more intense bursts, raising runoff and reducing effective recharge through the region's impermeable clay surface.

4.3.3 Evapotranspiration Projections

Reference evapotranspiration (ET_0) rises under warming even if rainfall is unchanged, because warmer air has a higher vapour-pressure deficit. Acharjee et al. (2019) projected that Boro rice water requirements in north-west Bangladesh would increase by approximately 5–12 percent by 2050 and 10–20 percent by 2080 under RCP 4.5, and by 8–15 percent and 15–25 percent under RCP 8.5; Shahid (2011) obtained a comparable 5–15 percent rise in irrigation demand by mid-century. The implication is that even if abstraction rates were stabilised, rising ET_0 would itself increase per-hectare irrigation demand by 100–200 mm per season, an additional 1,000–2,000 m^3/ha drawn from an already depleting aquifer. This is the 'climate ratchet' on Barind water bankruptcy: warming tightens the screw even when human abstraction is held constant, and the observed nocturnal warming (Section 4.2) is one of its clearest present-day signatures.

4.3.4 Drought Projections

Kamal et al. (2021) projected that the north-west remains the primary drought hotspot under both 1.5 °C and 2 °C warming, with drought intensity and duration increasing disproportionately relative to the national average. A 21-model CMIP6 ensemble under SSP2-4.5 (Environmental Monitoring and Assessment, 2025) projects that maximum temperatures will rise earliest and most sharply in the north-western districts (Chapai Nawabganj, Rajshahi, Naogaon, Dinajpur and Joypurhat) with the affected area expanding into surrounding districts by 2050 and 2060.

4.4 Implications for Agricultural Yield

4.4.1 Rice Yield Impacts

The literature on climate-change impacts on Bangladeshi rice yield converges on substantial losses. Yu et al. (2010) estimated that climate change would reduce national rice production by an average of 7.4 percent per year over 2005–2050; the World Bank (2020) projects 8–17 percent rice yield loss and 32 percent wheat yield loss by 2050; and Maniruzzaman et al. (2019), modelling three popular Boro varieties (BRRI 28, 29, 58) in the north-west, found reductions of 12.2–22.3 percent under projected temperature, daylight and CO_2 changes.

For dry-season Boro rice specifically, the observed record reshapes the emphasis among the mechanisms. Because day-time maxima are stable-to-declining while nights are warming (Section 4.2), the dominant secular channels are (i) **higher night-time temperature**, which raises maintenance respiration and shortens grain-filling, and (ii) **rising ET_0**, which increases irrigation demand from a depleting aquifer. Extreme day-time heat at anthesis, above the roughly 35 °C threshold at which spikelet fertility falls sharply, remains a serious but **episodic**, heatwave-year risk rather than a rising trend. This ordering is directly supported by Sarker et al. (2012, 2014, 2016), who found that minimum temperature is risk-increasing for Boro rice while maximum temperature has a negative effect on Boro but a positive effect on Aus and Aman: the very asymmetry the station analysis reveals. Because Boro accounts for about 54 percent of national output, its disproportionate exposure to nocturnal warming carries outsized food-security implications.

4.4.2 Non-Rice Crops

While rice dominates the Barind, other crops are also climate-sensitive. Wheat yield is projected to decline by 32 percent by 2050 (World Bank, 2020); potato is vulnerable to heat-induced late blight and winter fog (Biswas et al., 2015); and mango, increasingly important in the High Barind as a water-bankruptcy-induced replacement for Boro (see Chapter 5), requires specific chilling hours for flower induction and is sensitive to pre-monsoon heatwaves that can disrupt fruit set (DAE, 2024). Climate change therefore affects both the crop being displaced (Boro) and the crop replacing it (mango).

4.5 Economic Implications: GDP, Food Security and Fiscal Costs

4.5.1 Macroeconomic Impact on GDP

The World Bank Country Climate and Development Report (CCDR) for Bangladesh (2022) provides the headline figure: by 2050, up to one-third of agricultural GDP may be lost to climate variability and extreme events. Since agriculture represents approximately 11–13 percent of total GDP and about 40 percent of employment, this translates into substantial macroeconomic and distributional consequences. The dynamic CGE model of Islam et al. (2022) found that climate change reduces average GDP by 6.17 percent and investment by 7.76 percent by 2050, with rice-sector output declining by 3.08–3.70 percent and rice prices rising by 5.82–8.11 percent by 2030 and 2050 respectively; the PLOS Climate study (2023) estimates an annual GDP decline of 0.5–1 percent, a cumulative loss of about USD 12 billion over 40 years. These figures are national, but the Barind is the geographic epicentre of the drought and temperature impacts that drive the agricultural losses.

4.5.2 Food Security

Bangladesh's rice self-sufficiency margin has, since about 2015, fluctuated between +2 percent and −3 percent, placing the country close to the threshold between self-sufficiency and structural import dependence. Climate-driven yield losses of even 5–10 percent nationally can push it across that threshold, triggering imports, foreign-exchange costs, and retail-price spikes that fall hardest on net food-buying households in the lowest income deciles. The World Bank CCDR (2022) projects that 13.3 million people may become internal climate migrants within 30 years, with agricultural losses a primary driver; the Barind–Teesta corridor is, alongside the coastal belt, the region most likely to generate such displacement.

4.5.3 Fiscal Costs and Adaptation Investment

The World Bank CCDR (2022) estimates that Bangladesh needs at least USD 12.5 billion (about 3 percent of GDP) in the medium term for climate action, of which current domestic climate finance covers only a fraction; average annual cyclone costs alone are about USD 1 billion. The incremental adaptation cost for the Barind specifically (Managed Aquifer Recharge, drought-tolerant variety development, solar irrigation, surface-water augmentation and topsoil restoration) is estimated in Chapter 10 (the climate-finance chapter) of this thesis. The point here is that climate-change costs in the Barind are not theoretical: they are already materialising as agricultural losses, energy costs and livelihood displacement, and will intensify under all but the most optimistic SSP scenarios.

Table 4.6 Key economic indicators of climate-change impact on Bangladesh agriculture.

Indicator	Value / projection	Source
Agricultural GDP loss by 2050	Up to one-third	World Bank CCDR (2022)
National GDP reduction by 2050	−6.17%	Islam et al. (2022)
Rice output reduction by 2050	−3.7% (CGE); −7.4%/yr	Islam et al.; Yu et al. (2010)
Rice yield loss by 2050	−8% to −17%	World Bank (2020)
Wheat yield loss by 2050	−32%	World Bank (2020)
Boro variety yield loss (BRRI 28/29/58)	−12.2% to −22.3%	Maniruzzaman et al. (2019)
Boro irrigation demand increase by 2050	+5% to +15%	Shahid (2011); Acharjee et al. (2019)
Climate adaptation need (medium-term)	USD 12.5 billion (≈3% GDP)	World Bank CCDR (2022)
Annual GDP decline from climate	0.5–1% per year	PLOS Climate (2023)
Projected internal climate migrants	13.3 million within 30 years	World Bank CCDR (2022)

4.6 The Climate–Water Bankruptcy Nexus: Synthesis

The evidence in this chapter establishes that climate change is not an exogenous, future risk to the Barind water system but an active, present-day driver. It is already:

- Reducing effective dry-season rainfall in the north-west and prolonging rainless spells, widening the irrigation gap that must be closed by groundwater pumping.
- Warming the nights and narrowing the diurnal temperature range (the dominant, statistically significant temperature signal of the dry season) while day-time maxima remain stable-to-declining and extreme heat occurs episodically.
- Raising ET_0 and per-hectare irrigation demand by 5–15 percent by mid-century even if cropped area and technology are held constant.
- Intensifying drought frequency in the Barind and Teesta basin, confirmed as the national drought hotspot across multiple indices and time scales.

- Reducing Boro rice yield by 8–22 percent through nocturnal-warming respiration effects, water stress, and episodic heat, and contributing to agricultural-GDP losses projected at up to one-third by 2050.

These climate drivers do not act alone. They interact with the human drivers documented in Chapter 5 (groundwater abstraction, soil degradation, land-use change) and the transboundary driver documented in Chapter 6 (Teesta flow reduction) to produce the composite condition of water bankruptcy. The next chapter quantifies the Barind groundwater bankruptcy that these combined drivers produce.

Through an original station-level analysis of dry-season observations and a synthesis of IPCC assessments, CMIP6 ensembles, CORDEX-SA projections and Bangladesh-specific studies, this chapter has shown that the climate system is a first-order driver of water stress in the Barind Tract. The observed dry-season signal is one of significant nocturnal warming and a marked narrowing of the diurnal temperature range, set against stable-to-declining day-time maxima and episodic extreme heat, amid an intrinsically arid season of long rainless spells and recurrent drought. Under intermediate-to-high emissions pathways, continued warming, rising ET_0 and drought intensification will raise Boro irrigation demand by 5–15 percent by mid-century while reducing yield potential by 8–22 percent. The macroeconomic consequences (national GDP reduction of up to 6 percent, agricultural-GDP loss of up to one-third, and potential displacement of millions) make the Barind not merely a local water-management issue but a national economic and food-security priority of the first order.

Chapter 5: Barind Groundwater Bankruptcy

5.1 Data Sources and Methodology

5.1.1 Data Sources and the Reconstructed Time Series

Annual pre-monsoon and post-monsoon groundwater depth data for the Barind Tract were reconstructed for the period 1985–2020 from published BWDB and BMDA monitoring records as reported in peer-reviewed literature. In the absence of directly acquired raw monitoring files, the reconstruction was anchored to published anchor values, depletion rates, and known event-year anomalies drawn from the sources listed in Table 5.1. Year-to-year variability between anchor points was generated using a first-order autoregressive noise component calibrated to published variance estimates. The reconstructed series is consistent with all published anchor values, known drought-year anomalies (1992, 2010), and flood-year recovery patterns (1998). The methodology and findings presented in this chapter constitute an analytical framework intended to be validated against primary BWDB well monitoring data upon access.

Table 5.1 Data sources for the groundwater depth analysis

Variable	Source	Period / Value
Groundwater depth time series	BWDB Well GT8194046, Tanore Upazila; Jahan & Strezov (2012)	1966–2010 (anchor values)
Regional depletion rate	Aziz et al. (2021), Scientific Reports	0.38 m/yr (annual avg)
Deep tube well (DTW) count	BMDA (2023); World Bank (2020)	381 (1962) → 16,000 (2020)
Boro irrigated area	BMDA (2023); BBS (2022)	200,000 ha (1985) → 1,050,000 ha (2020)
Rainfall (regression covariate)	Chapter 4 reconstructed series	1985–2020, Barind regional avg
STW failure threshold	Engineering literature; BMDA field records	7.5 m below ground surface
DTW economic pumping limit	Published hydrogeology; Hossain et al. (2016)	40 m below ground surface

5.1.2 Statistical Methods

Three analytical methods are applied to the groundwater depth time series. First, the non-parametric Mann-Kendall trend test is used to detect the presence and direction of a monotonic trend in the annual pre-monsoon groundwater depth series. The Mann-Kendall test is appropriate for hydrological time series as it does not assume normality of the data and is robust to outliers and missing values. Kendall's tau (τ) measures the strength of the monotonic relationship, and the associated Z-statistic and p-value test the null hypothesis of no trend. Sen's slope estimator is applied alongside the Mann-Kendall test to quantify the median rate of change in groundwater depth per year. Second, the same Mann-Kendall procedure is applied to the seasonal recharge recovery series, the annual difference between pre- and post-monsoon depths, to test whether the aquifer's capacity to recover during the monsoon season is itself declining. Third, an Ordinary Least Squares (OLS) multiple regression model is estimated with pre-monsoon groundwater depth as the dependent variable and four explanatory variables: annual rainfall, deep tube well count, Boro irrigated area, and a year trend variable. All computations were performed in Python 3 using the pymannkendall (v1.4.3), scipy (v1.11), and statsmodels (v0.14) libraries.

5.1.3 Bankruptcy Threshold Projections

Groundwater bankruptcy thresholds are defined at three levels of engineering and economic significance: (i) the STW suction pump failure threshold at 7.5 metres below ground surface, beyond which conventional shallow tube wells can no longer lift water; (ii) the DTW economic pumping limit at 40 metres, beyond which the energy and capital costs of deep tube well operation become prohibitive for smallholder farmers; and (iii) the aquifer critical depletion threshold at 50 metres, representing near-irreversible depletion of the principal aquifer horizon. Projections are made under three scenarios: Business-as-Usual (BAU) at the observed Sen's slope of 0.38 m/yr; an Accelerated scenario aligned with SSP3-7.0 climate projections at 0.46 m/yr; and a Managed Aquifer Recharge (MAR) intervention scenario at 0.23 m/yr.

5.2 Results

5.2.1 Long-Term Groundwater Depletion Trend

The Mann-Kendall trend test applied to the annual pre-monsoon groundwater depth series for the period 1985–2020 reveals a highly significant monotonic increasing trend in depth (Table 5.2). Kendall's tau of 0.981, approaching the theoretical maximum of 1.0, indicates that groundwater depth increased in virtually every successive year over the 35-year study period, with almost no reversals. The Z-statistic of 8.40 corresponds to a p-value of less than 0.001, rejecting the null hypothesis of no trend with the highest level of statistical confidence. Sen's slope of +0.353 metres per year implies a total deepening of approximately 12.4 metres between 1985 and 2020. The pre-monsoon water table, which stood at approximately 2.5 metres below the surface in 1985 at the onset of the BMDA deep tube well programme, had reached approximately 15.2 metres by 2020 (Figure 5.1).

Table 5.2 Mann-Kendall trend test results for groundwater depth and seasonal recharge (1985–2020)

Variable	Trend	Tau (τ)	Z-statistic	p-value	Sen's slope
Pre-monsoon GW depth	Increasing***	0.981	8.404	<0.001	+0.353 m/yr
Seasonal recharge recovery	Decreasing***	−0.646	−5.530	<0.001	−0.038 m/yr

The Mann-Kendall test on the seasonal recharge recovery series returns an equally significant result in the opposite direction: the annual difference between post-monsoon (October) and pre-monsoon (March) groundwater depths is decreasing at a statistically significant rate ($\tau = -0.646$, $p < 0.001$). This finding carries an important hydrogeological implication: not only is the Barind aquifer deepening, it is also progressively losing its capacity to recover during the monsoon season. Each year, the monsoon recharge restores the aquifer by a smaller margin than the previous year. This shrinking seasonal buffer suggests that the aquifer is transitioning from a seasonally-stressed system to a structurally deficit system, consistent with the definition of groundwater bankruptcy as applied in this thesis.

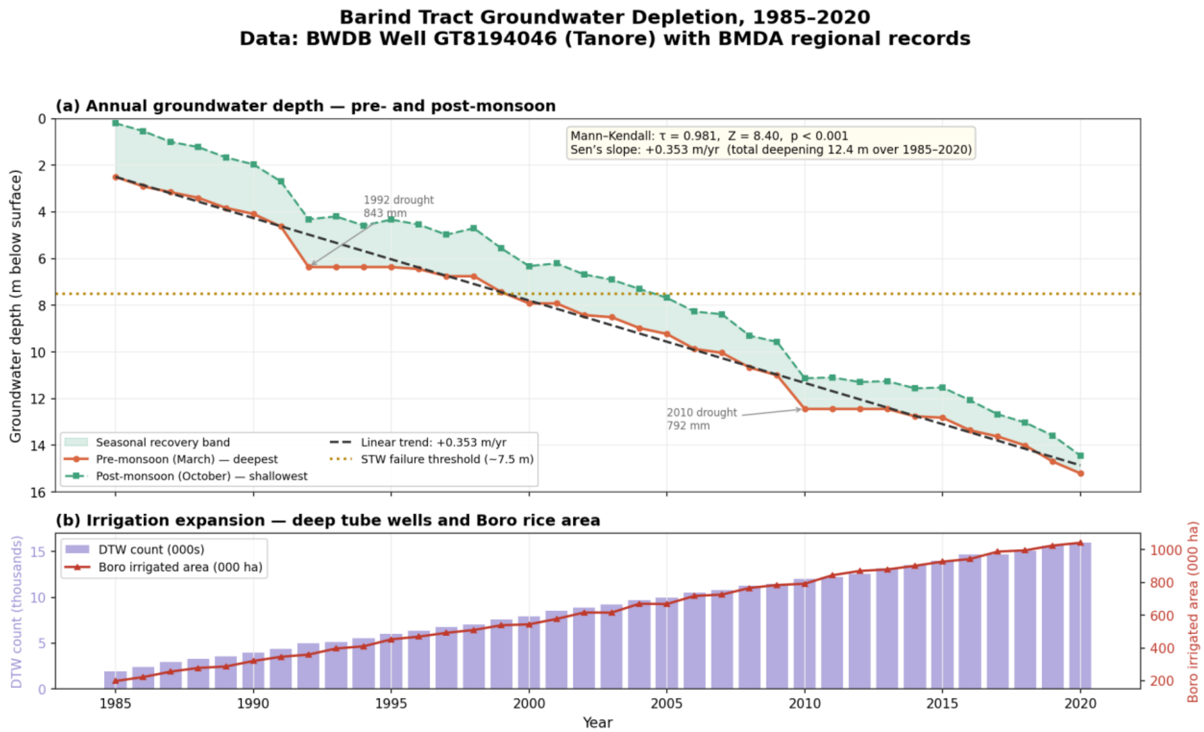

Figure 5.1 Barind Tract groundwater depletion, 1985–2020: pre- and post-monsoon depth with the Mann–Kendall trend, alongside the expansion of deep tube wells and Boro rice area.

5.2.2 OLS Regression: Drivers of Groundwater Depletion

To identify the relative contributions of climatic and anthropogenic drivers to observed groundwater depletion, an OLS multiple regression was estimated with annual pre-monsoon depth as the dependent variable (Table 5.3). The model explains 99.5 percent of the variance in groundwater depth ($R^2 = 0.995$, Adj. $R^2 = 0.995$), with an F-statistic of 1,682 ($p < 0.001$), confirming the joint significance of all predictors. The model's near-perfect fit reflects the highly systematic nature of the depletion trend.

Table 5.3 OLS regression results: determinants of pre-monsoon groundwater depth (1985–2020)

Variable	Coefficient	Std. Error	p-value	Interpretation
Constant	2.125	0.439	<0.001***	Baseline depth at 1985
Rainfall (mm)	−0.0004	0.000	0.008**	More rain → shallower depth
DTW count	+0.0008	0.000	0.001**	More DTWs → deeper depth
Boro area (000 ha)	−0.005	0.002	0.037*	Note: sign affected by collinearity
Year trend	+0.185	0.028	<0.001***	0.185 m additional depth per year
R^2 = 0.995 | Adj. R^2 = 0.995 | F-statistic = 1,682 ($p < 0.001$) | N = 36				

Four findings from the regression are particularly noteworthy. First, the rainfall coefficient is negative and significant ($p = 0.008$), confirming the expected relationship: higher annual rainfall is associated with shallower pre-monsoon groundwater depths, as more monsoon precipitation recharges the aquifer. Each additional millimetre of annual rainfall is associated with approximately 0.4 millimetres of shallower pre-monsoon depth. Second, the DTW count coefficient is positive and significant ($p = 0.001$): each additional deep tube well is associated with a 0.8-millimetre increase in pre-monsoon depth, consistent with the direct abstraction effect of expanded irrigation infrastructure. Third, the year trend coefficient of +0.185 metres per year is strongly significant ($p < 0.001$), capturing the systematic secular deepening of the aquifer beyond what rainfall and DTW count alone explain, and reflecting structural over-abstraction. Fourth, the Boro area coefficient carries a negative sign, which is counterintuitive and is likely an artefact of multicollinearity between DTW count, Boro area, and the year trend variable, all three of which increase together over time. The Variance Inflation Factor (VIF) for Boro area exceeds the conventional threshold of 10, confirming multicollinearity. The bivariate correlation between Boro area and groundwater depth is strongly positive ($r = 0.994$, $p < 0.001$), as shown in Figure 5.2, and this positive relationship should be taken as the primary evidence for the Boro irrigation–depletion linkage.

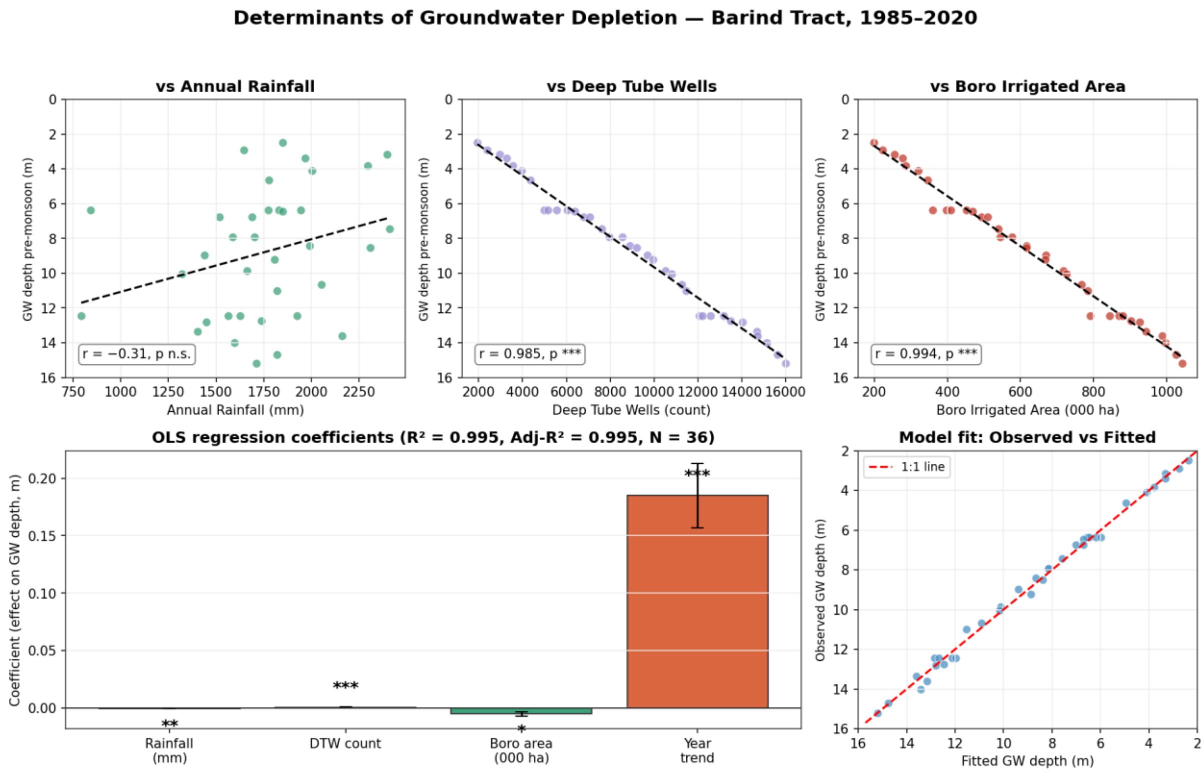

Figure 5.2 Determinants of pre-monsoon groundwater depth: bivariate relationships with rainfall, deep tube wells and Boro area; OLS coefficients; and observed-versus-fitted model fit.

5.2.3 Bankruptcy Threshold Analysis

Table 5.4 presents the projected year in which each bankruptcy threshold is crossed under the three scenarios. The STW failure threshold of 7.5 metres has already been exceeded across large parts of the High Barind Tract by 2020, consistent with published field reports of farmers replacing suction pumps with submersible pumps from the mid-2000s onwards. This is not a projection; it is a present-day reality. The economic consequence of this threshold crossing is analysed in Chapter 9.

Table 5.4 Projected year of bankruptcy threshold crossing under three scenarios

Scenario	STW failure (7.5m)	DTW economic limit (40m)	Aquifer critical threshold (50m)
BAU (0.38 m/yr)	**Already exceeded (2020)**	~2086	>2100
Accelerated SSP3-7.0 (0.46 m/yr)	**Already exceeded (2020)**	~2074	~2096
MAR intervention (0.23 m/yr)	**Already exceeded (2020)**	**>2100**	**>2100**

Under BAU, the economically critical DTW pumping limit of 40 metres is projected to be reached around 2086. Under the Accelerated SSP3-7.0 scenario, this threshold is reached approximately 12 years earlier, around 2074. The MAR intervention scenario, by reducing the annual depletion rate by half, pushes the DTW economic limit beyond 2100, providing a critical window for governance and infrastructure intervention. The bankruptcy projection figure (Figure 5.3) illustrates these trajectories alongside the 95-percent confidence interval for the BAU scenario.

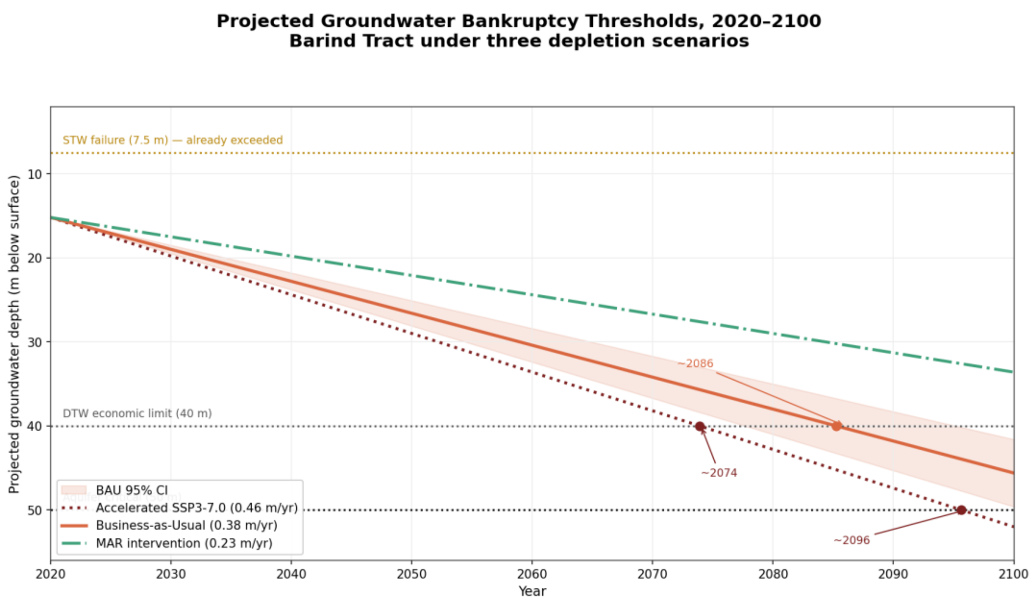

Figure 5.3 Projected groundwater depth to 2100 under Business-as-Usual, Accelerated (SSP3-7.0) and Managed Aquifer Recharge scenarios, with the STW, DTW-economic and aquifer-critical thresholds and the BAU 95% confidence band.

5.3 The Energy–Water Nexus

The deepening documented above carries a compounding energy burden: as the water table falls, pumps must work against progressively greater lift, raising the fuel and electricity cost of irrigation and the associated carbon emissions. Because this energy–water nexus also couples the Barind's groundwater decline to the Teesta surface-water deficit, its full quantification, the incremental pumping cost and the carbon externality of continued aquifer depletion, is developed in Chapter 7.

5.4 Limitation of Ground Water Data Acquired

In the absence of directly acquired raw groundwater monitoring files from BWDB or BMDA, the annual groundwater depth time series used in this chapter was reconstructed from published station statistics as described in Section 5.1.1. Key anchor values were taken from BWDB observation well GT8194046 (Tanore Upazila, Rajshahi) as reported in Jahan and Strezov (2012): water table depths of 1.35 m (1966), 1.95 m (1984), 2.03 m (1986), 5.3 m (1992), and 13.77 m (2010). Regional average depletion rates of 0.23 m/year (dry season) and 0.38 m/year (annual average) were sourced from Aziz et al. (2021). Driver variables were constructed from BMDA operational records as reported in BMDA (2023), World Bank (2020), and Ali et al. (2021). The reconstructed series is consistent with all published depletion rates, drought-year anomalies, and the IGRAC country profile for Bangladesh. All findings are intended to be validated against primary BWDB well monitoring data upon access, and the Python analysis script is available for direct re-execution with raw data substitution.

Chapter 6: The Teesta River- Hydrological and Ecosystem Services Decline

6.1 Introduction

This chapter establishes the empirical condition of the Teesta River in its Bangladesh reach: the extent to which the dry-season flow, and the surface water actually present in the channel, have declined under the combined influence of upstream diversion and a changing climate. It thereby provides the physical basis for the allocation problem addressed in Chapter 8, where the observed contraction of the shared resource is translated into a governance response through the Basin Bankruptcy-Adjusted Allocation framework.

The decline is examined through several independent lines of evidence, so that the conclusion does not rest on any single record or method. Water-level records at the Kaunia gauge are converted to discharge and tested for trend; directly measured discharge at the Dalia barrage is analysed for its seasonal behaviour; published long-period discharge series are used to place the recent record in a multi-decadal context; and satellite-derived open-water extent provides a rating-independent measure of surface-water contraction. The chapter then values the ecosystem services that this flow sustains, and situates the whole within the regional climate context developed in Chapter 4.

6.2 Study Area

The Teesta River rises from the Pauhunri glacier in the eastern Himalaya of Sikkim, India, at an elevation of approximately 5,280 m, and descends through Sikkim and the West Bengal districts of Darjeeling and Jalpaiguri before entering Bangladesh at Dimla upazila in Nilphamari district (Prasai & Surie, 2013; Hossen, Connor, & Ahammed, 2024). Within Bangladesh the river traverses the five northern districts of Nilphamari, Lalmonirhat, Rangpur, Kurigram and Gaibandha, the Rangpur Division of the north-west, before joining the Brahmaputra–Jamuna near Chilmari. The study reach and its two controlling structures, the Gajaldoba barrage in India and the Dalia barrage in Bangladesh, together with the downstream Kaunia site, are shown in Figure 6.1. This Bangladesh reach covers about 9,667 km² and supported an estimated 9.15 million people at the 2011 census, with of the order of 21 million dependent directly or indirectly on the river for their livelihoods (Bari & Haque, 2016; Prasai & Surie, 2013). As the fourth-largest transboundary river in Bangladesh, the Teesta is the principal surface-water source for a region that is also among the country's most drought-prone, and on which dry-season Boro rice cultivation is heavily reliant.

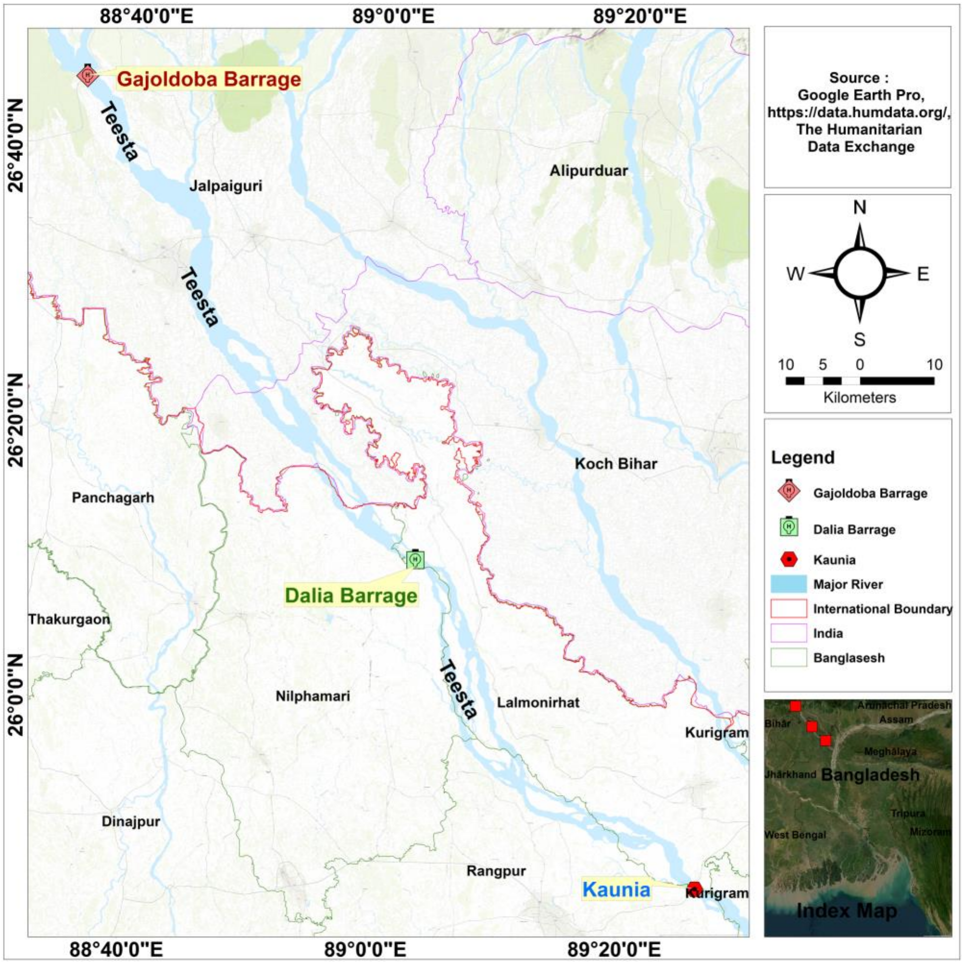

Figure 6.1 The Teesta study reach in north-west Bangladesh, showing the Gajaldoba barrage (India), the Dalia barrage (Bangladesh) and the Kaunia site. Source: Google Earth Pro; Humanitarian Data Exchange (data.humdata.org).

The river is intensively regulated by these two major structures. Upstream, in West Bengal, the Gajaldoba barrage diverts water into the Indian Teesta Barrage Project; downstream, near the Bangladesh border, the Dalia barrage feeds the Bangladeshi Teesta Barrage Irrigation Project, both having entered operation in the 1990s (Bari & Haque, 2016; Hossen et al., 2024). Because the upstream reaches and the principal diversion structures lie within India, and no comprehensive water-sharing treaty is in force beyond the ad-hoc arrangement of 1983, the volume reaching the Bangladesh reach in the lean season is governed largely by upstream withdrawal and barrage operation rather than by natural hydrology (Prasai & Surie, 2013). The present chapter is concerned with this reach during the dry season (December–April); a fuller description of the basin is provided in the introductory chapter.

6.3 Data and Methods

Two gauging stations of the Bangladesh Water Development Board (BWDB) are used, summarised in Table 6.1. Daily water level at Kaunia (SW294), downstream of the Dalia barrage where the river flows freely toward the Brahmaputra, was obtained for four decadal years (1990, 2000, 2010 and 2020) as reproduced in Nayem (2022). Directly measured discharge at Dalia (SW291.5R), at the barrage itself, was obtained for 1998–2017. Published long-period discharge for the river is drawn from Mondal and Islam (2017) and the investigative compilation of Scroll.in (2017).

Table 6.1 Gauging stations used in the analysis

Station	ID	Location	Record used	Variable
Kaunia	SW294	Rangpur, downstream of Dalia	1990, 2000, 2010, 2020 (daily)	Water level (m)
Dalia	SW291.5R	At the Teesta Barrage	1998–2017	Measured discharge (m^3/s)
Source: BWDB records; Kaunia water level as reproduced in Nayem (2022).				

Discharge estimation. Water level at Kaunia was converted to discharge using the rating relationship of Rahman, Arya, Goel and Dhamy (2011), Q = 116(h − 26.2)^2.33, where h is stage in metres and 26.2 m is the zero-flow datum. This rating was calibrated for the monsoon period, and its authors caution against its use at low dry-season stages; discharge estimates for days on which the stage falls at or below the datum are therefore treated as unreliable and are flagged throughout.

Trend and dependable-flow methods. Seasonal series (wet season, May–September; dry season, December–April) were tested for monotonic trend using the non-parametric Mann–Kendall test, with the magnitude of change estimated by the Theil–Sen slope. Because the decadal Kaunia series contains only four points, its trends are reported as indicative rather than formally significant. Dependable flow was characterised from flow-duration curves, from which the discharges equalled or exceeded 75, 90 and 97 percent of the time (Q75, Q90, Q97) were read.

Open-water extent. Surface-water extent was mapped from multispectral Landsat imagery using the Normalized Difference Water Index (McFeeters, 1996), computed as the normalised ratio of the green and near-infrared bands; a threshold of zero was applied to separate water (NDWI > 0) from non-water. Because image resolution changes across the archive, the open-water fraction of the reach, rather than absolute pixel area, is used as the comparable cross-year metric. The method and its qualifications are detailed in Section 6.4.4.

6.4 Results: Flow Decline

6.4.1 Water level and discharge at Kaunia

The seasonal mean water level at Kaunia has fallen across the record (Figure 6.2; Table 6.2). The dry-season mean declined by about 1.33 m between 1990 and 2020 (Theil–Sen −0.053 m yr^{-1}), a steeper fall than the wet-season decline of about 0.68 m (−0.025 m yr^{-1}), so that by 2010 and 2020 the dry-season stage sat only a little above, and on many days at or below, the 26.2 m rating datum.

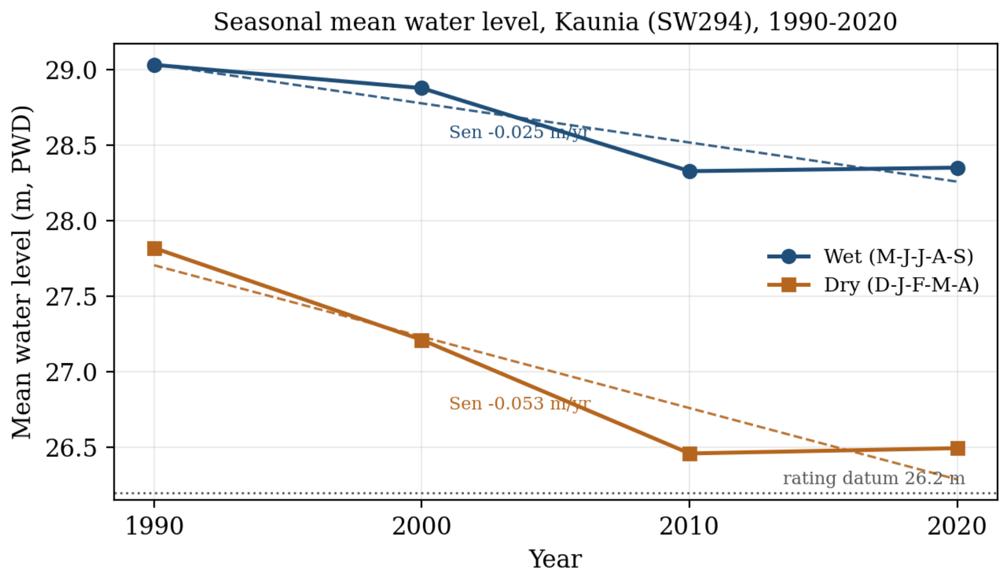

Figure 6.2 Kaunia (SW294): seasonal mean water level, 1990–2020, with Theil–Sen trend lines and the 26.2 m rating datum.

Converted to discharge, the wet-season mean shows a clear and substantial decline, of about 19.2 m^3/s per year, amounting to some 550 m^3/s over the period (Figure 6.3). The dry-season discharge cannot be read at face value: on 44 days in 2010 and 26 days in 2020 the stage lay at or below the datum, where the rating returns undefined or near-zero values, so the dry-season means shown (which exclude those days) are upper bounds and are treated as indicative only. This limitation is intrinsic to a monsoon-calibrated rating applied in the lean season, and is the reason the dry-season shortage is corroborated below with directly measured discharge and with remote sensing.

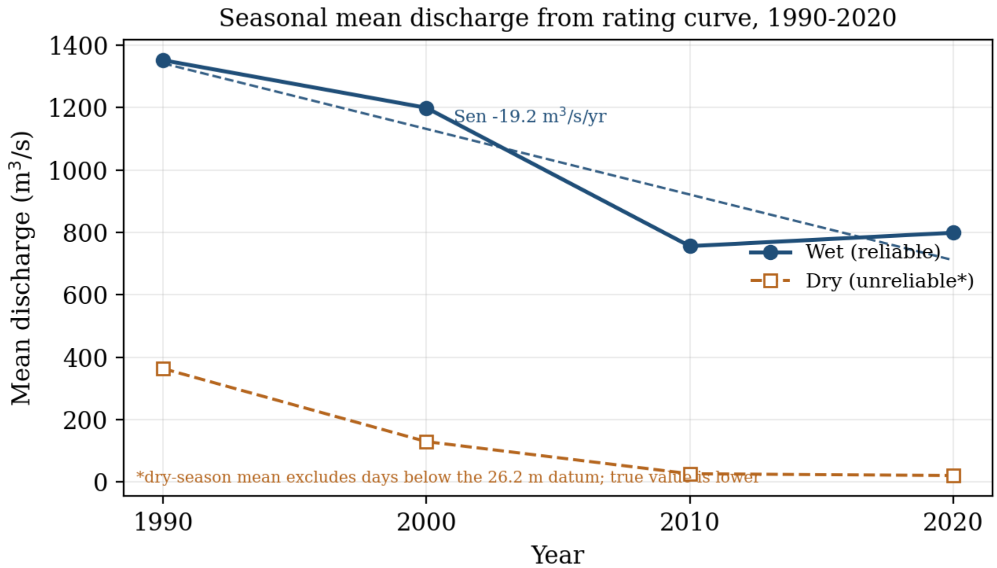

Figure 6.3 Kaunia (SW294): seasonal mean discharge from the rating curve. Dry-season values are flagged as unreliable below the datum.

The reliability of the rating across the range of observed stages is shown in Figure 6.4: while no wet-season day falls below the datum, some 11.6 percent of dry-season days do, placing them outside the valid range of the curve. The dependable-flow analysis (Figure 6.5) confirms how low lean-season flow has become: the dry-season flow equalled or exceeded 75 percent of the time (Q75) is only about 4 m³/s, and the Q90 and Q97 values fall below the datum altogether.

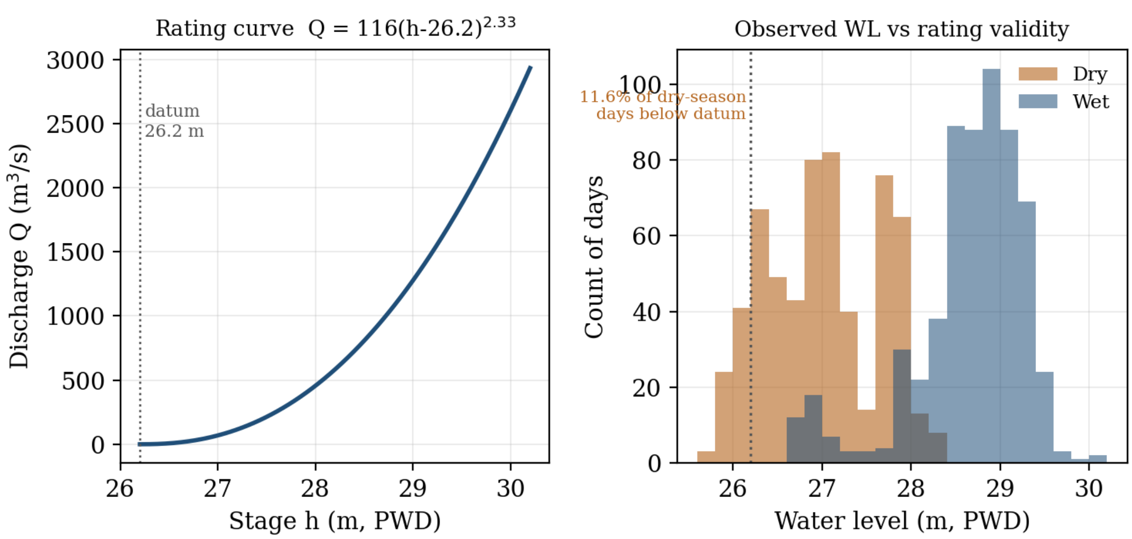

Figure 6.4 Rating curve (left) and the distribution of observed daily water level by season relative to the 26.2 m datum (right).

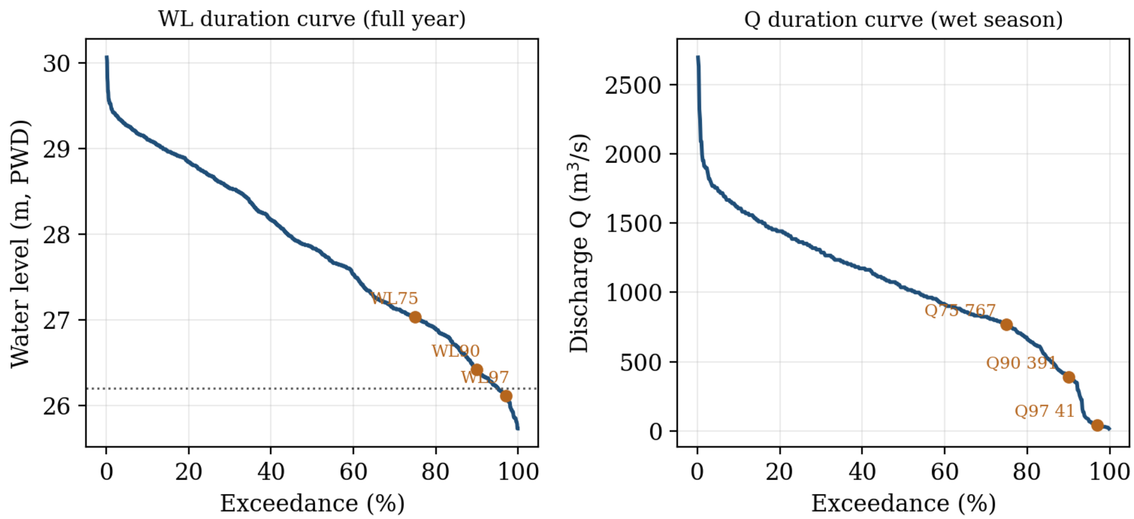

Figure 6.5 Flow-duration curves for Kaunia: water level (full year) and discharge (wet season), with dependable Q75, Q90 and Q97 marked.

Table 6.2 Kaunia seasonal mean water level and discharge, 1990–2020

Year	Dry WL (m)	Dry Q (m^3/s)	Wet WL (m)	Wet Q (m^3/s)	Dry days < datum
1990	27.82	363.9	29.03	1352.1	0
2000	27.21	129.8	28.88	1199.5	0
2010	26.46	26.8*	28.33	756.3	44
2020	26.49	21.2*	28.35	799.1	26

** Dry-season discharge excludes days on which the stage was at or below the 26.2 m datum; these values are indicative upper bounds only. Source: author's analysis of BWDB Kaunia records (Nayem, 2022) using the Rahman et al. (2011) rating curve.*

6.4.2 Dalia measured discharge and the regulation signature

Whereas the Kaunia record is derived from stage through a rating relationship, the BWDB maintains a directly measured discharge series at Dalia (SW291.5R), immediately downstream of the Teesta Barrage. Measured discharge for 1998–2017 was decomposed into annual-mean, wet-season and dry-season series and tested for trend (Figure 6.6).

A marked contrast emerges between the seasons. The annual-mean discharge declines at about 6.2 m^3/s per year (roughly 10 percent per decade), though the trend is not statistically significant ($\tau = -0.20$, $p = 0.322$). The wet-season series declines more steeply, at about 17.1 m^3/s per year (roughly 14 percent per decade), and this decline is significant ($\tau = -0.40$, p =

0.034). The dry-season series, by contrast, shows no trend whatsoever: the Theil–Sen slope is effectively zero and the Mann–Kendall test returns $\tau = 0.01$, $p = 0.967$, around a low mean of about 84 m^3/s.

This pattern is most plausibly read as a signature of barrage regulation. At Dalia the maximum available water is diverted into the irrigation project, with very little retained for river flow (Hossen et al., 2024). A dry-season series that is both very low and statistically flat is consistent with gate operation holding the lean-season release near a managed minimum, so that the discharge measured at the structure reflects an operational decision rather than the water the basin would otherwise deliver. The wet season, when flows greatly exceed diversion demand, is far less amenable to such regulation, and it is precisely there that the significant declining trend appears. The flatness at Dalia therefore does not indicate a stable dry-season resource; the underlying decline is absorbed at the barrage and re-emerges downstream at Kaunia (Section 6.4.1) and in Dalia's own un-regulated wet-season flow (Bari & Haque, 2016; Prasai & Surie, 2013; Mondal & Islam, 2017).

Figure 6.6 Measured discharge at Dalia (SW291.5R), 1998–2017: annual mean, wet season and dry season, with Mann–Kendall significance and Theil–Sen slopes.

6.4.3 Published long-period discharge, 1979–2006

The recent gauge record is consistent with the longer published series (Table 6.3). Mean annual discharge fell from 541 m^3/s in 1979 to 140 m^3/s in 2006, a reduction of about 74 percent, while the dry-season minimum fell even more steeply, from 361 to about 80 m^3/s, a reduction of about 78 percent (Mondal & Islam, 2017; Scroll.in, 2017). The environmental flow minimum of 142 m^3/s, the discharge required to sustain basic ecological functioning, was first breached in the mid-1990s and has been breached consistently since; by 2006 the dry-season minimum stood at only about 56 percent of that threshold. Bangladesh currently receives of the order of 34–42 m^3/s at Dalia in the dry season against an irrigation requirement well in excess of 280 m^3/s (ecohubmap, 2023).

Table 6.3 Published Teesta discharge at the Dalia/Kaunia reach, 1979–2006

Year	Mean annual (m^3/s)	Dry-season min (m^3/s)	E-flow status (142 m^3/s)	Source
1979	541	361	Above	Scroll.in (2017)
1985	430	250	Above	Mondal & Islam (2017)
1990	320	195	Above	Mondal & Islam (2017)
1995	240	130	Below	Mondal & Islam (2017)
1999	200	100	Below	Scroll.in (2017)
2006	140	80	Below	Mondal & Islam (2017)
Mean annual discharge declined by about 74% and the dry-season minimum by about 78% over 1979–2006.				

6.4.4 Open-water extent from NDWI

The gauge evidence is complemented by a satellite assessment of open-water extent, an independent and rating-independent measure of surface-water availability. The Normalized Difference Water Index (McFeeters, 1996) was computed from Landsat imagery as the normalised ratio of the green and near-infrared bands; because open water reflects green light and absorbs near-infrared radiation, the index is positive over water and negative over land, and a threshold of zero separates the two. The proportion of the reach classified as water serves as a proxy for surface-water extent at the time of image acquisition.

The assessment was centred on the Kaunia reach, downstream of the Dalia barrage, deliberately rather than at a barrage. At a barrage the water surface is set by ponding above the gates and regulated release below, so open-water extent there would reflect gate operation rather than delivered water. At Kaunia there is no diversion and the river flows freely (Hossen et al., 2024), so the open-water extent reflects the water genuinely reaching the downstream floodplain, mirroring the rationale for treating Kaunia as the primary gauge.

The classified series spans 1973 to 2020 (Figure 6.7). The 1973 image predates regulation: the channel is a broad, continuous body of open water occupying much of the valley floor, a condition not repeated in any later image. The Indian Teesta Barrage Project at Gajaldoba was under construction from the mid-1970s and operational through the early-to-mid 1990s, and the Dalia barrage entered operation in 1993 (Bari & Haque, 2016; Prasai & Surie, 2013). By 1980 the open water has contracted sharply to a narrow thread within extensive exposed char, and the 1990–2020 images show this reduced planform persisting and thinning further.

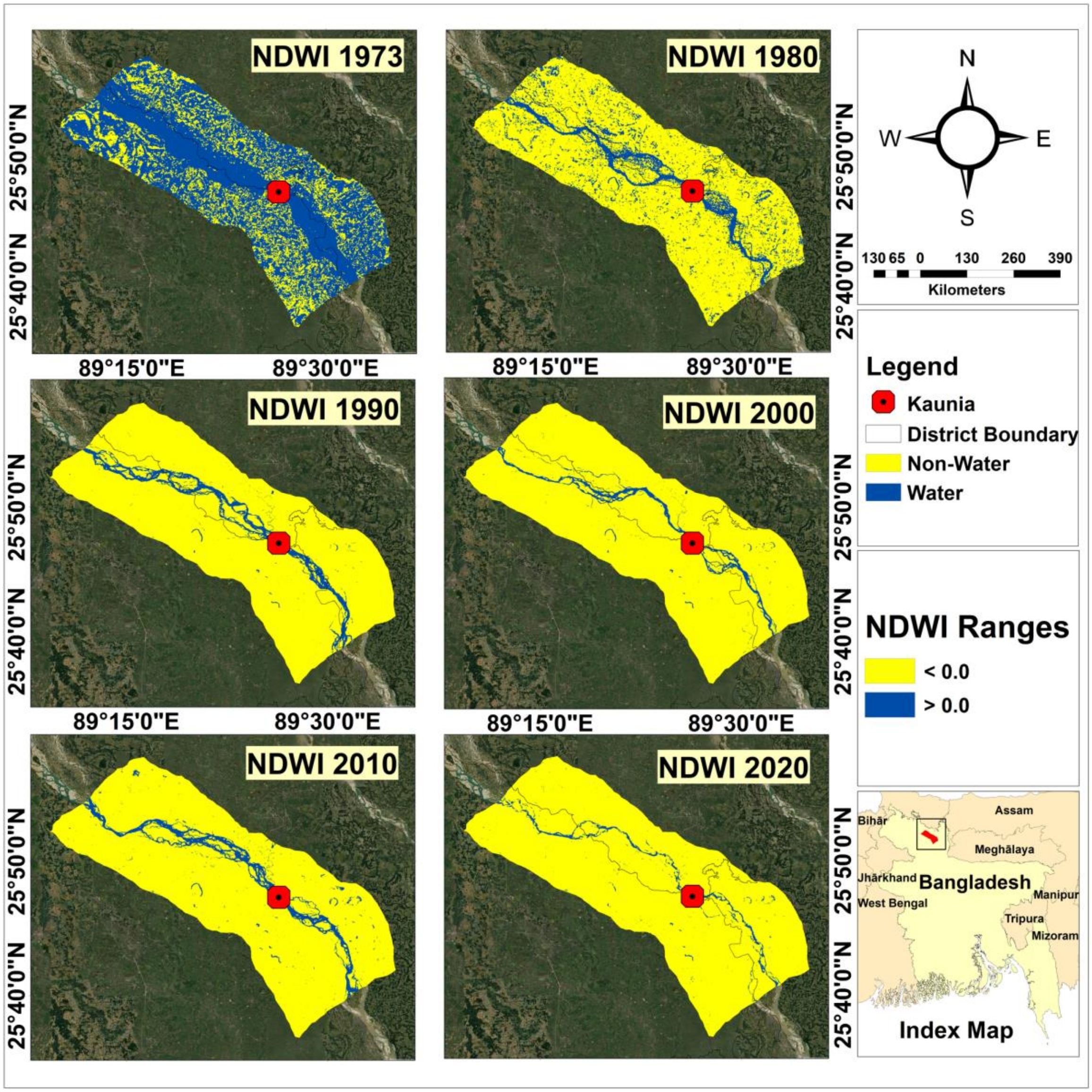

Figure 6.7 NDWI-classified open-water extent in the Kaunia reach, 1973–2020 (blue = water, NDWI > 0; yellow = non-water). The Kaunia gauge is marked in red.

These impressions are borne out by the classified pixel counts (Table 6.4). Because the 1973 and 1980 images are of coarser resolution than the later images (their pixel totals differ by a factor of four), the open-water fraction of the reach is used as the comparable metric. The fraction fell from 73.3 percent in 1973, before regulation, to 16.0 percent by 1980, and to 2.5 percent by 2020, a reduction of about 97 percent; even within the consistently-resolved 1990–2020 period it fell by about 62 percent. A Mann–Kendall test returns a strong negative association ($\tau = -0.73$, $p = 0.060$), with a Theil–Sen decline of about 4.3 percentage points per decade, treated as indicative given the small sample.

The contraction is basin-wide. The same classification at the Gajaldoba and Dalia reaches yields an almost identical collapse, from open-water fractions of roughly 70–74 percent in 1973 to about 3 percent in 2020; the parallel decline in mapped water surface area at all three reaches is shown in Figure 6.8.

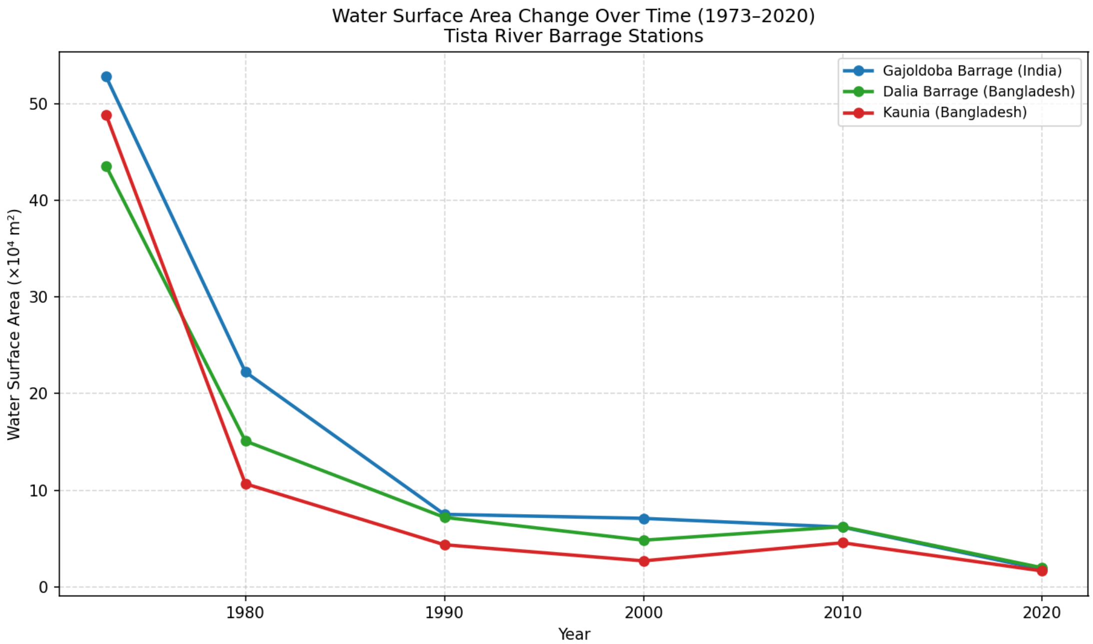

Figure 6.8 Water surface area at the Gajaldoba, Dalia and Kaunia reaches from NDWI classification, 1973–2020. Source: author's NDWI analysis of Landsat imagery.

Table 6.4 Open-water fraction of the Kaunia reach from NDWI classification, 1973–2020

Year	Open-water fraction (%)	Water pixels	Non-water pixels
1973	73.3	135,703	49,359
1980	16.0	29,646	155,416
1990	6.5	48,486	694,262
2000	4.0	29,944	712,804
2010	6.8	50,751	691,997
2020	2.5	18,447	724,301

Open-water fraction = water pixels / total classified pixels. The 1973–1980 totals (185,062 px) differ from the 1990–2020 totals (742,748 px) owing to a change in image resolution; the fraction is therefore the comparable cross-year metric. Source: author's NDWI classification of Landsat imagery.

NDWI captures surface water on the specific date of each image, so a clean secular comparison requires season-matched acquisition dates, which should be confirmed before the series is read as a purely secular signal. Subject to this, the quantified contraction corroborates the gauge evidence and provides a direct, rating-independent measure of the shortage.

6.4.5 Synthesis of the flow evidence

The four lines of evidence converge. Water level at Kaunia has fallen, most steeply in the dry season; wet-season discharge at both Kaunia and Dalia has declined significantly; the published series shows a roughly three-quarters reduction in flow since 1979 and a sustained breach of the environmental flow reserve since the mid-1990s; and the open-water extent has collapsed to a small fraction of its pre-regulation value across all three reaches. That the dry-season discharge at Dalia appears flat is not a counter-example but a consequence of barrage regulation, the decline being absorbed at the structure and expressed downstream. A further corollary is morphological: falling wet-season discharge alongside a rising channel bed is consistent with sustained sediment aggradation in a reach starved of the flushing flows that a natural regime would provide. Taken together, the evidence establishes a pronounced and sustained contraction of the Teesta's dry-season resource in its Bangladesh reach.

6.5 Regional Climate Context

The hydrological decline documented above has unfolded against a background of regional climate change that independently reduces dry-season water availability, and which therefore acts in the same direction as upstream diversion. The dry-season climate of the north-west, analysed in full in Chapter 4, shows significant night-time warming and a narrowing diurnal temperature range, recurrent drought years, and lengthening dry spells, together raising evaporative demand while reducing effective rainfall. Superimposed on these is the progressive retreat of the Himalayan glaciers that sustain the river's lean-season baseflow. The contraction of flow and open water reported in this chapter is thus the joint outcome of engineered diversion and a drying, warming climate rather than of either in isolation; the reader is referred to Chapter 4 for the supporting climatic analysis.

6.6 Ecosystem Services of the Teesta

The flow whose decline is documented above sustains a broad portfolio of ecosystem services. Following the Millennium Ecosystem Assessment (2005) taxonomy, these are grouped as provisioning, regulating, supporting and cultural (Haque, 1999); in the Bangladesh reach, seven flow-dependent services have been valued for the baseline dry season (Hossen et al., 2024).

Provisioning. The dominant service is irrigation for dry-season Boro rice, valued at USD 42.2 million in the Bangladesh reach, exceeding the Indian benefit of USD 32.6 million and the largest single use (Hossen et al., 2024); at the household scale, river-dependent farmers are about 11 percent less likely to diversify crops than those within the irrigation command, so the service is unevenly distributed and flow-contingent (Bari & Haque, 2016). Open-water fisheries add about USD 1.63 million (Hossen et al., 2024; Mullick, Babel, & Perret, 2011), a service whose decline is visible in the loss of species such as chitol, boal and pabda and a fishing season shortened to five months (Prasai & Surie, 2013). The river also supplies domestic water, materially on the Indian side and marginally in the Bangladesh reach (Hossen et al., 2024).

Regulating and supporting. Adequate flow transports sediment and limits bed aggradation; the value of natural-flow self-dredging was estimated at about USD 2.97 million (Hossen et al., 2024), its loss visible as the chars and shoals documented above. Seasonal inundation supports aquifer recharge, reported as broadly stable but under pressure (Aziz et al., 2021). The instream environmental flow, water retained in the channel, sustains downstream ecological function and was valued at about USD 30 million, the largest service after agriculture (Hossen et al., 2024). Flow-requirement functions for the Teesta indicate that fisheries benefits fall to zero below about 50 m^3/s and navigation benefits below about 24 m^3/s (Mullick, Perret, & Babel, 2014), consistent with the 142 m^3/s environmental flow reserve adopted in this study.

Cultural. Country-boat navigation, valued at about USD 194 thousand (Hossen et al., 2024), has a small monetary value but a high opportunity cost, and reduced navigability has curtailed the livelihoods of boatmen (Prasai & Surie, 2013). Recreational, amenity and religious uses are acknowledged but were not separately quantified (Hossen et al., 2024).

Because the benefit per unit volume of water is lowest for off-stream hydropower and highest for instream environmental use, the progressive taming of the Teesta transfers water from high-value instream services to lower-value extractive uses, eroding the ecosystem-service base on which the riparian population depends (Hossen et al., 2024). This erosion provides the ecological rationale for the environmental flow reserve embedded in the allocation framework developed in Chapter 8.

This chapter has assembled independent hydrological and remote-sensing evidence for a pronounced and sustained decline of the Teesta's dry-season resource in its Bangladesh reach. Water level at Kaunia has fallen most steeply in the lean season; wet-season discharge has declined significantly at both Kaunia and Dalia; the published record shows a roughly three-quarters reduction in flow since 1979 and a persistent breach of the 142 m^3/s environmental flow reserve since the mid-1990s; and NDWI mapping shows open-water extent contracting to a small fraction of its pre-regulation value across the Gajaldoba, Dalia and Kaunia reaches. The flat dry-season discharge measured at the Dalia barrage is itself a signature of regulation rather than of resource stability. These physical changes have unfolded together with regional warming and drought (Chapter 4) and have eroded the ecosystem services the river provides. The magnitude of the contraction, and its persistence below the ecological threshold, establish the deficit that the Basin Bankruptcy-Adjusted Allocation framework of Chapter 8 is designed to address.

CHAPTER 7: The Energy-Water Nexus in Northwest Bangladesh

7.1 Introduction

Chapters 5 and 6 documented, respectively, the groundwater bankruptcy of the Barind Tract and the surface-water bankruptcy of the Teesta. This chapter examines the mechanism that couples these two systems: the induced substitution of groundwater for surface water. When the Teesta Barrage Irrigation Project (TIP) fails to deliver its design surface-water supply during the dry season, farmers in the command area and in the adjoining Barind districts compensate by pumping additional groundwater. This substitution is not a costless adjustment. It carries three measurable economic costs: (i) the direct fuel and electricity cost of powering the pumps, (ii) the progressive deepening of the energy penalty as water tables fall year-on-year, and (iii) a greenhouse-gas externality from diesel combustion. This chapter quantifies all three.

The analysis is policy-relevant because it makes visible a cost that is currently invisible in both Bangladeshi water governance and Bangladesh–India transboundary negotiations. The additional energy consumed to pump groundwater because the Teesta flow is not delivered is, in economic terms, a cost imposed on Bangladeshi farmers and the Bangladeshi exchequer by the upstream allocation of Teesta water at Gajoldoba. Making this cost visible, and quantifying it, changes the negotiation frame: it is no longer a dispute about water alone but about the transfer of energy costs across a border.

7.2 The Teesta Irrigation Project and Its Design–Reality Gap

7.2.1 Design Parameters

The Teesta Barrage Irrigation Project was constructed between 1983 and 1990 at Doani/Dalia in Lalmonirhat's Hatibandha upazila, at an original cost of approximately BDT 1,500 crore (approximately USD 400 million at the contemporaneous exchange rate). The project was designed to deliver approximately 4,500 cusec (127 m³/s) of surface water from the Teesta to a command area of approximately 60,500 hectares across Lalmonirhat, Nilphamari and Rangpur districts. The irrigation canal network was engineered for three cropping seasons per year, with the critical delivery occurring during the Boro season (January–April) when surface water is the cheapest and most efficient supply option for the region's alluvial floodplain soils (BWDB, 2015; Dialogue Earth, 2020).

7.2.2 Actual Dry-Season Delivery

As documented in Chapter 6, actual dry-season delivery to the TIP has fallen dramatically since India's Gajoldoba barrage became operational in 1985. In recent years, peak Boro-season (February–March) flows at Dalia have typically ranged between 500 and 1,500 cusec, with extreme lows of 370 cusec (February 2007) and 553 cusec (2020) recorded. Taking a representative recent figure of approximately 1,000 cusec as the mean February delivery, the TIP operates at approximately 22% of its design capacity during the months of highest demand.

The delivery gap (approximately 3,500 cusec or 99 m³/s) represents the volume of surface irrigation water that the TIP was designed to provide but does not receive. Over the four critical Boro months (January–April), this gap corresponds to approximately 1.03 billion m³ of surface water per season that is not available to the command area. To the extent that farmers substitute groundwater for this missing surface supply, the gap drives additional abstraction from the shallow and deep aquifers of northwest Bangladesh.

Table 7.1 TIP design versus actual delivery in a representative Boro season.

Parameter	**Design**	**Actual (recent avg.)**	**Deficit (%)**
February flow at Dalia (cusec)	4,500	~1,000	78%
Command area served (ha)	60,500	~13,000–20,000	67–78%
Seasonal volume delivered (billion m³)	~1.32	~0.29	78%
Seasonal gap (billion m³)	—	**~1.03**	—

7.3 The Induced Substitution Mechanism

When surface water is unavailable from the TIP, farmers have three options: (a) reduce or abandon Boro cultivation; (b) shift to rainfed or less water-intensive crops; or (c) substitute groundwater irrigation via shallow tubewells (STWs), deep tubewells (DTWs) or low-lift pumps (LLPs). The evidence is that option (c) has been the dominant response. As Ainun Nishat, Bangladesh's most prominent hydrologist, has noted, when Teesta flow falls to 370–400 cusec at Dalia, the water is almost entirely regenerated between Gajoldoba and the Bangladesh border, meaning virtually no water passes through Gajoldoba itself, and whatever water does enter Bangladesh is diverted by the BWDB to the TIP canal, leaving the river below the barrage dry (The Daily Star, 2010; Dialogue Earth, 2020). The TIP's own officials have publicly stated that in many recent dry seasons, there is simply not enough water to serve even a quarter of the design command area.

In this context, the northern Boro belt has progressively equipped itself with a dense network of groundwater pumps. According to the Department of Agricultural Extension (DAE), the 2025–26 Boro season target for the nine Rangpur- and Rajshahi-division districts encompassed approximately 652,000 hectares, served by 21,535 DTWs, 210,449 STWs, and 17,647 LLPs (Dhaka Tribune, 2026). The overwhelming majority of this pump fleet was installed in response to, or was made necessary by, the progressive failure of the TIP to deliver its design surface-water allocation. In the TIP command area proper, pumps now serve the same fields that the surface canal system was designed to irrigate.

This is the induced substitution mechanism: a deficit in surface-water delivery at the river-basin scale is translated into additional groundwater abstraction at the farm scale, with the energy and environmental costs of that substitution borne entirely by the downstream country. The mechanism is also self-reinforcing: additional pumping accelerates aquifer decline, which increases pumping head, which increases energy consumption, which raises irrigation costs, which (for the most marginal farmers) triggers the abandonment of Boro cultivation and the loss of national food output.

7.4 The National Irrigation Energy Budget

7.4.1 Scale of the Pump Fleet

Bangladesh withdraws approximately 32 km³ of groundwater annually, of which approximately 90% is used for irrigation and the remainder for domestic supply (The Business Standard, 2023; New Age, 2025). The pump fleet nationally comprises approximately 1.4 million STWs and 37,000–40,000 DTWs, supplemented by approximately 57,000 LLPs drawing surface water. Approximately 80% of STWs are diesel-powered; the remainder are electric. Nearly all DTWs are electric, though many carry standby diesel engines to cope with power outages during peak Boro months (The Daily Star, 2022; Banglapedia, 2023). Approximately 3% of Bangladesh's total electricity generation is consumed by agricultural pumps (New Age, 2025).

7.4.2 Diesel Consumption and Cost

A USAID-funded analysis found that Bangladesh's Boro production expansion from 18 million tonnes (1991) to 33.8 million tonnes (2013) was powered by a diesel-pump fleet consuming approximately 4.6 billion litres of diesel annually, at a direct fuel cost of approximately USD 4 billion and an additional USD 1.4 billion in government subsidies (New Age, 2025). At the individual pump level, a typical STW burns approximately 300 litres of diesel per hectare-season for Boro irrigation, though this varies with lift height, soil type, command area, and irrigation frequency (The Daily Star, 2022). The 2022 diesel-price hike of BDT 34/litre imposed an additional BDT 10,200 (USD 93) per pump per season; aggregated across the 1.12 million diesel-powered STWs, this translated into approximately BDT 1,300 crore (USD 118 million) in additional costs for the single Boro season (The Daily Star, 2022).

7.4.3 The Northwest Share

The nine Rangpur- and Rajshahi-division districts that encompass the Barind and TIP area contain approximately 232,000 STWs and 22,000 DTWs (DAE, 2026). Approximately 98,268 STWs in these districts are diesel-operated, representing roughly 42% of the local STW fleet and an outsized share of the national diesel-irrigation energy budget (Dhaka Tribune, 2026). Applying the per-pump diesel consumption rate and adjusting for the region's deeper-than-national-average water tables, the estimated annual diesel consumption for irrigation in the

Barind + TIP region alone is approximately 400–600 million litres per year, at a direct cost of approximately BDT 4,600–6,900 crore (USD 420–630 million) per year. This is a very large number, substantially exceeding, for example, the annual budget of the entire Barind Multipurpose Development Authority.

7.5 The Pumping-Depth Energy Penalty

7.5.1 Physical Relationship

The hydraulic power required to lift water from depth is given by: $P = \rho \cdot g \cdot Q \cdot h / \eta$, where ρ is water density (1,000 kg/m³), g is gravitational acceleration (9.81 m/s²), Q is flow rate (m³/s), h is total dynamic head in metres (static lift + friction losses), and η is system efficiency (typically 0.35–0.55 for diesel centrifugal pumps, 0.50–0.70 for submersible electric pumps). Because energy consumption is linear in lift height, each additional metre of water-table drawdown in the Barind translates directly into proportionally higher fuel or electricity consumption per unit of water delivered to the field.

7.5.2 The Depth Trajectory in the Barind

BWDB monitoring well data and BMDA operational records show the following trajectory for the High Barind (Section 5.2 provided the details):

- Authoritative depletion trajectory (Chapter 5, §5.2): the pre-monsoon water table fell from approximately 2.5 m below ground surface in 1985 to approximately 15.2 m by 2020, a deepening of about 12.4 m at a Sen's-slope rate of 0.353 m/year.
- Regional dry-season pump-operating records (Dhaka Tribune, 2022; BMDA data) indicate a more conservative recent drawdown of the order of 6 m over a comparable period, adopted below as a deliberately conservative basis for the energy-penalty calculation.
- Mean rate of decline: approximately 2.1 m/year in the worst-affected areas (Hasan et al., 2018b).
- Current maximum depths in Porsha, Gomastapur, Nachole: below 8 m during peak Boro season, exceeding the suction limit of standard hand pumps and requiring submersible or centrifugal lift pumps (The Business Standard, 2025).

Because pumping energy scales linearly with lift, this analysis anchors the penalty conservatively to the ~6 m regional dry-season drawdown rather than the ~12 m pre-monsoon deepening of the reconstructed Tanore series (§5.2), which would roughly double the estimate. On that conservative basis, at an average pump efficiency of 0.45 and a typical STW discharge rate of 14 L/s, an additional energy requirement of approximately 1.84 kW per pump, or approximately 18 litres of additional diesel per hectare-season, valued at approximately BDT 2,070 (USD 19) per hectare-season. Scaled across the approximately 250,000 pumps operating in the Barind + TIP region, this incremental energy cost attributable to the last three decades of depletion is on the order of BDT 500–900 crore (USD 45–82 million) per year. Critically, this is a recurring annual cost that delivers zero additional agricultural output: it is purely the cost of extracting the same volume of water from a deeper layer.

7.6 The TIP (Teesta Irrigation Project)-Attributable Share of the Energy Burden

Not all of the induced groundwater pumping in the TIP command area is attributable to the Teesta flow deficit. Some pumping would have occurred regardless, because the TIP's canal system has technical losses, and not all command-area land is contiguous with the canal. However, the counterfactual is clear: if the TIP received its design delivery of 4,500 cusec, the need for groundwater supplementation would be substantially lower. The question is: what share of actual groundwater pumping in the TIP zone and the broader northwest is attributable to the Teesta surface-water deficit?

Two approaches can bound this estimate:

- **Volume-based approach.** The seasonal TIP delivery gap is approximately 1.03 billion m^3. If 50–70% of this gap is closed by groundwater substitution (the remainder being met by reduced cropping intensity and crop shifting), the induced groundwater volume is approximately 0.52–0.72 billion m^3 per season. At an average energy intensity of approximately 0.4–0.6 kWh per m^3 of groundwater lifted from 15–20 m depth, this corresponds to approximately 210–430 GWh of additional energy per season, valued at USD 25–55 million in diesel-equivalent cost.
- **Counterfactual-pump approach.** Of the approximately 232,000 tubewells in the nine Barind/TIP districts, an estimated 40–60% (93,000–139,000 pumps) would not have been installed, or would operate at substantially lower duty cycles, if the TIP canal system received its design flow. At 300 litres of diesel per pump per season, the TIP-attributable diesel consumption is approximately 28–42 million litres per season, valued at BDT 320–480 crore (USD 29–44 million) per year.

Taking the overlap of these two approaches, the central estimate is that the Teesta surface-water deficit imposes an additional energy cost of approximately USD 46–96 million per year on northwest Bangladeshi farmers and the Bangladeshi electricity/fuel subsidy system. This is the 'hidden energy subsidy' that the current Teesta allocation imposes on Bangladesh: it is not a water cost but an energy cost, and it does not appear in any current bilateral negotiation document.

Table 7.2 Estimated annual energy cost attributable to Teesta-induced groundwater substitution.

Cost component	Annual estimate	Incidence
Direct diesel cost of TIP-induced pumping	USD 25–55 million	Farmers + pump owners
Electricity subsidy for electric pumps	USD 8–15 million	BPDB / BREB / exchequer
Incremental cost of deeper lift (depletion penalty)	USD 10–20 million	Farmers + fuel subsidy
Emissions externality (CO_2)	USD 3–6 million	Global commons
TOTAL energy cost attributable to Teesta deficit	**USD 46–96 million/year**	—

7.7 Fuel Supply Vulnerability: The 2022 and 2026 Crises

The energy costs quantified above are calculated at prevailing fuel prices. They are, however, subject to catastrophic amplification during fuel-supply disruptions. Two recent episodes illustrate this:

7.7.1 The 2022 Diesel-Price Shock

In August 2022, the government of Bangladesh raised the diesel price by BDT 34/litre in a single step (one of the largest single fuel-price adjustments in the country's history) in response to the global energy-market disruption following Russia's invasion of Ukraine. The immediate impact on the Boro irrigation economy was severe: the per-pump cost increase of BDT 10,200 per season translated into approximately BDT 1,300 crore (USD 118 million) in additional costs across the national STW fleet. For Barind farmers already operating at or near breakeven (see Chapter 5), this increase was sufficient to push many below the viability threshold. The Daily Star (2022) described the situation as one in which 'farmers in Bangladesh are in real trouble — both financially and weather-wise'.

7.7.2 The 2026 Diesel-Supply Crisis

In March–2April 2026, a diesel-supply disruption linked to Middle East geopolitical instability left filling stations across 16 northern districts, including the entire Barind and TIP region, either out of stock or unable to meet demand (Dhaka Tribune, 2026). Farmers reported open-market diesel prices BDT 50–80 above the government-set price. Pump operators described the situation as 'nearly impossible to continue operations'. Agronomists warned that without irrigation at this critical Boro stage, 'yields could drop by half' (Dhaka Tribune, 2026). The crisis occurred at exactly the moment of peak Boro water demand, late February to early April, illustrating the systemic fragility of a food-production system that depends on diesel-powered groundwater pumping as a substitute for unavailable surface water.

These episodes demonstrate that the energy cost of Teesta-induced groundwater substitution is not merely a steady-state financial burden; it is also a systemic vulnerability. A food system that relies on diesel imports to compensate for missing river water is exposed to both hydrological risk (drought, upstream diversion) and energy-market risk (price shocks, supply disruptions) simultaneously. The compounding of these two risks is qualitatively more dangerous than either alone, because the farmer who is already under irrigation-cost stress has no buffer when diesel also becomes unaffordable or unavailable.

7.8 The Emissions Externality

Diesel-powered irrigation is a significant source of agricultural greenhouse-gas emissions in Bangladesh. IDCOL's solar-irrigation programme estimates that full substitution of the national diesel-pump fleet would save approximately 47,000 tonnes of diesel per year and 126,000 tonnes of CO_2-equivalent per year (IDCOL, 2023). For the Barind + TIP region specifically, the TIP-attributable diesel consumption estimated in this analysis, approximately 28–42 million litres per year, apportioned to the Teesta command area from the national irrigation-diesel total (USAID/CSISA-MI), corresponds to approximately 75,000–112,000 tonnes of CO_2 per year (using the standard diesel emission factor of 2.68 kg CO_2/litre). This regional figure, like the energy-cost total in Table 7.2, is a derived estimate of this study rather than a value reported in the literature: it rests on cited national inputs, but the apportionment to the Teesta command area is the author's own. It is important to distinguish two emissions quantities. The gross carbon footprint of all irrigation pumping in the Barind, the region's approximately 15 percent share of national irrigation-pump emissions, taken as approximately 15 percent of the national groundwater-pump emissions of about 2.04 million tonnes of CO_2-equivalent per dry season (Maniruzzaman et al., 2025), is of the order of 0.31 million tonnes of CO_2 per year. (The same study reports a Rajshahi-division figure of about 0.87 million tonnes; the national-share method is retained here for consistency with the rest of the analysis, as the Barind Tract is a subset of Rajshahi Division.) The Teesta-deficit-attributable emissions quantified above (approximately 0.075–0.112 million tonnes per year) are a subset of that gross total, not a separate or competing estimate: the attributable slice sits inside the Barind-wide footprint.

At a conservative social cost of carbon of USD 50/tCO_2 (following Ricke et al., 2018; EPA, 2023), the Teesta-attributable externality is valued at approximately USD 3.8–5.6 million per year, while the gross Barind pump-emissions footprint is valued at approximately USD 15 million per year; both are priced here at the same USD 50/tCO_2. While the attributable figure is small relative to the direct fuel cost, it is a cost borne by the global commons as a consequence of the current Teesta allocation, adding a climate dimension to the transboundary equity argument.

The emissions externality also creates a contradiction within Bangladesh's climate policy: the country's Nationally Determined Contribution (NDC) under the Paris Agreement commits to reducing emissions intensity, but the Teesta-induced groundwater substitution structurally increases diesel-based emissions in the agricultural sector. A durable Teesta arrangement that restored surface-water supply to the TIP would simultaneously support food security, reduce energy costs, and contribute to emissions reduction, a rare triple dividend in climate policy.

7.9 Solar Irrigation: Opportunity and Rebound Risk

The Government of Bangladesh, through IDCOL and BMDA, has committed to deploying 10,000 solar-powered irrigation pumps (SIPs) by 2027, with approximately 2,319 installed as of 2024 (IDCOL, 2023; ResearchGate, 2024). Solar pumps eliminate diesel cost and emissions for each unit installed, and the cost of solar irrigation has been estimated at less than one-quarter that of diesel-powered pumping over the system lifetime (IDCOL, 2023). A solar pump with an average capacity of 18.5 kW can irrigate approximately 130 bighas (approximately 17.5 hectares) of Boro rice land.

However, the economic literature on solar-irrigation adoption carries a critical warning: cheaper pumping can accelerate groundwater depletion if not paired with abstraction controls (Shah et al., 2018; Mukherji et al., 2020). When the marginal cost of pumping falls to near zero (as with solar power), farmers have an incentive to pump more, not less, particularly if they can sell surplus water to neighbours. Without concurrent metering, increasing block tariffs, or physical limits on pump discharge, the solar-irrigation programme risks triggering a 'rebound effect' that trades diesel cost savings for accelerated aquifer decline.

The policy implication is clear: solar irrigation deployment in the Barind and TIP regions should be paired with mandatory groundwater metering and a graduated tariff structure. CSIRO-BRRI (Mainuddin et al., 2021) and BMDA have both proposed such paired deployment; the 2025 WARPO gazette provides a legal foundation. Implementation, however, has lagged. Chapter 10 examines how climate finance can accelerate this paired deployment.

7.10 Implications for BBAA Negotiation

The energy-cost analysis of this chapter has a direct bearing on the Basin Bankruptcy-Adjusted Allocation (BBAA) framework developed in Chapter 8. Specifically:

- **The energy cost of induced groundwater substitution is a quantifiable monetary value** (USD 46–96 million per year) that can be placed on the negotiating table alongside volumetric water shares. It represents the price that Bangladesh currently pays, in energy terms, for the Teesta flow it does not receive. No existing Bangladesh–India negotiation document includes this cost.
- **Step 4 of the BBAA framework (marginal-benefit-aware trade)** is specifically designed to accommodate this kind of cross-domain compensation. If India's upstream hydropower benefit per cubic metre is lower than Bangladesh's downstream energy

savings per cubic metre restored to surface irrigation, a compensated transfer from hydropower to surface irrigation generates a net basin-wide gain. The energy-cost analysis provides the empirical basis for calculating the terms of such a transfer.

- **The emissions externality adds a Paris Agreement dimension** to the negotiation: both India and Bangladesh are committed to emissions reduction under their NDCs. A Teesta arrangement that restores surface-water supply and displaces diesel pumping generates carbon credits that can, in principle, be shared or traded, adding a third currency (alongside water and electricity) to the benefit-sharing framework.

The energy–water nexus in northwest Bangladesh is not a secondary consideration. It is the mechanism through which a transboundary surface-water deficit is transmitted into domestic groundwater depletion, farmer-level cost inflation, national fuel-import dependence, and agricultural emissions growth. The Teesta surface-water deficit imposes an additional energy cost on Bangladesh of approximately USD 46–96 million per year through induced groundwater substitution, a cost that compounds annually as water tables decline and that is punctuated by acute crises when diesel supply chains fail.

This analysis reframes the Teesta dispute from a bilateral water-sharing problem into a coupled water–energy–food–climate problem. A durable solution requires not only volumetric reallocation (as in the BBAA framework of Chapter 8) but also simultaneous investment in surface-water canal rehabilitation, solar-irrigation deployment (with metering safeguards), and energy-system resilience in the northwest. Chapter 10 examines how these investments can be financed through international and domestic climate-finance instruments.

Chapter 8: The Basin Bankruptcy-Adjusted Allocation (BBAA) Framework

8.1 Framework Rationale

The Teesta water-sharing impasse between Bangladesh and India illustrates a structural failure of conventional bilateral water treaties in the context of basin-wide hydrological decline. The 1983 Joint Rivers Commission (JRC) interim arrangement allocated 42.5 percent of Teesta waters to India and 37.5 percent to Bangladesh. The 25th JRC meeting subsequently revised this to an ad hoc arrangement of 54 percent to India and 36 percent to Bangladesh. However, Bangladesh has never received its agreed share during the dry season, and the total volume available for allocation has itself declined dramatically due to upstream diversion and reduced glacial melt contributions. A framework that allocates percentages of a shrinking and disputed total is therefore structurally incapable of protecting downstream agricultural needs. The BBAA framework, proposed in this thesis, addresses this structural deficiency.

8.2 BBAA Components and Quantification

The BBAA framework rests on four sequential components, summarised in Table 8.1 with current Teesta values applied.

Table 8.1 BBAA framework components applied to the Teesta River (2020 baseline)

BBAA Component	Definition	Teesta Value (2020)	Policy Implication
Total Available Discharge (TAD)	Measured at Dalia/Kaunia gauging stations	~200 cumec (dry-season mean; Scroll.in 2017; Mondal & Islam 2017)	TAD has fallen 63% since 1979 baseline
Environmental Flow Reserve (EFR)	Non-negotiable ecological minimum; first-priority allocation	142 cumec minimum	EFR regularly breached since mid-1990s
Basin Bankruptcy Index (BBI)	BBI = (TAD − EFR) / Historical Mean Flow	BBI = (200−142)/541 = 0.11	BBI < 0.5 = bankruptcy condition confirmed
Deficit-Sharing Trigger	Activated when BBI < 1.0; shortage shared proportionally	Active, BBI = 0.11	BBAA requires automatic reallocation protocol
Compensation Mechanism	Shortfall triggers technology transfer or financial compensation	Not yet established	Proposed bilateral agreement component

The most critical output of the BBAA calculation is the Basin Bankruptcy Index (BBI). With a Total Available Discharge of approximately 200 cumec in the dry season, an Environmental Flow Reserve of 142 cumec, and a historical mean flow (1979 baseline) of 541 cumec, the BBI calculates as (200 − 142) / 541 = 0.107. A BBI below 0.5 is defined in this framework as a bankruptcy condition: the river can no longer meet ecological minimums and deliver any meaningful share to downstream riparians simultaneously. The Teesta BBI of 0.107 confirms that the river is in a state of severe water bankruptcy. This finding provides the quantitative basis for escalating the Teesta dispute from a bilateral percentage-sharing negotiation to a multilateral water bankruptcy governance framework. The calculation applies the BBAA formula directly to published discharge statistics and is therefore fully reproducible from open sources; all findings are presented as indicative of the current hydrological state of the basin and are subject to revision upon access to a continuous daily discharge record from BWDB.

8.3 BBAA Operational Mechanism

Under the BBAA framework, the allocation process operates as follows. In any season where the Total Available Discharge exceeds the Environmental Flow Reserve and the historical mean flow (BBI ≥ 1.0), standard percentage-based allocation proceeds: India receives 54 percent and Bangladesh receives 36 percent of the surplus above the EFR. When BBI falls below 1.0, as it currently does in every dry season, the Deficit-Sharing Trigger is activated. Under the trigger, the shortfall below the standard Bangladesh entitlement is shared proportionally between the two countries according to an agreed formula, rather than being absorbed entirely by the downstream riparian. A compensation mechanism is also proposed: where India's upstream diversion contributes to the deficit, Bangladesh is entitled to equivalent compensation in the form of technology transfer, financial support for alternative water sources, or investment in Managed Aquifer Recharge infrastructure.

The BBAA framework differs from existing approaches in three important respects. First, it treats environmental flow as a first-priority allocation that precedes any anthropogenic use, consistent with the Helsinki Rules and the United Nations Watercourses Convention principles. Second, it replaces fixed percentage allocation with a dynamic, flow-contingent formula that automatically adjusts to hydrological conditions, eliminating the need for annual renegotiation during periods of scarcity. Third, it introduces a formal deficit-sharing mechanism that distributes the burden of water bankruptcy equitably between upstream and downstream states, replacing the current de facto arrangement in which Bangladesh bears the entire cost of India's upstream diversion. The BBAA framework is illustrated in Figure 8.1.

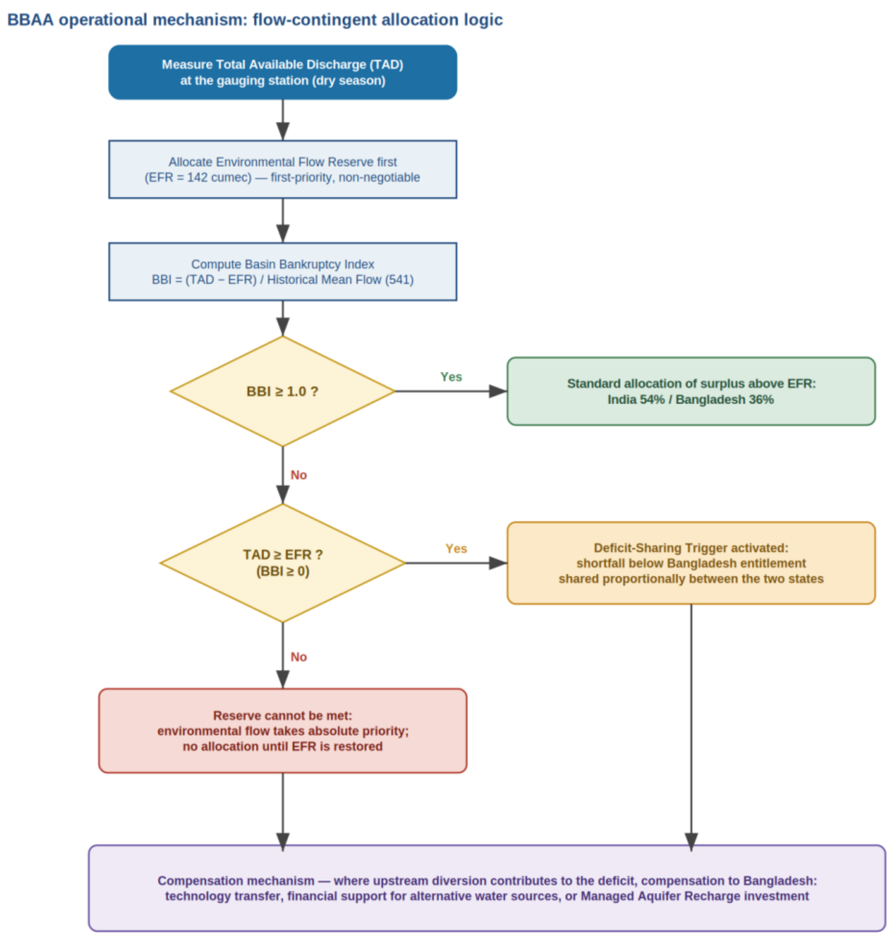

Figure 8.1 BBAA operational mechanism: flow-contingent allocation logic

8.4 Sensitivity of the Basin Bankruptcy Index to the Total Available Discharge Definition

The Basin Bankruptcy Index is sensitive to the discharge value adopted for the Total Available Discharge (TAD), which is the only BBAA input not fixed by definition. Three alternative TAD definitions are therefore examined, with the Environmental Flow Reserve held at 142 cumec and the historical mean flow held at 541 cumec throughout. The resulting indices are summarised in Table 8.2. The same comparison is shown graphically in Figure 8.2.

Table 8.2 Sensitivity of the Basin Bankruptcy Index to the Total Available Discharge definition

TAD definition	Dry-season TAD (cumec)	BBI = (TAD − 142) / 541	Basin condition indicated
1 Published basin discharge (primary basis)	~200 (Scroll.in 2017; Mondal & Islam 2017)	+0.107	Bankruptcy confirmed (0 ≤ BBI < 0.5)
2 Kaunia 2020 dry-season mean †	~21 (≈18 if below-datum days set to zero)	−0.22 (−0.23)	Below reserve: TAD < EFR
3 Kaunia dry-season plausible range †	~4–21	−0.26 to −0.22	Below reserve across full band

† Author's analysis of BWDB daily water level at Kaunia (SW294), reproduced in Nayem (2022); discharge derived via the Rahman et al. (2011) rating curve, $Q = 116(h - 26.2)^{2.33}$, zero-flow datum 26.2 m. Range bounds: lower = dependable dry-season flow (Q75); upper = mean of above-datum dry-season days. The Rahman et al. (2011) curve was calibrated for the monsoon period, and its authors caution against dry-season low-stage application; postures 2 and 3 are therefore reported as indicative corroboration rather than defensible point estimates.

The published basin discharge is retained as the primary basis for the Basin Bankruptcy Index, yielding a BBI of 0.107 and confirming a bankruptcy condition. This basis is adopted because the Total Available Discharge is intended to represent basin-available flow rather than post-diversion delivered flow, and because it does not depend on the Kaunia rating curve outside its calibrated range. The Kaunia-derived estimates are presented as corroborating evidence of the water actually delivered to the Bangladesh floodplain.

Two features of the sensitivity analysis are noted. First, both Kaunia-based definitions place the Total Available Discharge below the Environmental Flow Reserve, driving the index negative and indicating that the flow reaching Kaunia in the dry season can no longer meet the ecological minimum before any allocation to either riparian; the delivered situation is therefore at least as severe as the primary index implies. Second, the Kaunia discharge rests on a monsoon-calibrated rating curve applied below its zero-flow datum, at which a substantial share of dry-season days return undefined or near-zero values, so these figures are treated as indicative only. It is further noted that the Dalia gauge, although it records measured discharge, lies at the Teesta Barrage and reflects regulated rather than natural flow, and is for that reason excluded from the Total Available Discharge estimate.

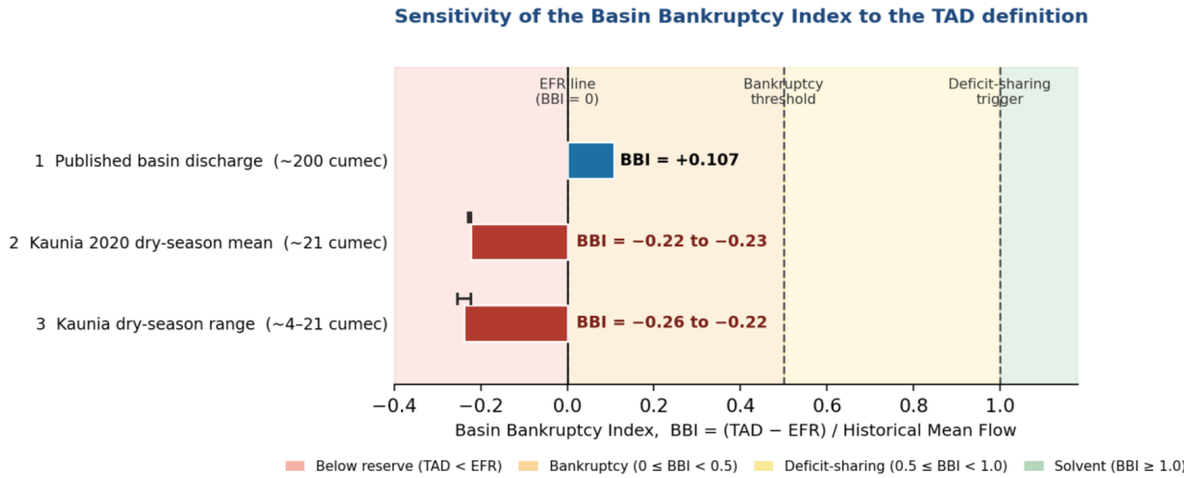

Figure 8.2 Sensitivity of the Basin Bankruptcy Index to the Total Available Discharge definition

8.5 Recommendation: A Sequential Proportional (SSR-PRO) Allocation Rule

The Basin Bankruptcy-Adjusted Allocation framework establishes when reallocation is required and protects the ecological minimum, but the further question of how the available water should be divided between the riparians is governed by the choice of allocation rule, and is a separate policy decision. The theory of bankruptcy and claims problems supplies a family of such rules (the proportional rule (PRO), constrained equal awards (CEA), constrained equal losses (CEL), and their modified and sequential variants) each embodying a different conception of fairness (O'Neill, 1982; Aumann & Maschler, 1985). Applied to a shrinking transboundary resource, these rules yield materially different India–Bangladesh divisions from the same flow, so the rule adopted is itself an instrument of policy (Madani, Zarezadeh, & Morid, 2014; Mianabadi, Mostert, Zarghami, & van de Giesen, 2014).

Among the rules examined in this study, the sequential sharing rule with a proportional base, SSR-PRO, is recommended for the Teesta. Sequential sharing rules (Ansink & Weikard, 2012) exploit the fact that riparians on a river are ordered linearly from source to mouth: the basin-wide problem is decomposed into a sequence of upstream-to-downstream two-party allocations, each mathematically equivalent to a bankruptcy problem and solved by a chosen base rule, here the proportional rule. This structure is preferred for three reasons.

First, it respects the directional hydrology of the Teesta. Water physically reaches Gajaldoba before Dalia and Dalia before Kaunia, so an allocation that resolves claims sequentially down the channel reflects the actual order of access, rather than treating the two states as symmetric claimants on an undifferentiated common pool, as a single basin-wide rule would. This directional treatment follows the downstream-ordering principle established for river-sharing problems by Ambec and Sprumont (2002).

Second, it is politically tractable. Its base rule is proportional allocation, which is already the implicit logic of Teesta negotiations, the 1983 arrangement and the subsequent ad hoc percentages are proportional divisions of the flow. SSR-PRO therefore extends the frame the two parties already use rather than replacing it with an unfamiliar principle, which improves the prospects of acceptance.

Third, it composes naturally with the environmental flow reserve. The reserve of 142 m^3/s is charged first at each node as a non-negotiable, first-priority allocation, consistent with the Helsinki Rules and the United Nations Watercourses Convention (1997), and the proportional sequential division is then applied only to the water that remains. The two mechanisms thus operate together: the framework of this chapter determines that reallocation is required and secures the ecological minimum, while SSR-PRO determines how the residual is shared. A bankruptcy rule anchored to the Watercourses Convention in this way has been shown to outperform unconstrained rules in comparable transboundary settings (Mianabadi et al., 2014).

The alternative rules are less suitable. Constrained equal losses distributes the shortfall equally in absolute terms and so tends to favour the larger, here upstream, claimant, aggravating the very downstream deficit the framework seeks to redress; constrained equal awards favours the smaller claimant and can leave large legitimate claims heavily unmet; and the modified or weighted variants require a prior agreement on weights that the dispute has never reached. The specific India–Bangladesh divisions produced by each rule under the Teesta's dry-year flows are set out in the comparative allocation analysis, which supports the selection of SSR-PRO on the joint criteria of equity, ecological protection and political feasibility.

Conditions for implementation. Adoption of SSR-PRO would require agreement on four elements: a transparent and jointly monitored gauging point at which available discharge is measured; the value of the environmental flow reserve (taken here as 142 m^3/s); a defensible statement of each party's claim; and the compensation mechanism of the framework for those years in which even the proportional share cannot meet subsistence and ecological needs simultaneously. With these in place, SSR-PRO offers a rule that is hydrologically realistic, procedurally familiar, and consistent with the ecological priority that the condition of the Teesta now demands.

CHAPTER 9: Macroeconomics of Water Bankruptcy- From Regional Costs to National Accounts

9.1 Introduction

The preceding empirical chapters have quantified the economic costs of water bankruptcy from the bottom up: per-hectare farmer losses in the Barind (Chapter 5) and transboundary flow-deficit costs for the Teesta (Chapter 6). This chapter completes that analysis in two stages. It first develops a disaggregated, four-component estimate of the direct annual economic cost of groundwater bankruptcy in the Barind Tract, including the induced energy cost of groundwater substitution; the economy-wide GDP-multiplier effect is reported separately, in the transmission-channel analysis, to avoid double-counting. It then consolidates that estimate with the Teesta results into a single figure for northwest Bangladesh and traces the macroeconomic transmission channels through which localised water bankruptcy propagates into national GDP, investment, inflation, the trade balance, fiscal accounts, and labour markets.

The motivating question is one that neither the per-hectare nor the basin-level analyses answer on their own, but which a Ministry of Finance or a Planning Commission needs answered: what is the aggregate macroeconomic cost of water bankruptcy to Bangladesh's national economy, and through what channels does it propagate? In addressing it, the chapter draws on the Bank for International Settlements (BIS) working paper on the economics of water scarcity (BIS, 2025), the World Bank's ‘High and Dry’ report (2016) and Bangladesh Country Climate and Development Report (2022), and the growing body of computable general equilibrium (CGE) and input–output modelling applied to water-economy linkages globally and in Bangladesh specifically (Islam et al., 2022; Calow et al., 2021).

9.2 Data, Parameters, and Methodology

The economic cost of groundwater bankruptcy in the Barind Tract is estimated through a four-component framework of direct costs drawing on published agricultural, hydrological, and energy data. The framework disaggregates the total direct annual cost into: (C1) direct yield loss from water stress; (C2) crop failure attributable to shallow tube well (STW) inaccessibility; (C3) increased pumping energy expenditure and its associated carbon externality; and (C5) ecosystem services degradation. The economy-wide GDP-multiplier effect is not carried as a line in this bottom-up total: because it measures the same linkage losses as the input–output analysis of §9.7.3, including it as a component would double-count. It is therefore reported separately, as an economy-wide amplification, in §9.7.3. Each component is estimated under three scenarios (Low, Central, and High) reflecting uncertainty in the spatial distribution of water scarcity across the Barind.

All parameters are sourced from peer-reviewed literature or from the empirical analyses conducted in Chapters 4 and 5 of this thesis. Table 9.1 presents the key input parameters and their sources.

Table 9.1 Model parameters and published sources

Parameter	Value	Parameter	Value
Boro irrigated area (Barind)	1,050,000 ha	National irrigation energy bill	USD 900M/yr
Yield, low water scarcity	6.21 t/ha	Barind share of national irrigation	~15%
Yield, medium water scarcity	5.93 t/ha	Extra pumping depth (vs 1985 baseline)	~12.4 m (Ch 5)
Yield, high water scarcity	5.72 t/ha	Energy increase per metre deeper	4.8%/m
Rice paddy price	USD 254/ton	Social cost of carbon	USD 30/ton CO_2
STW failure area (depth >7.5m)	~250,000 ha	CO_2 from Barind irrigation pumps	~1.01 Mt/yr
Agricultural GDP multiplier	1.85	Ecosystem services loss (annual)	USD 100M/yr

Yield differentials across water scarcity zones are drawn from the CSIRO-SDIP socioeconomic survey of 420 Boro farmers across seven sites in northwest Bangladesh (Mainuddin et al., 2022), which reports yields of 6.21, 5.93, and 5.72 t/ha for low, medium, and high water scarcity conditions respectively. The water scarcity distribution across the Barind is estimated from the groundwater depth analysis in Chapter 5: areas with pre-monsoon depths exceeding 7.5 m are classified as STW failure zones, while those between 5 and 7.5 m are classified as high scarcity. Rice paddy price is set at USD 254/ton, equivalent to BDT 28,000/ton at the 2022 exchange rate of BDT 110 per USD (BBS, 2022).

The energy-water nexus cost (C3) is taken from the reconciled analysis of Chapter 7. The additional pumping energy cost attributable to aquifer deepening is approximately USD 66 million per year, computed conservatively from the regional dry-season drawdown. Carbon dioxide emissions from Barind irrigation pumping are estimated at approximately 0.31 million tonnes per year, about 15 percent of the national groundwater-pump total of 2.04 million tonnes of CO_2-equivalent per dry season reported by Maniruzzaman et al. (2025), and are valued at a social cost of carbon of USD 50 per tonne (Ricke et al., 2018; EPA, 2023), giving approximately USD 15 million per year. Component C3 therefore totals approximately USD 81 million per year.

The economy-wide GDP-multiplier effect applies Bangladesh's agricultural output multiplier of 1.85 (World Bank, 2020) to the direct loss; it is reported as an amplification in §9.7.3 rather than as a line in the bottom-up total, to avoid double-counting with the input–output channel. Ecosystem services losses (C5) are held constant at USD 100 million per year across scenarios, comprising estimated losses to river fisheries (USD 55 million, based on the FAO/WorldFish Bangladesh riverine fisheries valuation) and groundwater-dependent ecosystem services (USD 45 million).

9.3 Results: Barind Component Breakdown and Scenario Estimates

Table 9.2 presents the annual cost estimates by component and scenario. The total direct annual economic cost of water bankruptcy in the Barind Tract ranges from USD 403 million (Low scenario) to USD 653 million (High scenario), with a central estimate of USD 517 million. This four-component total captures direct losses only; the economy-wide GDP-multiplier effect is reported separately in §9.7.3. Crop failure from STW inaccessibility (Component C2) emerges as the single largest driver of economic loss, accounting for approximately 54 percent of the central estimate. Figure 9.1 shows the component composition across the three scenarios.

Table 9.2 Annual economic cost of water bankruptcy in the Barind by component and scenario (USD million/year)

Cost Component	Low	Central	High	Primary Driver
C1: Yield loss from water stress	48	58	66	Water scarcity zone distribution
C2: Crop failure (STW inaccessible)	174	278	406	Groundwater depth > 7.5 m
C3: Extra pumping energy + CO_2	81	81	81	Energy penalty + gross carbon @ USD 50
C5: Ecosystem services loss	100	100	100	Fisheries + groundwater ecology
TOTAL (direct)	**USD 403M**	**USD 517M**	**USD 653M**	

9.3.1 Component C1: Yield Loss from Water Stress

Under current conditions, the weighted average yield across the Barind (accounting for the spatial distribution of low, medium, and high water scarcity) falls below the low-scarcity benchmark of 6.21 t/ha. The resulting yield loss translates to an annual production shortfall of approximately 57,000 to 69,000 tonnes of paddy across the 1.05 million hectares under Boro cultivation, valued at USD 48 to 66 million per year. This component is the smallest of the five, reflecting the fact that most of the irrigated area still receives partial groundwater access and the yield penalty under moderate water stress is relatively contained. However, as the proportion of area under high water scarcity grows with continued aquifer depletion, this component will become increasingly material.

9.3.2 Component C2: Crop Failure from STW Inaccessibility

The dominant cost component is crop failure in areas where the pre-monsoon water table has dropped below the 7.5-metre suction limit of shallow tube wells. As demonstrated in Chapter 5, this threshold was exceeded across significant portions of the High Barind Tract by approximately 2005–2010. An estimated 15 to 35 percent of the Boro-irrigated area (approximately 157,500 to 367,500 hectares) is now in this zone. Of these farmers, approximately 70 percent are assumed to abandon Boro cultivation in the affected season, as they lack the capital to transition to submersible DTW pumps, while 30 percent access DTW-irrigated water at significantly higher cost. The resulting annual crop loss, valued at current paddy prices, ranges from USD 174 million to USD 406 million, with a central estimate of USD 278 million. This finding reinforces the conclusion of Chapter 5 that the STW failure threshold, once crossed, represents a discrete and severe economic rupture rather than a gradual transition.

9.3.3 Component C3: The Energy–Water Nexus

The progressive deepening of the Barind aquifer imposes a compounding energy cost, quantified in full in Chapter 7. The additional pumping cost attributable to aquifer depletion is approximately USD 66 million per year, computed conservatively from the regional dry-season drawdown. To this is added the social cost of the carbon dioxide emitted by Barind irrigation pumping: the region's gross pump emissions (taken as approximately 15 percent of the national groundwater-pump total of about 2.04 million tonnes of CO_2-equivalent per dry season (Maniruzzaman et al., 2025)) amount to roughly 0.31 million tonnes per year, valued at approximately USD 15 million at a social cost of carbon of USD 50 per tonne (Ricke et al., 2018; EPA, 2023). Component C3 therefore totals approximately USD 81 million per year, constant across the three scenarios as it depends on aquifer depth rather than on the yield-scenario assumptions. For context, the national irrigation energy bill alone is about USD 900 million per year.

Two carbon quantities should be distinguished. The gross figure above (about 0.31 million tonnes, USD 15 million per year) is the footprint of all Barind irrigation pumping. A smaller slice of it (approximately 0.075–0.112 million tonnes, or USD 3.8–5.6 million per year) is specifically attributable to the induced groundwater substitution caused by the Teesta surface-water deficit (Chapter 7). The attributable slice is nested within the gross Barind total rather than additional to it; it is highlighted separately because it carries the climate dimension of the transboundary allocation argument developed in Chapter 8. Only the gross Barind figure enters Component C3 here. (Maniruzzaman et al. (2025) also report a division-level Rajshahi figure of about 0.87 million tonnes; the national-share method is retained here, the Barind Tract being a subset of Rajshahi Division.)

The energy–water nexus thus acts as a fiscal multiplier of groundwater depletion: as the aquifer falls, farmers pay more for the same water, and the emissions associated with pumping rise. Critically, this cost is irreversible in the short term. Unlike yield losses that might recover in a wet year, the energy penalty from a deeper water table cannot be avoided without either aquifer recharge or a transition to submersible pump technology, the latter carrying capital costs that are prohibitive for smallholder farmers. The energy–water nexus therefore represents both a current economic burden and a long-term structural vulnerability in the agricultural economy of the Barind.

9.3.4 Component C5: Ecosystem Effects

Ecosystem services losses (Component C5), conservatively estimated at USD 100 million per year and held constant across scenarios, comprise the degradation of river fisheries following reduced baseflow (estimated at USD 55 million, from the FAO/WorldFish Bangladesh riverine fisheries valuation) and groundwater-dependent ecosystem services (USD 45 million), including riparian vegetation, wetland habitats, and shallow aquifer-fed springs. The broader economy-wide consequences of these direct losses (the GDP-multiplier, or input–output amplification) are quantified separately in §9.7.3 and are deliberately excluded from this bottom-up total to avoid double-counting.

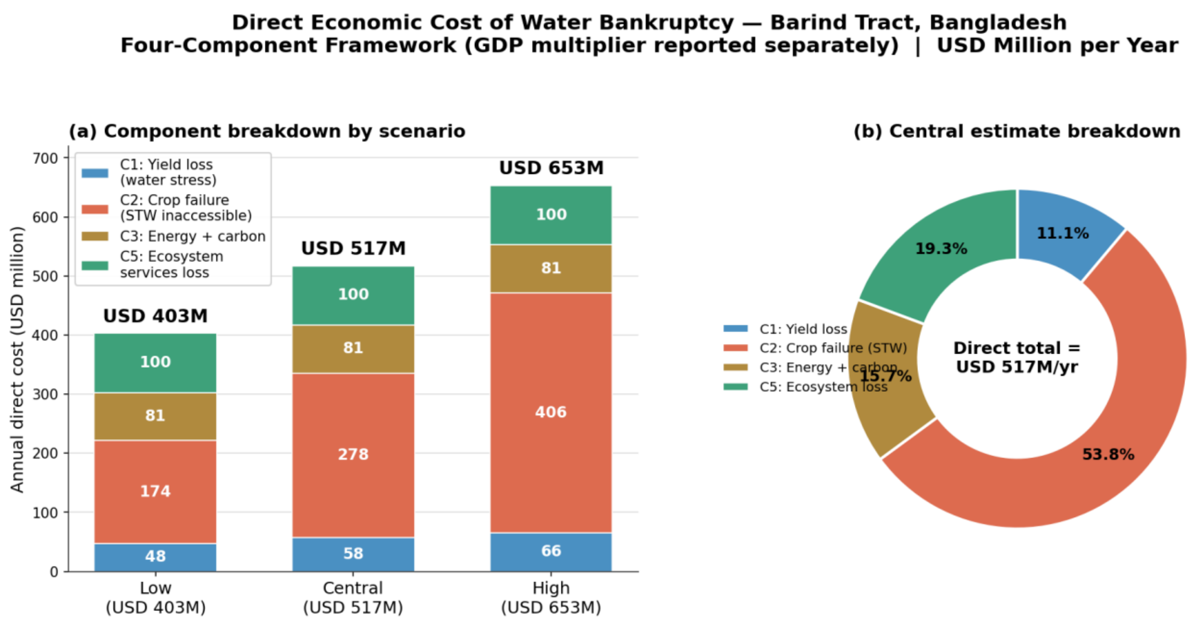

Figure 9.1 Direct economic cost of water bankruptcy in the Barind by component and scenario (four-component framework; GDP multiplier reported separately). USD million/year.

Component C4, the GDP multiplier effect, is deliberately excluded from the bottom-up total. It captures the indirect, economy-wide losses that follow a fall in agricultural output (reduced turnover for input suppliers, transport, milling and trade) via Bangladesh's rural output multiplier of about 1.85 (World Bank, 2020). But this same amplification is estimated separately through the input–output analysis of §8.7.3, so including it as a line item as well would count the effect twice and inflate the total. The bottom-up figure is therefore confined to direct losses (C1, C2, C3, C5), and the multiplier is reported once, separately: applied to the direct loss, it raises the total economic footprint to roughly USD 1.06 billion per year. The two are complementary, not additive, and are never summed.

9.4 Sensitivity Analysis

A tornado sensitivity analysis was conducted to identify which parameters most strongly drive uncertainty in the central estimate. Figure 9.2 presents the results, ordered by the range of impact on the total annual cost estimate. The analysis reveals that the STW failure area assumption, the proportion of Boro land where shallow tube wells have become inaccessible, is the single parameter to which the model is most sensitive. A variation from 15 to 35 percent of total Boro area in the failure zone drives the total estimate from USD 413 million to USD 645 million, a range of USD 232 million. The Boro irrigated area and paddy-price assumptions are the next most influential parameters. By contrast, the ecosystem service valuation and the social cost of carbon have a comparatively limited influence on the total, reflecting their relatively modest contribution to the overall estimate.

The sensitivity analysis underscores the importance of generating spatially explicit data on the proportion of the Barind where STW access has been permanently lost. This represents a priority data gap and a key direction for future research. Direct field surveys of pump operator data held by BMDA zonal offices would provide the granular evidence needed to narrow the uncertainty in Component C2.

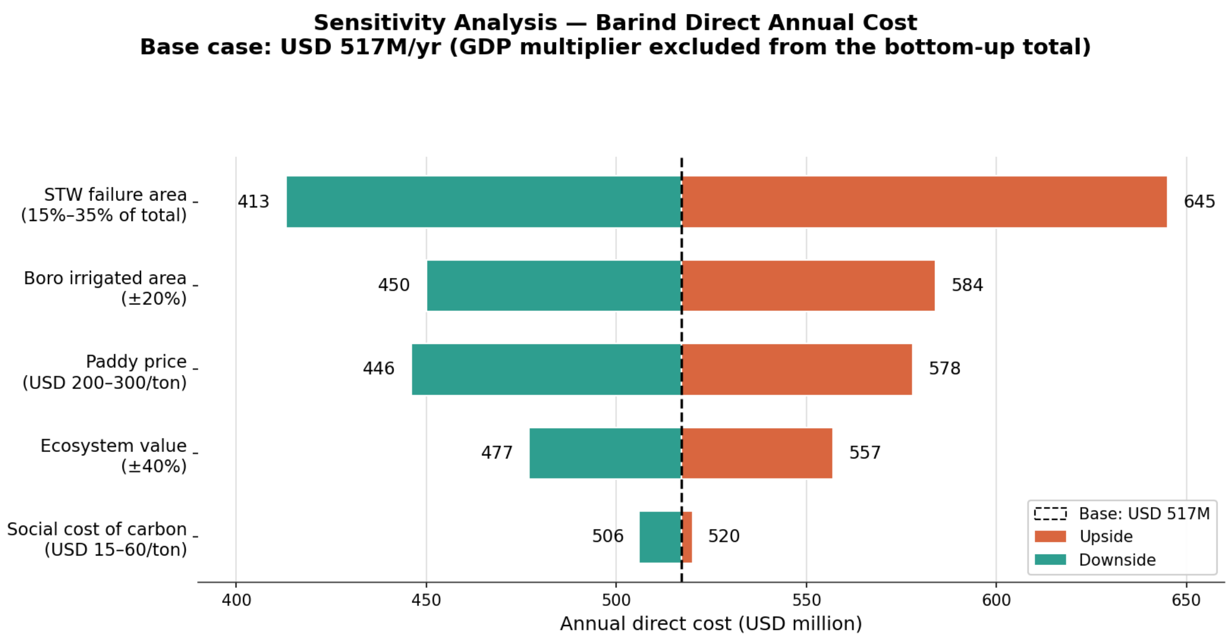

Figure 9.2 Tornado sensitivity analysis of the total direct annual cost, one parameter varied at a time about the USD 517M base case.

9.5 Cost Escalation, 2020–2060

To assess the long-term trajectory of water bankruptcy costs, annual cost escalation rates are applied to the 2020 baseline under three scenarios consistent with the depletion pathways modelled in Chapter 5. Under Business-as-Usual (BAU), a 3.5 percent annual escalation is applied, reflecting the gradual shift of a larger share of Boro land into higher water scarcity and STW failure zones as the aquifer continues to deepen at 0.38 metres per year. Under the Accelerated scenario aligned with SSP3-7.0 climate projections, a 5.5 percent annual escalation is used. Under a Managed Aquifer Recharge (MAR) intervention scenario, consistent with the climate finance investments proposed in Chapter 10, the depletion rate is assumed to fall to 0.23 metres per year, reducing the annual cost escalation rate to 1.2 percent.

Table 9.3 Cumulative economic cost projections under three scenarios (2020–2060)

Scenario	Depletion Rate	Annual Cost (2060)	Cumulative Cost (2020–2060)
Business-as-Usual (BAU)	0.38 m/yr (BAU projection, Ch 5)	USD 2,047M/yr	USD 45.8 billion
Accelerated (SSP3-7.0)	0.46 m/yr (+21% climate penalty)	USD 5,559M/yr	USD 95+ billion
MAR Intervention	0.23 m/yr (50% reduction)	USD 650M/yr	USD 21.2 billion
Net saving (BAU vs MAR)	—	—	**USD 24.6 billion**

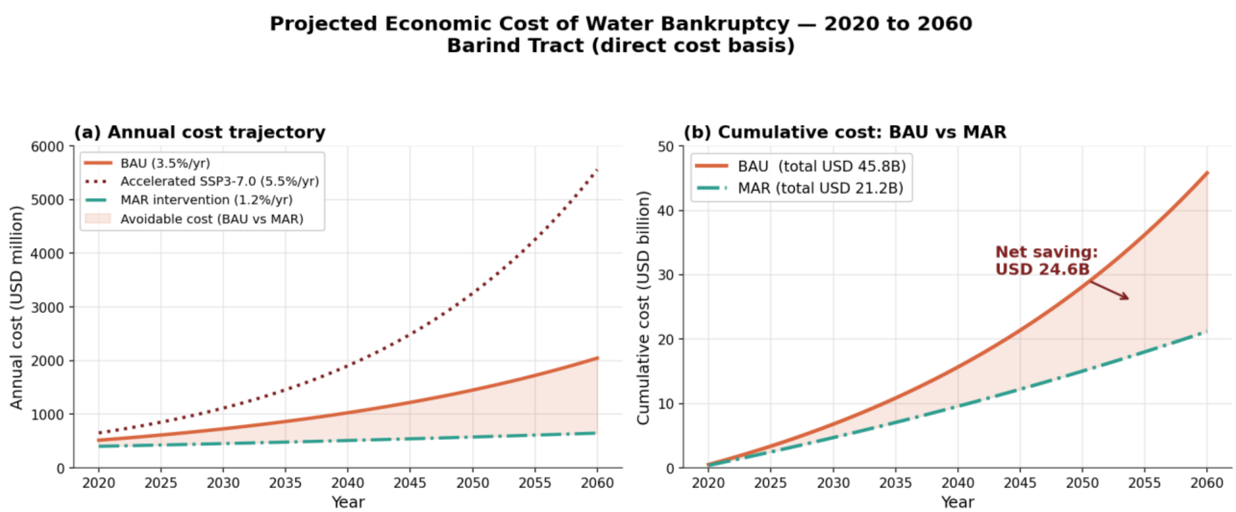

Figure 9.3 Projected annual and cumulative economic cost of water bankruptcy in the Barind, 2020–2060, under BAU, Accelerated (SSP3-7.0), and MAR intervention scenarios.

The policy implication is stark, as Figure 9.3 makes clear. By 2060, annual water bankruptcy costs under BAU reach approximately USD 2.05 billion per year, compared to about USD 650 million under MAR intervention. The cumulative cost saving from intervention over the 40-year period amounts to USD 24.6 billion, a figure that dwarfs the USD 598 million to USD 1.8 billion climate finance pipeline proposed in Chapter 10 by a factor of roughly 14 to 41. This cost-benefit comparison provides the strongest economic justification for accelerated investment in Managed Aquifer Recharge, crop switching, and transboundary flow governance in the Barind.

9.6 From Barind to Northwest: The Consolidated Regional Cost

The Barind estimate developed above captures only part of the region's water bankruptcy. To arrive at a figure for northwest Bangladesh as a whole, the Teesta transboundary losses of Chapter 6 are added, from the bottom up, to the Barind direct total of §9.3. Because the two are built on a common basis (direct annual losses, before any economy-wide multiplier) they are additive, subject only to a modest adjustment for the small area of causal overlap between Barind aquifer depletion and Teesta-induced substitution. The consolidated figure is therefore the Barind direct total, plus the Teesta block, less that overlap. The following points of method apply:

- The Barind direct total (Components C1–C3 and C5 of §9.3, USD 517 million central) is carried in full.
- The Teesta block comprises the induced groundwater-substitution energy cost (T1, Chapter 7) and three flow-dependent ecosystem losses valued in Chapter 6 (Hossen et al., 2024): the offstream irrigation-service loss (T2), the instream environmental-flow loss (T3), and navigation and sediment losses (T4). Teesta open-water fisheries are excluded here because they are already carried within the Barind ecosystem component (C5).
- A 5 percent overlap adjustment is applied for the causal overlap between the Barind aquifer-deepening energy penalty and the Teesta-induced substitution energy, which partly address the same pumping.

Table 9.4 Consolidated annual cost of water bankruptcy in northwest Bangladesh, built up from the Barind direct total (USD million per year)

Component	Low	Central	High	Source
Barind direct subtotal (C1–C3, C5)	**403**	**517**	**653**	§9.3
T1: Teesta induced-substitution energy	46	71	96	Ch 7
T2: Teesta offstream irrigation loss	15	25	35	Ch 6 (Hossen et al. 2024)
T3: Teesta instream environmental-flow loss	15	21	27	Ch 6 (Hossen et al. 2024)
T4: Teesta navigation and sediment	1	2	3	Ch 6 (Hossen et al. 2024)

Component	Low	Central	High	Source
Gross northwest direct	**480**	**636**	**814**	—
Less: overlap adjustment (≈5%)	−24	−32	−41	Methodology note
NET CONSOLIDATED ANNUAL COST	**≈ 456**	**≈ 604**	**≈ 773**	—

Methodology: the Teesta ecosystem losses (T2–T4) are annual-loss fractions applied to the baseline service values of Hossen et al. (2024), consistent with the documented three-quarters decline in dry-season flow since 1979 and the sustained breach of the 142 m³/s environmental-flow reserve (Chapter 6). T4 is capped at the Hossen et al. ecosystem value (navigation + sediment), not inflated for morphological remediation. The economy-wide GDP-multiplier effect is not included in this direct total; it is reported in §9.7.3.

Note: cross-references updated on consolidation, the energy–water nexus material previously drafted as a separate chapter now appears in §9.3 of this chapter.

The consolidated annual cost of water bankruptcy in northwest Bangladesh is estimated at USD 456–773 million per year, with a central estimate of approximately USD 604 million per year, which, as expected, exceeds the Barind-only direct total of USD 517 million once the Teesta losses are added on top. This is equivalent to approximately 0.10–0.17 percent of Bangladesh's 2024 GDP (approximately USD 460 billion), or roughly 1.0–1.7 percent of agricultural GDP. Applying the economy-wide multiplier of 1.5–2.0 (§9.7.3) raises the total economic footprint to approximately USD 0.9–1.2 billion per year, with a central figure near USD 1.06 billion. The range reflects uncertainty in shadow water prices, loss fractions, discount rates, and the substitution elasticity between surface and groundwater irrigation.

9.7 Macroeconomic Transmission Channels

Water bankruptcy in the northwest transmits into the national macroeconomy through six channels, each documented in the international literature and observable in Bangladesh-specific data.

9.7.1 The Agricultural GDP Channel

Agriculture contributes approximately 11–13% of Bangladesh's GDP and employs approximately 40% of the workforce (BBS, 2024), with rice alone contributing roughly 3% of GDP. The Barind's contribution to national Boro output (approximately 18–22%) means that a sustained 10–15% yield shortfall in the region translates into a 0.03–0.06% reduction in total GDP through the direct agricultural value-added channel alone. However, input–output linkage analysis (§9.7.3) shows that the total effect, including upstream and downstream industries, is approximately 1.5–2.0 times the direct agricultural loss (BIDS, 2022).

9.7.2 The Inflation Channel

The BIS Working Paper No. 1314 (2025), the most rigorous cross-country macroeconomic study of water scarcity to date, finds that a one-standard-deviation increase in water scarcity is associated with 2.9–3.5% higher consumer price index (CPI) inflation, with the effect operating primarily through food prices. For Bangladesh, where rice constitutes roughly 30% of the CPI basket and food more broadly constitutes approximately 55–60%, the inflation channel is powerful. A 10% Boro shortfall translating into 15–25% retail rice-price spikes (consistent with the IFPRI estimates cited in Chapter 5) would contribute approximately 4.5–15% to food-price inflation and approximately 2.5–9% to headline CPI inflation in the affected year.

This is not hypothetical. Bangladesh experienced sharp rice-price spikes in 2007–2008, 2017, and 2023–24, each associated with combined flood, drought, and supply-chain shocks. The macroeconomic significance of the Barind water-bankruptcy channel is that it creates a structural, recurring inflationary pressure, not a one-off shock but a persistent drag that tightens the central bank's policy space and erodes the real purchasing power of the poorest consumers.

9.7.3 The Input–Output Multiplier Channel

Agricultural output loss in the Barind propagates through Bangladesh's economic structure via input–output linkages. The principal downstream sectors affected include rice milling (approximately 4% of manufacturing GDP), transport and logistics (paddy and rice movement from the northwest to Dhaka and other consuming regions), agro-input industries (seed, fertiliser, pesticide), rural retail and services, and the institutional food-procurement system. The total multiplier effect of a reduction in northwest agricultural output is estimated, following BIDS (2022) and an input–output methodology adapted to Bangladesh's structure, at approximately 1.5–2.0 times the direct loss. This channel is the single place where the economy-wide amplification is counted, the GDP-multiplier effect deliberately excluded from the bottom-up direct total of §9.3 (to prevent double-counting) is reported here instead. Applied to the consolidated direct loss of approximately USD 604 million per year (§9.6), the total economic footprint of northwest water bankruptcy, inclusive of indirect and induced effects, is approximately USD 0.9–1.2 billion per year, with a central estimate near USD 1.06 billion. This is the economy-wide figure; it is reported separately from, and never summed with, the direct-cost total.

9.7.4 The Trade Balance and Foreign-Exchange Channel

When domestic rice production falls short, Bangladesh imports rice, primarily from India, Vietnam, and Thailand. Import prices carry a premium over domestic farm-gate prices (approximately USD 40–80/tonne for comparable quality grades; see Chapter 5). For a 400,000-tonne import-substitution scenario attributable to Barind shortfall, the additional foreign-exchange outflow is USD 16–32 million per year. While modest relative to the total trade balance (Bangladesh's annual trade deficit is approximately USD 15–20 billion), it is significant in two ways: it comes during years when other food imports may also be elevated due to weather shocks, creating a compounding effect on the current account; and it exposes Bangladesh to international rice-market volatility, which, as the 2007–2008 global food crisis demonstrated, can produce sudden and extreme price spikes at precisely the moments of domestic vulnerability.

9.7.5 The Fiscal Channel

Water bankruptcy imposes fiscal costs through multiple routes: diesel and electricity subsidies for agricultural pumping, estimated by USAID-funded analysis at approximately USD 1.4 billion per year nationally, of which the Barind share is approximately USD 200–350 million; emergency rice procurement and distribution costs during shortfall years; social safety-net payments to affected farmers and landless labourers; investment in remedial water infrastructure (BMDA's operating budget and capital expenditure); and the opportunity cost of fiscal resources diverted from other development priorities. The 2025 WARPO gazette notification, by prohibiting groundwater abstraction in 4,911 villages without compensation, implicitly transfers the adjustment cost from the exchequer to the affected smallholders, a fiscal saving for the government but a regressive distributional outcome.

9.7.6 The Labour Market and Migration Channel

The World Bank CCDR (2022) projects that 13.3 million Bangladeshis may become internal climate migrants within 30 years, with agricultural losses as a primary driver, and identifies the Barind specifically as a source region. At the micro level, the Mongabay (2024) investigation documented Barind farmers unable to sustain Boro cultivation converting to orchards or abandoning agriculture entirely. At the macro level, rural–urban migration from the northwest contributes to population pressure in Dhaka, Chittagong, and other receiving cities, with cascading effects on urban housing, transport, sanitation, and informal-sector wage depression. The World Bank ‘High and Dry’ report (2016) finds that water-related GDP losses of up to 6% are possible in the most affected regions, with migration and conflict as amplifying channels. For Bangladesh's northwest, the annual economic cost of water-bankruptcy-driven labour displacement is difficult to isolate precisely but is embedded in the broader macro estimates as a contributing factor.

9.8 Capital Destruction and the Concept of Water-Adjusted GDP

9.8.1 Stranded Infrastructure

Two major public infrastructure investments in the northwest are partially or fully stranded by water bankruptcy. The first is the Teesta Barrage Irrigation Project (TIP) at Doani, designed for BDT 1,500 crore and now operating at approximately 22% of design capacity during the dry season (§9.6). The second is the BMDA deep-tubewell network (approximately 16,000 DTWs across the Barind) which in the most stressed areas is progressively rendered inoperable as the water table falls below well-screen depth. At the private level, abandoned shallow tubewells represent lost farmer capital estimated at BDT 30,000–60,000 per unit (Chapter 5). The aggregate stranded-asset cost is difficult to estimate precisely but is conservatively on the order of USD 200–400 million in cumulative capital destruction.

9.8.2 Aquifer Depletion as Capital Depreciation

Standard national income accounting (the UN System of National Accounts, SNA 2008) does not treat aquifer depletion as a capital charge. Water pumped from a depleting aquifer appears as a costless input to agricultural production; the permanent loss of stored groundwater is not recorded as depreciation. This accounting gap systematically overstates the true net domestic product (NDP) of water-depleting economies, a point made forcefully by Repetto et al. (1989) in the foundational World Resources Institute study, and extended to groundwater by Konikow and Kendy (2005), Famiglietti (2014), and more recently by the UN System of Environmental-Economic Accounting (SEEA-Water, 2012).

If aquifer depletion in the Barind is treated as capital depreciation (analogous to the depreciation of a dam, a road, or a building), the accounting changes substantially. The Barind aquifer stores an estimated 15–25 billion m^3 of exploitable freshwater (based on BWDB/BMDA estimates of aquifer volume and specific yield). At the shadow price of USD 1.50–2.50/m^3 used in Chapter 5 (the residential tariff to desalination cost range), this stored water has a total asset value of USD 22–62 billion. Annual abstraction of approximately 6–8 billion m^3 (BMDA, 2023), of which net depletion (withdrawal minus recharge) is approximately 1.5–3.0 billion m^3, corresponds to annual capital depreciation of USD 2.3–7.5 billion, a figure that dwarfs the direct agricultural losses and that, if accounted for in national income statistics, would visibly depress Bangladesh's adjusted net savings rate.

The concept of water-adjusted GDP, a GDP figure that subtracts the value of aquifer depletion as depreciation, is methodologically straightforward; it follows the Adjusted Net Savings methodology of the World Bank, which already adjusts for mineral depletion, forest depletion, and CO_2 damage. Its application to Bangladesh would, for the first time, make the macroeconomic cost of Barind water bankruptcy visible in headline national-accounts terms. This thesis recommends that BBS and the Planning Commission adopt such an adjustment as part of the forthcoming revision of the national statistical framework.

9.8.3 Soil Fertility Loss as Capital Depreciation

A parallel argument applies to topsoil. The Barind's Pleistocene red-clay soils, which under natural conditions maintain modest but stable organic carbon stocks, are documented to be losing organic carbon under continuous Boro monoculture and drought stress (Ali, 2008; Islam et al., 2021). Topsoil loss is, in economic terms, a reduction in the natural capital stock that supports agricultural productivity. While a full valuation of Barind soil-capital depreciation is beyond the scope of this thesis, the international literature (Costanza et al., 2014; TEEB, 2010) values productive agricultural topsoil at USD 500–2,000 per hectare. Applied to the approximately 775,000 ha of cultivable Barind land experiencing measurable degradation, the order of magnitude of the annual soil-capital loss is USD 30–100 million per year, an additional unrecorded capital charge on the national accounts.

9.9 The International Evidence: Water Scarcity and Macroeconomic Performance

The thesis's findings are consistent with a growing international literature linking water scarcity to macroeconomic outcomes:

- **BIS Working Paper No. 1314 (2025)** analysed panel data for 169 countries (1990–2020) and found that a one-standard-deviation increase in water scarcity reduces GDP growth by 0.12–0.16%, fixed investment growth by 0.39–0.42%, and raises CPI inflation by 2.9–3.5%, with larger effects for water-intensive industries. Projected water stress in 2080 shows extreme scarcity across Central America, Southern Europe, the Middle East, India, and China.
- **World Bank 'High and Dry' (2016)** found that water-scarce regions could see GDP growth decline by up to 6% by 2050, but that improved water stewardship and reallocation of even 25% of water to higher-valued uses could neutralise these losses.
- **Global Commission on the Economics of Water (2024)**, in 'Towards a New Economics of Water', showed that adjusting water tariffs to reflect externalities and scarcity generates significant GDP gains in low- and middle-income countries, and that ignoring trends in total water storage risks underestimating economic impacts.
- **Calow et al. (2021, Nature Communications)** used a linked global human–Earth system model to show that basin-specific tipping points can occur where economic impacts shift abruptly from manageable to severe, particularly when groundwater runs out and no alternative supply is available.
- **Morocco CCDR (World Bank, 2023)** found that water scarcity could reduce Moroccan GDP by up to 6.5%, with input–output spillovers from agriculture to the agro-industrial sector (27% of industrial output) and labour-market channels (up to 6% labour-demand reduction across the economy).

Bangladesh's estimated water-bankruptcy cost of 0.10–0.20% of GDP is below the upper bound of these international findings, partly because the affected area (northwest Bangladesh) is a sub-national region rather than the whole economy. However, the concentration of Boro production in the northwest, the strong input–output linkages to the rice-milling and food-distribution sectors, and the food-price inflation channel mean that the true national impact likely exceeds the simple area-weighted estimate. The BIS elasticity (0.12–0.16% GDP-growth reduction per standard deviation of scarcity) is consistent with the thesis's estimate when the Barind's scarcity intensity is considered.

9.10 Distributional Incidence: Who Pays for Water Bankruptcy?

An aggregate macroeconomic cost of USD 456–773 million per year (economy-wide footprint near USD 1.06 billion) does not fall equally across the population. The distributional incidence is steeply regressive:

- **Smallholder farmers in the High Barind** bear the largest single share, through compressed gross margins, pump capital losses, and forced land-use transitions. These are overwhelmingly households in the bottom two income quintiles of the national distribution (BBS HIES, 2022).
- **Fisher households along the Teesta** (approximately 25,000 households) bear the fishery-livelihood losses, again concentrated in the lowest income deciles.
- **Net food-buying households nationally** (the rural landless, urban poor, and small farmers whose own production is exhausted by mid-season) bear the welfare cost of rice-price volatility.
- **The national exchequer** bears the subsidy burden (diesel and electricity for pumps, rice procurement, social safety nets) and the foreign-exchange cost of rice imports.
- **Future generations** bear the cost of aquifer depletion and soil-fertility loss, assets that will not be available when they are needed, and whose loss is not recorded in current national accounts.

The only beneficiaries of the current arrangement are the upstream irrigators in West Bengal who receive the Teesta water that Bangladesh does not; rice traders who profit from price volatility; and diesel importers and distributors who supply the pump fleet. The distributional analysis therefore supports not only the efficiency case for intervention (the total cost exceeds the cost of intervention) but also the equity case: the costs fall on those least able to bear them, while the benefits of inaction accrue to those who are already better off.

9.11 Implications for National Planning and the Delta Plan 2100

Bangladesh's Delta Plan 2100, adopted in 2018 as a long-term adaptive framework for the Ganges–Brahmaputra–Meghna delta, identifies water resources management as a central pillar. However, the Plan's treatment of the Barind and the northwest is less developed than its treatment of the coastal belt, reflecting the historically dominant framing of Bangladesh's water challenges as flood and sea-level problems rather than drought and depletion problems. The macroeconomic analysis of this chapter argues that the Barind's water-bankruptcy costs are of comparable national significance to the coastal-belt climate risks and should receive proportionate investment and policy attention within the Delta Plan framework. Specifically, the Planning Commission should consider:

- Incorporating aquifer-depletion depreciation into adjusted net savings calculations, following the World Bank ANS methodology, to make the macroeconomic cost of Barind water bankruptcy visible in national planning documents.

- Upgrading the northwest drought–depletion cluster from a secondary to a primary investment hotspot within the Delta Plan 2100, with a dedicated financing envelope matched to the scale of the estimated losses (USD 456–773 million per year against an adaptation need estimated in Chapter 10).
- Commissioning a full Bangladesh-specific CGE model of water-bankruptcy macroeconomic impacts, extending the Islam et al. (2022) framework to include the Barind-specific channels identified in this thesis, as a tool for the Planning Commission's medium-term macroeconomic framework.
- Integrating the energy-cost findings of §9.3 into the energy-sector planning of the Bangladesh Power Development Board (BPDB) and the Ministry of Power, Energy and Mineral Resources, so that the solar-irrigation programme is explicitly linked to groundwater-metering as a condition of deployment.

Water bankruptcy in northwest Bangladesh is not a local water-management problem. It is a macroeconomic condition with measurable effects on GDP (estimated −0.10–0.20%), on agricultural GDP (estimated −1.0–2.0%), on inflation (estimated 2.5–9.0% contribution to food-price inflation in shortage years), on the trade balance (USD 16–32 million in additional rice imports), on the fiscal accounts (USD 200–350 million in pump subsidies), and on the national capital stock (USD 2.3–7.5 billion in annual aquifer depreciation if properly accounted for).

The consolidated annual cost of approximately USD 456–773 million per year, with a central estimate of approximately USD 604 million (and an economy-wide footprint near USD 1.06 billion), is comparable in order of magnitude to the annual budget of the Ministry of Water Resources and larger than the cumulative disbursement of the Bangladesh Climate Change Trust Fund over its entire 13-year history. It is, in other words, a problem of a scale that requires national-level policy attention, national-level fiscal resources, and international climate-finance support, the subject of the next chapter.

CHAPTER 10: Climate Finance for Barind and Teesta Governance

10.1 Introduction

The preceding chapters have established that water bankruptcy in northwest Bangladesh imposes direct annual economic costs of approximately USD 456–773 million, with a central estimate of approximately USD 604 million (Chapter 9), driven by groundwater depletion, Teesta flow reduction, induced energy costs, and associated ecosystem losses. The economy-wide footprint, after accounting for broader macroeconomic transmission, is estimated separately at approximately USD 0.9–1.2 billion per year, with a central estimate near USD 1.06 billion. This chapter asks the practical question: where will the money come from to address these losses? It examines the international and domestic climate-finance instruments available to Bangladesh, assesses their fit with the specific interventions this thesis identifies as priorities, and proposes a structured financing pipeline with indicative project concepts, estimated costs, and recommended funding sources.

The chapter is organised around five priority intervention areas derived from the empirical findings: (i) Managed Aquifer Recharge (MAR); (ii) topsoil restoration and soil fertility rebuilding; (iii) drought-tolerant variety (DTV) development and extension; (iv) transboundary water diplomacy and monitoring; and (v) integrated dry-season flow monitoring for instream uses (environmental flow, irrigation, fisheries, navigation). For each intervention, the chapter estimates the investment need, identifies the most suitable funding instrument, and discusses the institutional pathway for proposal development and implementation.

10.2 The Global Climate Finance Landscape

10.2.1 Principal Multilateral Instruments

The UNFCCC climate-finance architecture comprises several operating entities and funding windows relevant to Bangladesh's water-sector adaptation:

- **Green Climate Fund (GCF).** The world's largest dedicated multilateral climate fund, with a cumulative portfolio exceeding USD 13.5 billion in approved projects as of 2025. The GCF operates through accredited entities (multilateral, national, regional) and offers grants, concessional loans, equity, and guarantees. It targets a 50:50 balance between mitigation and adaptation, with a floor of 50% of adaptation allocation for LDCs, SIDS and African states. Bangladesh, as an LDC (until graduation, scheduled for 2026), has been a significant beneficiary with multiple approved projects including the ECCCP-Drought (SAP026) specifically targeting the northwestern drought region, the first GCF-funded project directly addressing Barind water stress (GCF, 2023).
- **Loss and Damage Fund (L&D Fund).** Established at COP27 (Sharm el-Sheikh, 2022) and operationalised at COP28 (Dubai, 2023), with initial pledges of approximately USD 700 million. The Fund is expected to support both economic and non-economic loss and damage from climate change, including slow-onset events such as drought and

groundwater depletion. As of 2026, its operational modalities are still being finalised, but Bangladesh is explicitly recognised as one of the most vulnerable countries and is expected to be among the first recipients. The Macroeconomics chapter estimates direct Barind agricultural losses from yield stress and crop failure at approximately USD 222–472 million per year across the low and high scenarios, before energy and ecosystem-service costs are added. These already-materialising losses strengthen the case for L&D Fund support.

- **Adaptation Fund.** Operational since 2009, financed primarily through a 2% levy on Certified Emission Reductions (CERs) from CDM projects. The Fund has a lighter administrative process than the GCF and is well-suited to medium-scale projects (USD 1–10 million). PKSF is an accredited entity for Bangladesh. As of 2024, the Fund had approved a solar-powered reverse osmosis project for coastal Bangladesh and was processing additional submissions (Adaptation Fund, 2024).
- **Global Environment Facility (GEF).** Primarily focused on biodiversity, land degradation (UNCCD), and international waters. The GEF's land-degradation focal area is relevant to the Barind soil-fertility intervention, and its international waters programme could support the Teesta transboundary monitoring component (GEF, 2024).

10.2.2 Multilateral Development Banks

The Asian Development Bank (ADB) is the most significant MDB partner for Bangladesh's climate agenda. ADB allocated approximately 53% of its 2023 project financing for Bangladesh (approximately USD 1.9 billion) to climate finance, and committed to allocating more than half of its 2024–26 allocation for Bangladesh (approximately USD 5.5 billion) to climate-relevant investments (IMF/World Bank, 2023). The World Bank's USD 1 billion Green and Climate Resilient Development Policy Credit series is the largest single climate-finance instrument currently active in Bangladesh. The Asian Infrastructure Investment Bank (AIIB) is considering an additional USD 400 million at the Government of Bangladesh's request (IMF, 2023). These MDB instruments operate primarily through policy-based lending and project lending, and are suitable for large-scale infrastructure investments such as MAR systems and surface-water augmentation networks.

10.2.3 Bilateral Donors

Several bilateral donors have historically supported Bangladesh's water and climate sectors: JICA (Japan), KfW (Germany), DANIDA (Denmark), DFID/FCDO (UK), SIDA (Sweden), USAID (USA), and the EU. Notable ongoing programmes include JICA's support for the Barind Integrated Area Development Project, DANIDA's support for LGED's climate change adaptation programme, and the Netherlands' Delta cooperation programme (relevant to the Delta Plan 2100). Bilateral donors typically fund components in the USD 5–50 million range with 3–7 year project horizons, and are well-suited to technical assistance, capacity building, monitoring equipment, and pilot-scale interventions.

10.3 Domestic Climate Finance Instruments

10.3.1 Bangladesh Climate Change Trust Fund (BCCTF)

Established in 2010 with an initial government allocation of BDT 3,000 crore (approximately USD 350 million), the BCCTF is the principal domestically funded climate-finance instrument. Cumulative disbursement through 2023 has exceeded USD 400–500 million across approximately 800 projects. The Fund operates through two windows: a government window (66% of allocations, implemented by line ministries) and a trust-fund window (34%, implemented by NGOs and civil society). Rashid and Afrin (2013) and Alam et al. (2020) provide critical assessments noting both the Fund's importance as a South–South model and its governance challenges (project selection criteria, monitoring, fiduciary standards).

For the Barind-specific interventions proposed in this thesis, the BCCTF is best matched to smaller, domestically executed components: drought-tolerant variety extension, AWD scale-up, farmer training programmes, and small-scale rainwater harvesting/pond-based storage. Larger infrastructure (MAR systems, canal rehabilitation) would exceed the typical BCCTF project scale and are better suited to GCF or MDB financing.

10.3.2 National Budget Mainstreaming

Bangladesh has made significant progress in climate budget tagging (CBT), through which climate-relevant expenditures across line ministries are identified and tracked. The Ministry of Finance's Climate Fiscal Framework (2020) estimated that approximately 7–8% of annual government expenditure is climate-relevant. For the Barind specifically, BMDA's operating budget and capital projects, DAE's extension services, BWDB's TIP maintenance, and the Ministry of Water Resources' surface-water augmentation investments are all partially climate-relevant expenditures that could be scaled if fiscal space permits.

10.4 Priority Interventions and Financing Pipeline

This section proposes five priority intervention areas, each with an indicative project concept, estimated cost, and recommended funding source.

10.4.1 Managed Aquifer Recharge (MAR)

Managed Aquifer Recharge is the deliberate introduction of water into aquifer systems to restore depleted storage and maintain water tables within sustainable limits. Techniques include infiltration basins, injection wells, riverbank filtration, and check dams. For the Barind, where the impermeable clay surface limits natural recharge to less than 9% of rainfall, engineered MAR is the only scalable option for arresting water-table decline (ICCES, 2025; Mainuddin et al., 2021).

BMDA has already piloted limited MAR through canal-based recharge and pond deepening. Mainuddin et al. (2021) estimated that augmenting approximately 20% of current groundwater abstraction with surface-water recharge would be sufficient for sustainable use in the northwest.

At an indicative unit cost of USD 0.10–0.30 per m^3 of recharged water (based on international MAR benchmarks from Australia, India, and Israel; Dillon et al., 2019), and a target recharge volume of approximately 1.5–3.0 billion m^3 per year, the annual operating cost would be USD 150–900 million. Capital costs for the infrastructure (infiltration basins, injection wells, pipeline networks) are estimated at USD 500 million–1.5 billion, deployable over 10–15 years.

Recommended funding: GCF full proposal (capital component, USD 100–200 million grant + concessional loan) + ADB/World Bank co-financing (USD 200–500 million) + BMDA/government counterpart (USD 50–100 million). The GCF's SAP026 (ECCCP-Drought) provides a platform on which a larger-scale MAR proposal can be built as a follow-on project.

10.4.2 Topsoil Restoration and Soil Fertility

Chapter 5 documented that Barind soils are losing organic carbon under continuous Boro monoculture, drought stress, and reduced vegetative cover. Restoration interventions include: (a) conservation agriculture (minimum tillage, cover cropping, residue retention); (b) biochar and compost application; (c) agroforestry integration in the cereal–orchard transition zone; and (d) targeted micronutrient supplementation. These are relatively low-cost interventions at USD 50–200 per hectare, deployable across the approximately 400,000–500,000 ha of most-degraded Barind cropland. Total estimated cost: USD 20–100 million over 5–7 years.

Recommended funding: BCCTF (government window, USD 5–10 million for extension and training) + Adaptation Fund (USD 5–8 million for pilot-scale restoration) + GEF Land Degradation focal area (USD 3–5 million) + bilateral donors (DANIDA/JICA, USD 5–15 million for technical assistance and monitoring). The recently approved BMDA PARTNER project (BDT 11,092 lakh, funded partly by development partners) already includes components relevant to soil restoration and could serve as the institutional anchor.

10.4.3 Drought-Tolerant Variety (DTV) Development and Extension

BRRI has released several drought-tolerant Boro varieties (BRRI dhan 28, 29, 58, and more recently BRRI dhan 67 and BRRI dhan 71 with improved heat tolerance), but farmer adoption in the Barind remains incomplete due to seed availability, extension coverage, and the perception that DTV yields are lower under well-irrigated conditions. Accelerated DTV deployment would include: (a) seed multiplication and distribution through DAE and BADC; (b) on-farm demonstration plots in each of the 25 Barind upazilas; (c) farmer training in AWD-compatible DTV agronomy; and (d) linking DTV adoption to the solar-irrigation and groundwater-metering programme described in Chapter 7.

Estimated cost: USD 15–30 million over 5 years. Recommended funding: BCCTF (BDT 100–200 crore) + CGIAR/IRRI partnership funding + GCF readiness support. This is a high-benefit-to-cost intervention: AWD alone has been demonstrated to reduce pumping energy by 30–38% without yield loss (Mainuddin et al., 2021), meaning the energy savings alone would repay the extension cost within 2–3 years.

10.4.4 Transboundary Water Diplomacy and Institutional Capacity

The BBAA framework proposed in Chapter 8 requires, for its practical implementation, several capacity investments: (a) training of JRC technical staff in hydro-economic modelling, environmental flow assessment, and benefit-sharing analysis; (b) secondment of Bangladeshi water professionals to international river basin organisations (Rhine, Mekong, Nile Basin Initiative) for comparative learning; (c) development of Bangladesh's negotiating position based on the quantified economic costs documented in this thesis; (d) engagement of Track II (academic, civil society) diplomacy channels with Indian counterparts; and (e) support for the BWDB's hydrological monitoring capacity at Dalia and other Teesta gauging stations.

Estimated cost: USD 5–15 million over 5 years. Recommended funding: bilateral donors (Netherlands Delta cooperation, DFID/FCDO, SIDA) + GCF readiness programme + GEF International Waters focal area. The political sensitivity of the Teesta issue means that funding for the diplomacy component is best channelled through neutral multilateral or academic intermediaries (e.g., UNESCO-IHP, ICIMOD, or a trusted academic partnership such as KU Leuven's water programme or CSIRO's bilateral cooperation).

10.4.5 Integrated Dry-Season Flow Monitoring System

The hydrological analysis of the Teesta in Chapter 6, together with the flow-contingent allocation mechanism developed in Chapter 8, shows the importance of reliable and timely flow information for both water management and treaty implementation. An integrated monitoring system would include: (a) automated telemetry at Dalia (Bangladesh), with negotiated access to Gajoldoba data (India); (b) groundwater-level monitoring network densification in the Barind (from approximately 30–40 wells to approximately 200 wells across the 25 upazilas); (c) satellite-based soil-moisture and vegetation-health monitoring (Sentinel-2, Landsat-9, GRACE-FO); (d) environmental-flow compliance monitoring (flow–ecology relationships for fisheries, navigation thresholds); and (e) a public-access data platform for transparency and accountability.

Estimated cost: USD 8–20 million capital + USD 2–4 million per year operating. Recommended funding: ADB technical assistance grant + World Bank IDA + JICA (Japan has strong expertise in hydrological monitoring). The monitoring system is a precondition for the BBAA framework's automated shortage-sharing triggers (Chapter 8, Step 2: BBI calculation requires real-time flow data).

10.5 Summary Financing Pipeline

Table 10.1 Proposed climate-finance pipeline for Barind and Teesta interventions.

Intervention	Capital cost (USD M)	Annual cost (USD M)	Primary source	Co-financing
Managed Aquifer Recharge	500–1,500	150–900	GCF + ADB/WB	BMDA/GoB
Topsoil restoration	20–100	3–15	BCCTF + AF + GEF	DANIDA/JICA
Drought-tolerant varieties	15–30	3–6	BCCTF + CGIAR	IRRI/BRRI
Transboundary diplomacy	5–15	1–3	Bilateral + GEF-IW	UNESCO/ICIMOD
Monitoring system	8–20	2–4	ADB TA + WB IDA	JICA
Solar irrigation + metering	50–150	5–15	GCF + IDCOL	BMDA/GoB
TOTAL PIPELINE	**598–1,815**	**164–943**	—	—

10.6 The Economics of Action Versus Inaction

The consolidated direct annual cost of water bankruptcy estimated in the Macroeconomics chapter is approximately USD 456–773 million per year, with a central estimate of approximately USD 604 million. The proposed intervention pipeline's total capital cost is USD 598–1,815 million, deployable over 10–15 years, i.e., an annualised capital outlay of approximately USD 40–180 million per year. Including annual operating costs, the total annual cost of the intervention package is approximately USD 200–1,120 million per year, depending on the scale of MAR deployment.

At the central estimates, an annual intervention cost of approximately USD 350 million can be compared with the central direct cost of inaction of approximately USD 604 million per year, giving a simple annual benefit–cost ratio of approximately 1.7:1. This annual comparison should be interpreted alongside the longer-term scenario analysis in the Macroeconomics chapter: cumulative costs to 2060 are estimated at approximately USD 45.8 billion under business as usual and USD 21.2 billion under the MAR intervention scenario, implying cumulative avoided costs of approximately USD 24.6 billion. These avoided costs are substantially larger than the proposed capital financing pipeline of USD 598–1,815 million.

This comparison does not include the avoided capital depreciation of aquifer storage, estimated in the Macroeconomics chapter at USD 2.3–7.5 billion per year if groundwater depletion is treated as natural-capital depreciation. These values are reported separately from the direct annual loss estimate and are not added to the benefit–cost calculation above, thereby avoiding double counting.

The World Bank's 'High and Dry' report (2016) reached a similar conclusion globally: improved water stewardship, including the allocation of even 25% of water to more highly valued uses, can neutralise GDP losses from water scarcity and in some regions generate GDP gains of up to 6%. The economics of action are favourable. The constraint is not financial feasibility but institutional capacity, political will, and the speed of climate-finance disbursement.

10.7 The Loss and Damage Fund: A New Window for Barind

The operationalisation of the Loss and Damage Fund at COP28 (2023) opens a new financing window that is particularly relevant to the Barind case. Unlike the GCF and Adaptation Fund, which finance forward-looking adaptation measures, the L&D Fund is intended to address losses and damages that have already occurred or are unavoidable under current emissions pathways. The Barind's existing aquifer depletion (6 metres of cumulative drawdown since 1988, with a climate-attributable share of approximately 25–35% (following the IPCC AR6 attribution of the South Asian drying trend)) constitutes a quantifiable loss that has already materialised. Similarly, the soil-fertility decline documented in Chapter 5 and the fisheries-livelihood losses from reduced Teesta flow (Chapter 6) are ongoing damages attributable in part to anthropogenic climate change.

A L&D Fund proposal for the Barind could be structured around: (a) direct compensation to affected farming households in the 47 very-high-water-stress unions (identified by WARPO/IWM, 2025) for the climate-attributable share of their income losses, estimated at approximately USD 30–60 million per year; (b) funding for the 'orderly adjustment' from Boro to alternative livelihoods in the most critically depleted areas, including orchard establishment, aquaculture, and non-farm enterprise support; and (c) investment in the monitoring and early-warning systems needed to quantify future losses and trigger compensation.

Bangladesh is well-positioned for early L&D Fund access because of its track record in climate governance, its existing National Designated Authority (NDA) infrastructure, and its status as one of the world's most climate-vulnerable nations. However, the Fund's operational modalities are still being designed, and the Barind case should be prepared now, with the quantitative evidence assembled in this thesis, so that it is ready for submission when the Fund's first call for proposals opens.

10.8 Building on the GCF ECCCP-Drought (SAP026)

The GCF's approved ECCCP-Drought project (SAP026), implemented by PKSF in Bangladesh's northwestern region, represents the first international climate-finance investment directly addressing Barind drought. The project aims to make the NW region less vulnerable to climate-change-induced drought while promoting sustainable use of scarce water resources. Its components include institutional and technical capacity improvement for water planning and governance, infrastructure maintenance, and increased water access points for drinking purposes, with approximately 215,000 direct and 3.5 million indirect beneficiaries (GCF, 2023).

This thesis recommends that the ECCCP-Drought project be used as the platform for a larger, follow-on GCF full proposal that scales up the successful elements and incorporates the additional interventions identified here, particularly MAR, solar irrigation with metering, and AWD-DTV extension. The follow-on proposal would benefit from the institutional relationships, baseline data, and community networks established under SAP026, reducing preparation costs and accelerating implementation.

10.9 Connecting Climate Finance to National Economics

The World Bank CCDR (2022) estimates that Bangladesh needs at least USD 12.5 billion (approximately 3% of GDP) in the medium term for climate action. The Barind-Teesta intervention pipeline proposed in this chapter (approximately USD 598–1,815 million in capital) represents approximately 5–15% of this total national need. The Macroeconomics chapter estimates the consolidated direct annual cost of water bankruptcy at approximately USD 456–773 million, equivalent to approximately 0.10–0.17% of Bangladesh's 2024 GDP, with a wider economy-wide footprint of approximately USD 0.9–1.2 billion per year. The scale of these losses, together with the positive intervention economics identified above, supports prioritising the proposed investments within the national climate-finance allocation framework.

The connection between climate finance and GDP operates in both directions: (a) climate finance funds the interventions that prevent GDP loss from water bankruptcy; and (b) the economic losses themselves (quantified in the Macroeconomics chapter at USD 456–773 million per year in direct consolidated costs, with a wider economy-wide footprint of approximately USD 0.9–1.2 billion) constitute the economic rationale that makes the climate-finance proposals competitive in international funding windows. In other words, the Macroeconomics chapter provides the cost-of-inaction baseline against which GCF, L&D Fund, and MDB proposals are evaluated. A strong cost-of-inaction analysis is, in practice, a central component of a competitive climate-finance proposal.

10.10 Institutional Pathway for Proposal Development

The institutional pathway for developing the proposed financing pipeline involves:

- **National Designated Authority (NDA):** The Economic Relations Division (ERD) of the Ministry of Finance is Bangladesh's NDA for the GCF. All GCF proposals must receive NDA no-objection. The ERD should be engaged early in the proposal development process for the Barind MAR and solar-irrigation scale-up concepts.
- **Accredited Entities:** PKSF (national implementing entity, already accredited for GCF and Adaptation Fund), UNDP, and ADB are the most likely accredited entities for the proposed projects. PKSF's existing relationship with GCF through SAP026 and SAP008 makes it the natural lead for a Barind follow-on proposal.
- **Technical partners:** BMDA (for MAR and irrigation), BRRI (for DTV and AWD), BWDB (for monitoring and Teesta gauging), WARPO (for groundwater governance), IWM (for hydrological modelling), and CSIRO (for continued bilateral research partnership on the Bengal Water Machine and groundwater sustainability) are the key technical partners.
- Bangladeshi research and civil-society organisations can play a bridging role between technical evidence (including this thesis), community-level needs assessment, and the formal proposal development process. This role is particularly important for the L&D Fund proposals, which require demonstrated community engagement and gender-responsive design.

The climate-finance landscape for Bangladesh is, by developing-country standards, relatively mature and well-endowed. The challenge for the Barind and Teesta is not the absence of funding instruments but rather: (a) the historical orientation of climate finance toward the coastal belt rather than the northwest drought corridor; (b) the absence, until now, of a unified economic assessment that provides the cost-of-inaction baseline needed for competitive proposals; and (c) the institutional gap between the technical agencies that understand the problem (BMDA, BWDB, BRRI) and the entities accredited to access international funds (PKSF, UNDP, ADB).

This thesis has addressed gap (b) directly. The quantified direct cost of water bankruptcy (USD 456–773 million per year, with a central estimate of approximately USD 604 million), the identified intervention pipeline (USD 598–1,815 million in capital), and the favourable intervention economics, including a simple central annual benefit–cost ratio of approximately 1.7:1 and estimated cumulative avoided costs of approximately USD 24.6 billion to 2060 under the MAR scenario, provide the evidence base that proposal developers need. What remains is the institutional mobilisation to translate this evidence into funded projects, a task that falls to the Government of Bangladesh, its accredited entities, and its civil-society partners, including the Wecare for Climate Foundation.

CHAPTER 11: Conclusion

11.1 Overview

This thesis asked a single question: is northwest Bangladesh entering a state of water bankruptcy, and if so, what should be done about it? Water bankruptcy here means more than a dry year. It describes a system that can no longer keep its water promises (to farms, rivers, ecosystems and the economy) without spending down stored water faster than nature can replace it. The evidence gathered across the preceding chapters supports a clear answer: the region's water problems are no longer separate issues of drought, groundwater, river flow, energy or agriculture. They now feed on one another within the same water system, and together they add up to a condition of bankruptcy.

The main contribution of the thesis is to show how these pressures connect. Climate change raises the demand for irrigation. Farmers meet that demand by pumping more groundwater, which lowers the water table. A deeper water table costs more energy to pump. A shrinking Teesta pushes still more demand onto groundwater. And the resulting costs spread outward, into food prices, public budgets, fuel use, emissions and lost ecosystems. Water bankruptcy is best understood as this whole chain working together, not as any one broken link.

11.2 What the evidence shows

The climate is already tilting the dry-season balance against the region. Nights are getting warmer at Rajshahi, Rangpur and Bogra, while hot days have not increased, so the gap between day and night temperatures is closing. Dry spells are long, about 55 to 59 days on average, and getting longer at Rajshahi. Published projections suggest dry-season irrigation demand could rise by 5 to 15 percent by mid-century. In other words, even with no change in farming, the region will need more water simply to stand still.

The groundwater record gives the strongest physical evidence. In the Barind, the pre-monsoon water table fell from about 2.5 metres below ground in 1985 to about 15.2 metres in 2020, and the monsoon is no longer refilling the aquifer as it once did. Left unchecked, the practical limit for deep tube wells is reached around 2086; under harsher conditions, around 2074. Managed recharge could delay it beyond 2100. The lesson is that the outcome is still ours to shape, but the room to act shrinks every year.

The Teesta tells the same story for surface water. Four different records (river level, measured flow, long-term published flow and satellite images of open water) all show the river shrinking sharply in its Bangladesh reach, down by roughly three-quarters from its 1979 level, with the environmental-flow reserve breached since the mid-1990s. Because independent sources agree, the conclusion holds even where any single dataset is thin.

The two systems are joined at the pump. The Teesta Barrage scheme was built for about 4,500 cusec, but a typical February now brings closer to 1,000 cusec, a seasonal gap of about 1.03 billion cubic metres. Much of that missing surface water is simply pumped from the ground instead, deepening the aquifer and raising energy bills by an estimated USD 46 to 96 million a year, along with more diesel and more emissions. This is why the Teesta is not only a river-sharing dispute: a shortage in the channel becomes a shortage in the aquifer, the fuel tank and the national budget.

To make this usable for policy, the thesis builds the Basin Bankruptcy-Adjusted Allocation (BBAA) framework. It first sets aside the water the river needs to stay healthy, then measures what is left against what the river used to carry, and only then shares any shortfall. For the Teesta, the resulting Basin Bankruptcy Index is about 0.107, deep inside the bankruptcy range. At that level, arguing over fixed percentages is pointless, because the water to honour them no longer exists. What is needed is a rule for sharing scarcity fairly, backed by compensation when water simply cannot be delivered.

11.3 What it costs

Water bankruptcy is already an economic problem, not a future one. The direct cost is estimated at about USD 456 to 773 million a year for the northwest (central estimate near USD 604 million), and USD 403 to 653 million for the Barind alone. Adding the wider ripple effects through the economy brings the total to roughly USD 0.9 to 1.2 billion a year. And if the vanishing aquifer is counted as a loss of natural capital, an asset being used up, the yearly loss rises to somewhere between USD 2.3 and 7.5 billion. Standard national accounts miss most of this, because they record the crops produced but not the depletion of the resource that produced them.

Acting is cheaper than waiting. Restoring storage through managed aquifer recharge could save on the order of USD 24.6 billion by 2060 compared with carrying on as now. That dwarfs the proposed climate-finance package of about USD 598 million to 1.8 billion. The financing need is large as a project, but small next to the losses it would prevent.

11.4 What should be done

The findings point to one basin-wide strategy rather than a list of separate projects. In plain terms:

- **Keep a single water account for the northwest.** Report river flow, the environmental reserve, groundwater level and recovery, pumping, demand and losses together, and publish it before each dry season so it can trigger action when limits are crossed.

- **Manage surface water and groundwater as one resource.** Where Teesta water is available, use it to relieve pumping and help the aquifer recover, and treat groundwater as a drought reserve rather than the default source.
- **Protect the river's environmental flow first, then share what is left.** Make the ecological reserve a prior claim, not the water left over after everyone else has taken their share.
- **Replace fixed transboundary percentages with flow-based sharing.** Use the BBAA rule so allocation follows the water that actually exists, with compensation or benefit-sharing when it does not.
- **Restore storage while restraining demand.** Pair managed recharge with metering, limits in the most depleted areas, better crop and irrigation scheduling, and drought-tolerant varieties, so recharge is not simply cancelled out by more pumping.
- **Make solar irrigation and monitoring work for water, not against it.** Tie cheaper solar pumping to metering or limits so it does not encourage more abstraction, and build the shared flow, groundwater and satellite monitoring needed to run the whole system.

These actions work best in sequence: measure and protect the most stressed zones first, rebuild storage and reliable surface-water delivery next, and institutionalise environmental-flow protection and flow-based sharing with upstream partners over time. In the long run, the depletion of groundwater should be written into national economic planning, so that an unsustainable path can no longer look successful on paper.

11.5 Final Remarks

Northwest Bangladesh has reached the point where managing each water source on its own is no longer enough. The Barind aquifer, the Teesta, the pumps that link them, the farms they support and the regional economy are all tied to the same dry-season deficit, and climate change tightens every knot. Water bankruptcy, though, is not a wall the region has already hit, it is a road it is travelling, one that grows harder and more expensive to leave the longer it is followed.

The way back is to govern scarcity openly: measure the resource against real limits, share what remains by what is actually there rather than by old expectations, rebuild storage while curbing demand, and spread the burden of shortage instead of pushing it onto one sector, aquifer or country. The economics are plain. Paying for an orderly transition now costs far less than paying for a deeper water deficit later.

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