

Water Scarcity and Industrial Productivity: Assessing the Economic Consequences of Corporate Water-Resource Management in Emerging Economies

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Abstract

Water is a small line in most manufacturers' cost accounts, which has led many firms and policy makers to treat scarcity as an environmental concern rather than a productivity concern. This paper argues that the economic consequences of scarcity operate mainly through reliability and not through price: a plant with committed capital and labor that cannot obtain enough water loses output on every shortage day, and the loss is far larger than the water bill. The paper synthesizes peer reviewed work published before 1 January 2023 on physical water scarcity, the macroeconomic effects of water variability, the plant level effects of infrastructure unreliability, and corporate environmental management and performance. The evidence shows widespread and seasonal scarcity, consistent growth and output losses at aggregate scale, and large firm level losses from unreliable utilities, but direct plant level evidence linking corporate water management to productivity in emerging economies is thin. The paper therefore develops an analytical model in which a plant faces shortages of frequency p and depth d , chooses a recycling and reuse share r and a storage buffer, and loses expected output $\Lambda = p(1 - \beta)(d - r)^+ / (1 - r)$. The model yields a resilience threshold ($r \geq d$), a gap between the market price and the shadow value of water, an investment rule with a corner solution at the threshold, a payback calculation, and a commons externality from private groundwater self-supply. It proposes a Water Stewardship Capability Index (WSCCI) built by geometric aggregation so that a weak component cannot be offset by strong ones, together with threshold, interaction, and event study tests. In an assumed numerical example, expected shortage loss is 2.2 times the water bill under high stress, and reuse to the resilience threshold raises annual profit by 8.5% with a payback of about four years. Corporate water management raises productivity chiefly where stress is high, where capability is balanced, and where private self-supply is coordinated.

1. Introduction

Industrial firms in emerging economies are expanding in places where water is becoming harder to obtain. Garment washing and dyeing, leather finishing, food processing, paper, chemicals, and pharmaceuticals all use water as a process input, a solvent, a coolant, or a cleaning medium, and many of the clusters that host them draw on shared rivers or shared aquifers. Global assessments show that scarcity is not a distant prospect. Mekonnen and Hoekstra (2016) find that several billion people live with severe scarcity for at least one month of the year, and Rodell et al. (2018) document groundwater depletion in several heavily used regions. In Dhaka, for example, long term decline in groundwater levels has been reported for the metropolitan area (Hoque et al., 2007), and textile wet processing in Bangladesh generates wastewater loads that place a second pressure on local water resources (Hossain et al., 2018).

Yet water rarely appears as a strategic item in corporate accounts. Tariffs and abstraction charges are low relative to labor, energy, and materials, so the water bill is a small share of cost. This framing hides the channel through which scarcity damages firms. A plant that has already committed capital and workers cannot easily scale them down when the water supply is interrupted, so each hour of shortage is an hour of idle machines and wages with no output. The relevant price of water in a shortage is then not the tariff but the contribution margin that water makes possible (Hanemann, 2006). Evidence from other utilities points the same way: electricity shortages in India and China reduced plant output and productivity, and firms responded by adapting their inputs and generation (Allcott et al., 2016; Fisher-Vanden et al., 2015), and a cross-country review of infrastructure disruptions reports that unreliable services impose substantial costs on firms in developing countries (Rentschler et al., 2019).

Corporate water-resource management is the set of practices by which a firm measures, reduces, recycles, stores, sources, and governs its water. Whether these practices raise productivity is an empirical and a theoretical question. The management literature suggests that firms with stronger environmental capabilities tend to perform bet-

ter (Hart, 1995; Russo and Fouts, 1997; Konar and Cohen, 2001), but those results are not specific to water, and the economics of adoption may be less favorable than engineering estimates suggest (Gerarden et al., 2017). For water in particular, three issues are unresolved: how large the productivity loss from scarcity is relative to the visible water cost, how much management is worth at different levels of stress, and whether private adaptation by individual firms improves or worsens the position of the group.

This paper asks: *What are the economic consequences of corporate water-resource management for industrial productivity under water scarcity in emerging economies?* It is organized around four research questions.

- RQ1** How does the reliability of water supply, as opposed to its price, shape realized industrial productivity?
- RQ2** At what level of recycling, storage, and capability does corporate water management eliminate the productivity loss from scarcity?
- RQ3** How do returns, payback, and financing needs vary with the degree of water stress?
- RQ4** When does firm level adaptation, such as private groundwater abstraction, harm other firms sharing the same source?

The paper makes five contributions. First, it recasts water scarcity as a reliability and capacity-utilization problem and derives a closed form expected loss Λ in terms of shortage frequency, depth, recycling share, and storage. Second, it identifies a resilience threshold at which the loss is eliminated and shows that the profit maximizing reuse share lies at or below it. Third, it separates the price of water from its shadow value and quantifies the gap. Fourth, it proposes a Water Stewardship Capability Index based on geometric aggregation, which treats the components of water management as complements rather than substitutes. Fifth, it adds a commons externality that explains why individually rational self-supply can leave the group worse off, and it states testable propositions for plant panels.

The evidence boundary is 31 December 2022; publications from 2023 onward are not used. Section 2 reviews the evidence. Section 3 develops the analytical model and a numerical illustration. Section 4 sets out measurement and empirical design. Section 5 synthesizes the evidence and adds sector and country context. Section 6 discusses implications, Section 7 states limitations, and Section 8 concludes. Figure 1 summarizes the framework.

2. Evidence Base

2.1 How Scarcity Is Measured

Scarcity is measured in several ways, and the choice shapes conclusions. The classic indicator relates annual renewable water per person to thresholds of stress, scarcity, and absolute scarcity (Falkenmark, 1989). Footprint accounting traces water use through supply chains (Hoekstra and Mekonnen, 2012), and life cycle methods convert use into a scarcity weighted measure (Boulay et al., 2018). A strand of work stresses temporal resolution: when availability is assessed month by month rather than annually, many more people and places are classified as severely stressed (Mekonnen and Hoekstra, 2016), and 20th century trends in scarcity are driven largely by population growth (Kummu et al., 2016). Basin level risk tools combine physical quantity, variability, and regulatory indicators (Hofste et al., 2019), and satellite based measurements show that wet regions are tending to become wetter and dry regions drier, with groundwater depletion in several heavily used areas (Rodell et al., 2018). The implication for firms is that annual averages understate exposure. What matters for a plant is how often and how deeply supply falls below need, which is the information summarized later by the frequency p and depth d of shortage.

At global scale, agriculture accounts for the largest share of water use, and industry is a smaller share of the total (Hoekstra and Mekonnen, 2012). Global aggregates therefore understate the importance of water for industrial clusters, where demand is concentrated in a few basins and the economic value per unit of water is high.

2.2 Macroeconomic Evidence on Scarcity and Variability

Aggregate studies connect water to growth, mainly through variability. Brown and Lall (2006) argue that hydrological variability and the capacity to buffer it help explain differences in economic development, and Grey and Sadoff (2007) develop the concept of water security as a condition for growth. The World Bank assessment of Damania et al. (2017) documents that rainfall shocks and drought are linked to adverse economic outcomes, with large differences across places. General equilibrium simulations indicate that restrictions on water supply have uneven regional and sectoral effects that are transmitted through trade (Berrittella et al., 2007). These results establish that water matters for aggregate output, but they cannot show how an individual plant responds, or what a plant can do about it.

2.3 Infrastructure Unreliability and Plant Productivity

The closest plant level evidence concerns other utilities. Allcott et al. (2016) study Indian manufacturing and find that electricity shortages reduce plant output and producer surplus, with some loss absorbed through self-generation. Fisher-Vanden et al. (2015) find that Chinese firms facing electricity shortages lose productivity but adapt by altering inputs and technology, so that naive estimates would overstate the damage. Rentschler et al. (2019) synthesize evidence on the business costs of unreliable infrastructure in developing countries, including water services, and report that outages impose costs on firms and induce investment in backup. The lessons transfer: reliability, not price, drives losses; firms adapt; and adaptation is costly. Water differs from electricity in two ways that matter here. It is harder to store and substitute at scale, and many firms draw on a source they share with others.

2.4 Corporate Environmental Management and Performance

The natural-resource-based view holds that capabilities in pollution prevention, product stewardship, and sustainable development can be sources of advantage (Hart, 1995). Empirical work links environmental performance to financial outcomes: Klassen and McLaughlin (1996) relate environmental management events to stock market returns, Russo

and Fouts (1997) find that environmental performance is positively related to profitability and that industry growth matters, and Konar and Cohen (2001) find that the market value of firms is related to their environmental performance. Porter and van der Linde (1995) argue that regulation and environmental improvement can spur innovation that offsets costs. In the productivity literature, management practices are among the many determinants of dispersion in productivity across plants (Syverson, 2011), and misallocation helps to explain lower productivity in China and India (Hsieh and Klenow, 2009). None of these studies is specific to water, and they do not isolate reliability. The economics of adoption also matters. Efficiency projects may not be undertaken even when they appear attractive (Gerarden et al., 2017), and credit constraints can limit investment by firms in emerging economies (Banerjee and Duflo, 2014).

2.5 Research Gap

Five gaps follow. First, the scarcity literature measures availability but rarely at the plant. Second, macro evidence on variability does not reveal plant mechanisms. Third, the strongest plant level evidence concerns electricity, not water. Fourth, the management literature is not water-specific and does not separate reliability, price, and regulatory channels. Fifth, no framework links shortage frequency and depth, reuse and storage, capability, financing, and shared-source externalities in a single account. This paper addresses these gaps with a model and a measurement design rather than a new dataset. Figure 10 in Section 5 maps the evidence by level and channel. In short, the support is strongest and best documented for physical scarcity, moderate for the reliability and management channels (where the evidence is mostly about electricity or about environmental performance in general), and weakest at the plant level for water itself.

3. Analytical Model

3.1 Water as a Binding Input

Consider a plant whose capacity $\bar{Q}$ (units per period) is set by capital and labor that are committed in advance. Each unit of output needs w cubic meters of process water. A share $r \in [0, 1]$ of this need is met by recycled or reused water, so the plant needs $w(1-r)$ cubic meters of external freshwater per unit. In any period the external supply is a fraction a of the freshwater needed at full capacity, which is the availability ratio. Output is then limited by the smaller of capacity and available water,

$$Q = \bar{Q} \min\left\{1, \frac{a}{1-r}\right\}. \quad (1)$$

Shortages are described by two parameters read from an availability series such as that in Figure 2. The frequency p is the share of time in shortage and the depth d is the average fraction of need that is unmet, so $a = 1 - d$ in a shortage period and $a = 1$ otherwise. A storage buffer covers a share $\beta \in [0, 1]$ of shortage time. Expected output is $\bar{Q}(1 - \Lambda)$ with

$$\Lambda(r, \beta) = p(1 - \beta) \frac{(d-r)^+}{1-r}, \quad (x)^+ = \max\{x, 0\}. \quad (2)$$

This is the expected share of capacity lost to water. Its properties are immediate. It rises with frequency and depth, and it falls with reuse and storage. It is zero when $r \geq d$, because a plant that already recycles at least as large a share of its water as the share it loses in a shortage never runs short. Call $r = d$ the *resilience threshold*. Below the threshold the marginal effect of reuse is

$$\frac{\partial \Lambda}{\partial r} = -p(1 - \beta) \frac{1-d}{(1-r)^2}, \quad (3)$$

which is largest in magnitude just before the threshold and jumps to zero beyond it. The loss function therefore has a kink, and reuse has sharply diminishing returns for the purpose of reliability once the threshold is reached. Figure 3 shows the surface.

3.2 Productivity Wedge

Because capital and labor are committed, a shortage lowers measured output without lowering measured inputs. Realized total factor productivity is then the potential level scaled by the share of capacity that is

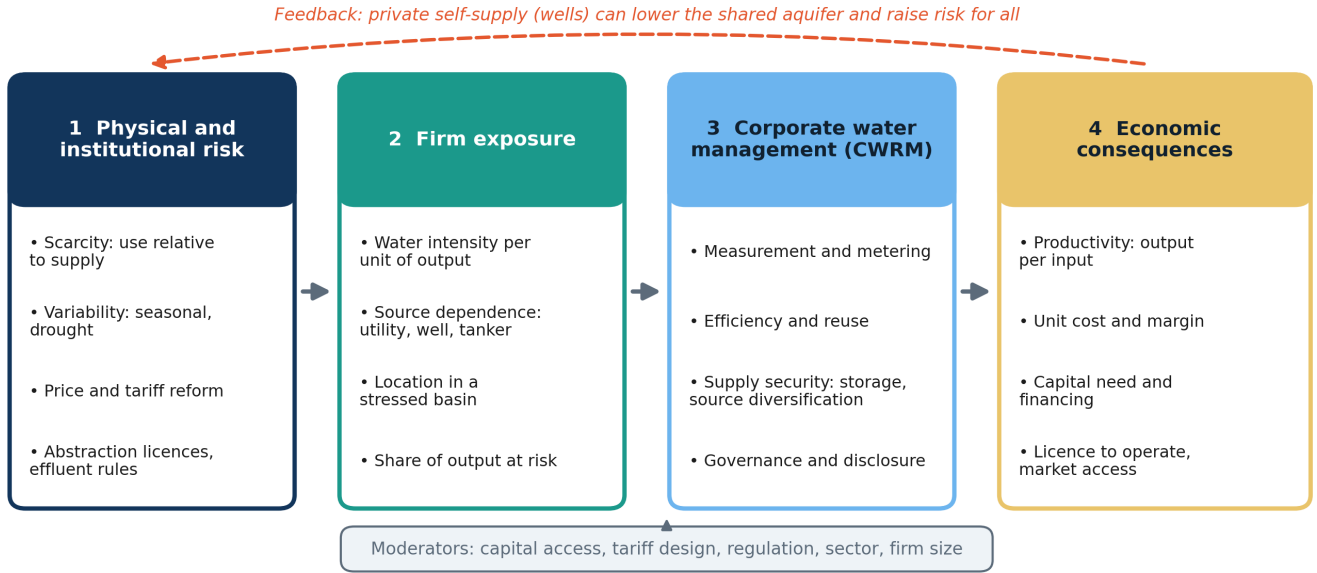


Figure 1. Physical and institutional water risk reaches the firm through its exposure, is mediated by four dimensions of corporate water-resource management, and produces economic consequences.

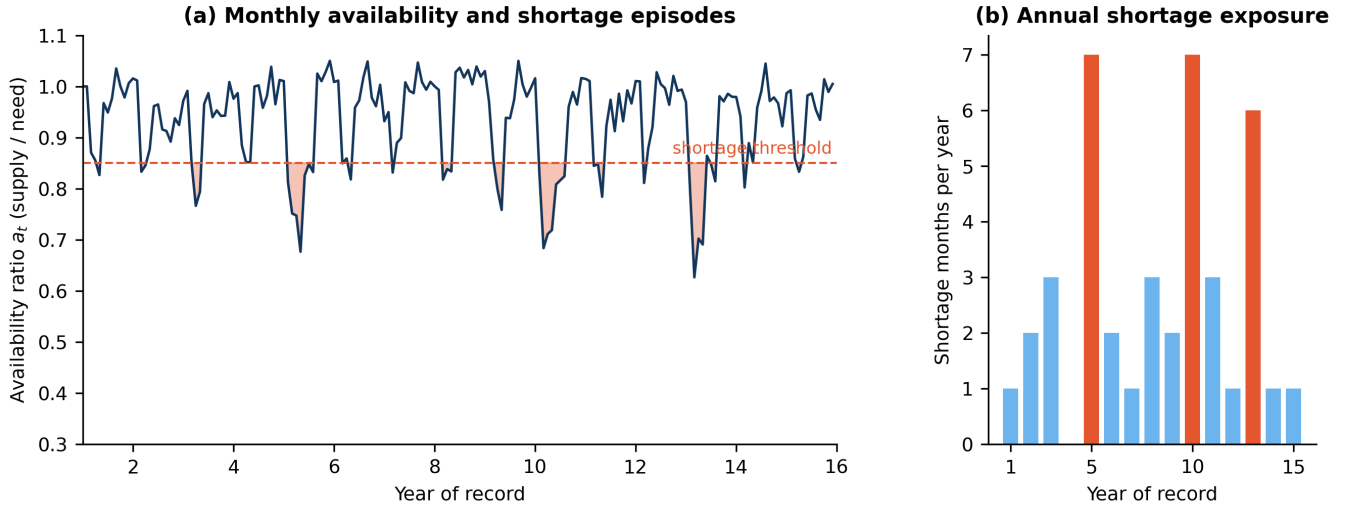


Figure 2. Illustrative monthly availability ratio over 15 years and its annual shortage exposure. The series is simulated from assumed seasonal dry months, three drought years, and autocorrelated noise. With a shortage threshold of 0.85, months below the threshold occupy 22.2% of the record ($\hat{p}$) with average depth 0.21 ($\hat{d}$). The series is not observed data.

actually used,

$$\ln \text{TFP}^{\text{obs}} = \ln \text{TFP}^{\text{pot}} + \ln(1 - \Lambda), \quad (4)$$

and labor productivity moves in the same proportion. The productivity wedge $\ln(1 - \Lambda)$ is a measurement of the economic cost of unreliability that does not require any change in technology. It also implies that two plants with identical technology can have different measured productivity if their water reliability differs, which is consistent with the dispersion that productivity researchers document (Syverson, 2011).

3.3 Price Versus Shadow Value

Let m be the unit contribution margin before water costs, π the tariff or abstraction cost per cubic meter, and ρ the operating cost of treating and reusing a cubic meter. When water binds, an extra cubic meter lets the plant produce $1/w$ more units, so its shadow value is

$$\lambda_w = \frac{m}{w}. \quad (5)$$

The ratio λ_w/π measures how much the price understates the value of water in a shortage. The annual cost of scarcity has two parts, the water bill $\bar{Q}_w\pi$ and the expected shortage loss $\bar{Q}_m\Lambda$. The bill is observed and the loss is not, which explains why firms underinvest in reliability. Because λ_w depends on the margin, the same shortage costs more for high margin products than for low margin ones.

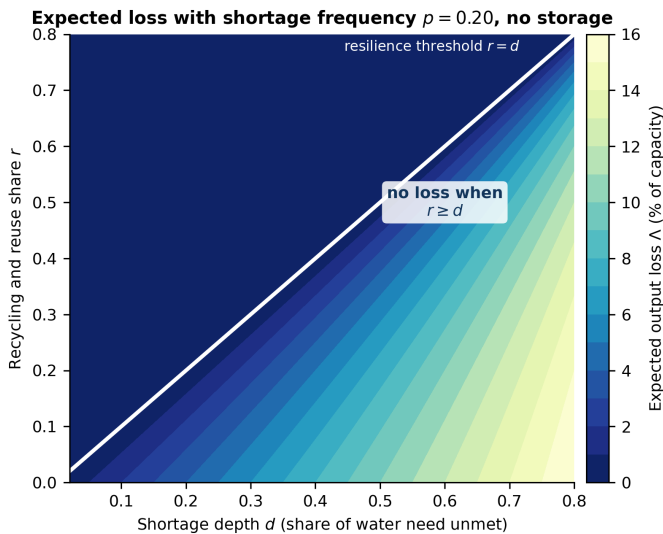


Figure 3. Output loss Λ versus shortage depth d and reuse share r for $p = 0.20$ without storage. The white line marks the resilience threshold $r = d$, above which loss is zero.

3.4 Profit and the Choice of Reuse and Storage

Expected annual profit, given reuse r and storage β , is

$$\Pi(r, \beta) = \bar{Q}(1 - \Lambda) [m - w\pi(1 - r) - \rho wr] - F_0 r^2 - H_0 \beta^2, \quad (6)$$

where $F_0 r^2$ is the annualized capital cost of recycling capacity, convex because the cleanest and cheapest streams are recycled first, and $H_0 \beta^2$ is the annualized cost of storage. Above the threshold, $\Lambda = 0$ and the marginal benefit of reuse is only the saving $w(\pi - \rho)$ per unit, which gives the bill-driven level $r_b = \bar{Q}w(\pi - \rho)/(2F_0)$. The optimum is therefore the larger of that level and the best choice below the threshold. The marginal benefit just below the threshold, taking the left derivative of (6) at $r = d$, is positive and large; the optimum is at the threshold itself if

$$\bar{Q} \left[\frac{p(1 - \beta)}{1 - d} (m - w\pi(1 - d) - \rho wd) + w(\pi - \rho) \right] \geq 2F_0 d. \quad (7)$$

When the inequality holds, a profit maximizing plant recycles exactly the share it loses in a shortage and no more. When it fails, the optimum is interior and lies below the threshold: the plant tolerates some residual loss. Storage and reuse are substitutes for the purpose of eliminating loss, because both reduce Λ , so a plant that has reached the threshold through reuse gains little from additional storage.

3.5 Payback and Financing

Let the recycling capacity be purchased at the start for $K = AF \cdot F_0 r^2$, where $AF = \sum_{t=1}^T (1 + i)^{-t}$ is the annuity factor over the horizon T at the discount rate i , so that the annualized capital cost equals $F_0 r^2$. The annual operating gain excludes the capital cost, $G = \Pi(r^*) - \Pi(0) + F_0 r^{*2}$, and

$$NPV = -K + \sum_{t=1}^T \frac{G}{(1 + i)^t}. \quad (8)$$

The payback period is the smallest t at which the cumulative discounted gain reaches K . Capital needs scale with r^2 , so high stress plants, which need higher reuse, face the largest upfront outlay in absolute terms. Where firms are credit constrained (Banerjee and Duflo, 2014), this outlay can delay adoption even when the payback is short.

3.6 Numerical Illustration

The numbers in this subsection are assumed for exposition and are not estimates from data. A plant has capacity $\bar{Q} = 10,000$ units per year, contribution margin $m = 30$ USD per unit before water costs, water need $w = 1.5 \text{ m}^3$ per unit, treatment operating cost $\rho = 0.35$ USD per m^3 , recycling capital parameter $F_0 = 120,000$ USD, and storage parameter $H_0 = 40,000$ USD. Three stress tiers differ in frequency, depth, and tariff, as shown in Table 1. The investment horizon is 10 years and the discount rate is 10%, so $AF = 6.145$.

Table 1. Assumed Stress Tiers for the Illustrative Plant

Parameter	Low	Moderate	High
Shortage frequency p	0.05	0.15	0.30
Shortage depth d (= threshold)	0.15	0.30	0.45
Tariff π (USD per m^3)	0.60	0.90	1.40
Shadow value m/w (USD per m^3)	20.0	20.0	20.0
Shadow value $\div$ tariff	33.3	22.2	14.3

Without management, the expected loss Λ is 0.75%, 4.5%, and 13.5% of capacity in the three tiers, which is 2,250, 13,500, and 40,500 USD per year. At full output the water bill would be 9,000, 13,500, and 21,000 USD. Because output falls in shortages, the realized bills are slightly lower (8,932, 12,892, and 18,165 USD). The expected shortage loss is therefore about a quarter of the bill in the low tier, roughly equal to it in the moderate tier, and 2.2 times the realized bill in the high tier. The shadow value of water is 14 to 33 times the tariff (Table 1). All of these ratios depend on the assumed margins and tariffs (Section 7). Figure 4 shows the cost stack before and after management.

The profit maximizing reuse shares are $r^* = 0.08$ (low), 0.27 (moderate), and 0.45 (high). In the high tier the optimum is at the resilience threshold, because condition (7) holds; in the other tiers it is interior

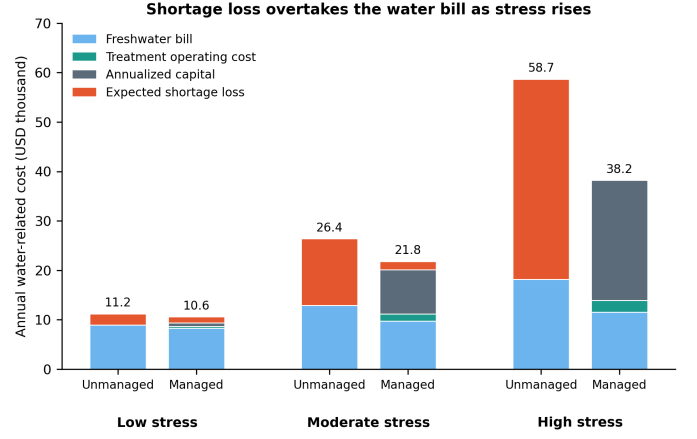


Figure 4. Annual water-related costs by stress tier, without management and at the optimal reuse share r^* . Components include freshwater, treatment, annualized capital, and expected shortage costs.

and lies below the threshold, so some residual loss is tolerated. Management raises annual profit from 288,818 to 289,425 USD (+608) in the low tier, from 273,608 to 278,200 USD (+4,593) in the moderate tier, and from 241,335 to 261,788 USD (+20,452, or 8.5%) in the high tier. Figure 5 shows the profit curves, and Figure 6 shows the payback, with upfront capital of 4,259, 55,155, and 149,313 USD in the three tiers, payback periods of 4.2, 5.5, and 4.3 years, and ten year net present values of 3,736, 28,220, and 125,672 USD.

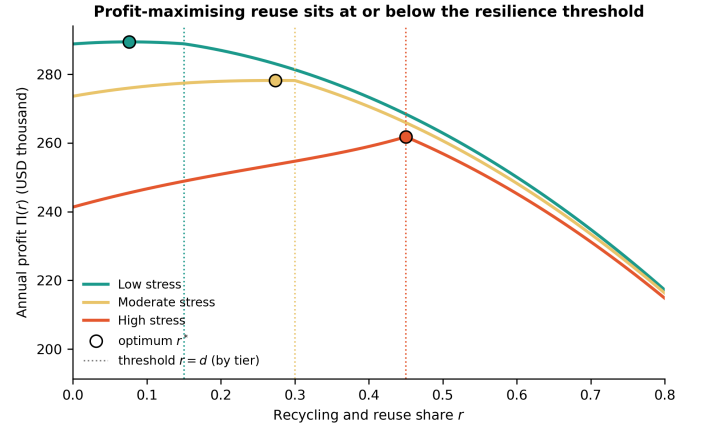


Figure 5. Annual profit versus reuse share across three stress tiers. Circles indicate optimal shares r^* , and dotted lines mark resilience thresholds $r = d$.

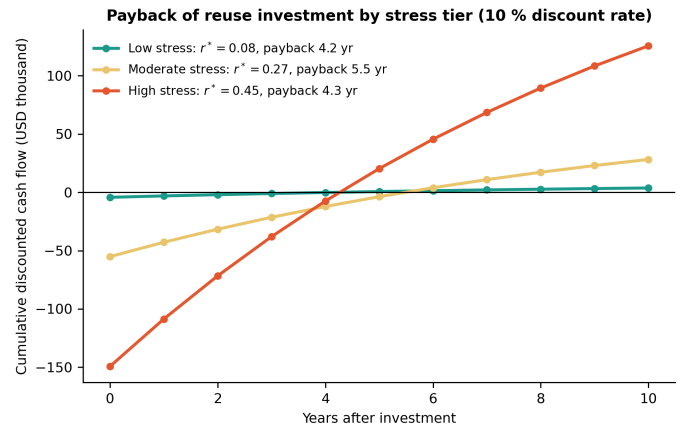


Figure 6. Cumulative discounted cash flow of reuse investment at the optimal share r^* over 10 years, using a 10% discount rate.

Two patterns stand out. The absolute return rises steeply with stress, from a few hundred USD per year to more than twenty thousand, while the payback period stays near four to five years. High stress plants therefore have the strongest case for investment and also the largest capital requirement, which is why financing matters. Second, strategies are substitutes. In the high tier, storage alone ($\beta = 0.4$) lowers

Λ from 13.5% to 8.1% and raises profit to 250,001 USD, reuse to the threshold removes the loss and gives 261,788 USD, and the combination of $r = 0.30$ with $\beta = 0.4$ gives $\Lambda = 3.9\%$ and 255,581 USD, which is lower than reuse alone because storage cost is spent on a loss that reuse has already largely removed.

3.7 Shared Sources and a Commons Externality

Many industrial clusters draw on one aquifer or river reach. Suppose n identical firms draw q each from a source with recharge R , so the drawdown index is $D = nq/R$. Water has value $vq - bq^2/2$ to each firm, and the cost of lifting or obtaining a cubic meter is $c_0 + c_1D$. A firm that chooses q privately takes into account its own effect on its own cost but ignores the effect on others, so the symmetric private equilibrium and the coordinated optimum are

$$q^p = \frac{v - c_0}{b + c_1(n+1)/R}, \quad q^s = \frac{v - c_0}{b + 2c_1n/R}. \quad (9)$$

For $n > 1$ the private level exceeds the coordinated one, and the gap grows with the number of firms because each additional firm raises the cost for all. The same logic is the standard commons problem (Hardin, 1968; Ostrom, 1990): private adaptation by each firm, such as sinking a deeper well, is individually sensible and collectively harmful. With assumed values $v = 12$, $b = 0.9$, $c_0 = 1$, $c_1 = 0.5$, and $R = 10$ in index units, total abstraction exceeds the coordinated level by 17% with 5 firms, 31% with 10 firms, and 49% with 20 firms, and the welfare loss relative to coordination is 9.6% with 10 firms and 23.7% with 20 firms (Figure 7). Reuse and storage reduce the demand on the shared source and so are the natural complements of coordination.

4. Measurement and Empirical Design

4.1 Research Design

The study is a structured secondary evidence synthesis combined with a theoretical model. The evidence boundary is 31 December 2022, and sources published from 1 January 2023 onward are excluded. Peer-reviewed articles, established reviews, and authoritative institutional reports are prioritized. Each source was coded by level (global or basin, local, economy-wide, firm or plant, conceptual) and by the channels it reports: physical scarcity, output or performance, cost or price, disruption or reliability, management or capability, and conceptual argument. No new plant dataset or causal estimate is claimed; the study provides a model and a design for later testing.

4.2 Water Stewardship Capability Index

The Water Stewardship Capability Index (WSCI) summarizes corporate water-resource management in four components that correspond to the third stage of Figure 1: measurement (MS), efficiency and reuse (ER), supply security (SS), and governance and disclosure (GD). Table 2 lists indicators. Each raw indicator is rescaled to $[1, 100]$, and the index is a weighted geometric mean,

$$WSCI_h = \prod_{j=1}^4 c_{jh}^{w_j}, \quad \sum_{j=1}^4 w_j = 1, \quad (10)$$

where c_{jh} is the rescaled score of component j for plant h . Geometric aggregation is chosen because the components are complements. Metering without reuse reveals losses but does not remove them, reuse without supply security leaves the plant exposed to outages, and none of them is sustained without governance. An arithmetic average would let a high score on one component offset a very low score on another, whereas the geometric mean falls sharply when any component is weak. Figure 8 shows three hypothetical firms with equal weights. Firm X scores 95 on three components and 5 on governance, giving an arithmetic score of 72.5 and a geometric score of 45.5; the balanced Firm Y scores 60 on both; and the metering-led Firm Z scores 60.0 and 57.9. The arithmetic index ranks X first and ties Y with Z, whereas the geometric index ranks Y first, Z second, and X last. Weights and aggregation should be reported with sensitivity checks. The WSCI describes capability and does not replace the outcome measures of productivity and shortage loss.

Table 2. WSCI Components and Example Indicators

Component	Example indicators
MS: measurement	Share of withdrawals and process uses sub-metered; leakage audits; water balance prepared
ER: efficiency and reuse	Water per unit of output; recycled share r ; effluent treatment and reuse capacity
SS: supply security	Storage days β ; number of independent sources; contingency plan tested
GD: governance	Named owner; water targets; board oversight; public disclosure of use and risk

4.3 Variables and Data

The main outcomes are realized total factor productivity, labor productivity, capacity utilization, and shortage days; the main exposures are the stress variables p and d and basin level indicators; and the main moderators are the WSCI, the reuse share r , and financing access. Water productivity, value added per cubic meter, is reported as a secondary outcome. Table 3 lists constructs and candidate sources.

4.4 Empirical Models for Future Testing

Productivity. Plant productivity is estimated from a production function with proxy methods that handle the endogeneity of inputs (Levinsohn and Petrin, 2003; Akerberg et al., 2015),

$$\ln Y_{it} = \beta_k \ln K_{it} + \beta_l \ln L_{it} + \beta_m \ln M_{it} + \omega_{it} + \varepsilon_{it}, \quad (11)$$

where ω_{it} is log productivity. Because capital and labor are committed, ω_{it} captures the wedge in (4); a variant that includes water as an input should be reported to show how much of the loss runs through reduced water use.

Stress and capability. The central regression is

$$\hat{\omega}_{it} = \alpha_0 + \alpha_1 S_{it} + \alpha_2 WSCI_{it} + \alpha_3 (S_{it} \times WSCI_{it}) + \alpha_4 X_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \quad (12)$$

with plant effects μ_i and time effects λ_t . Stress is expected to lower productivity ($\alpha_1 < 0$), and capability is expected to buffer it ($\alpha_3 > 0$).

Threshold. The kink in (2) can be tested with a piecewise specification,

$$\hat{\omega}_{it} = \gamma_0 + \gamma_1 \min\{r_{it}, d_{it}\} + \gamma_2 \max\{r_{it} - d_{it}, 0\} + \gamma_3 X_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \quad (13)$$

where $\gamma_1 > 0$ and γ_2 close to zero would indicate a resilience threshold.

Event study. Drought shocks, defined from basin level drought indicators, arrive at different times in different basins. The response of productivity is traced by an event study with relative-time coefficients δ_k , estimated separately for plants with high and low WSCI, using estimators that are robust to staggered timing and heterogeneous effects (Callaway and Sant'Anna, 2021; Sun and Abraham, 2021), since two way fixed effects can be biased in that setting (Goodman-Bacon, 2021). The expected pattern is a dip at the shock that is smaller and shorter for high capability plants (Figure 9). Placebo tests on lead coefficients and on sectors that do not use water should be reported.

Commons. Spillovers are tested by relating the groundwater level in a basin to the number of abstracting plants, $\ln D_{bt} = \kappa_0 + \kappa_1 \ln N_{bt} + \kappa_2 \text{Recharge}_{bt} + \mu_b + \lambda_t + \varepsilon_{bt}$, where $\kappa_1 > 0$ is the first test of the externality in (9).

4.5 Data for a Bangladesh Application

A Bangladesh application could focus on textile and garment wet processing, leather, and food processing. Candidate sources include a purpose built plant survey that records shortage frequency and depth, water sources, reuse, storage, and management practices; utility and tanker invoices; production and financial records; groundwater records held by public water agencies; and environmental compliance records for effluent treatment. Enterprise surveys that include questions about water supply could provide benchmarks. Availability of each source, sampling, consent, and confidentiality conditions must be confirmed before fieldwork.

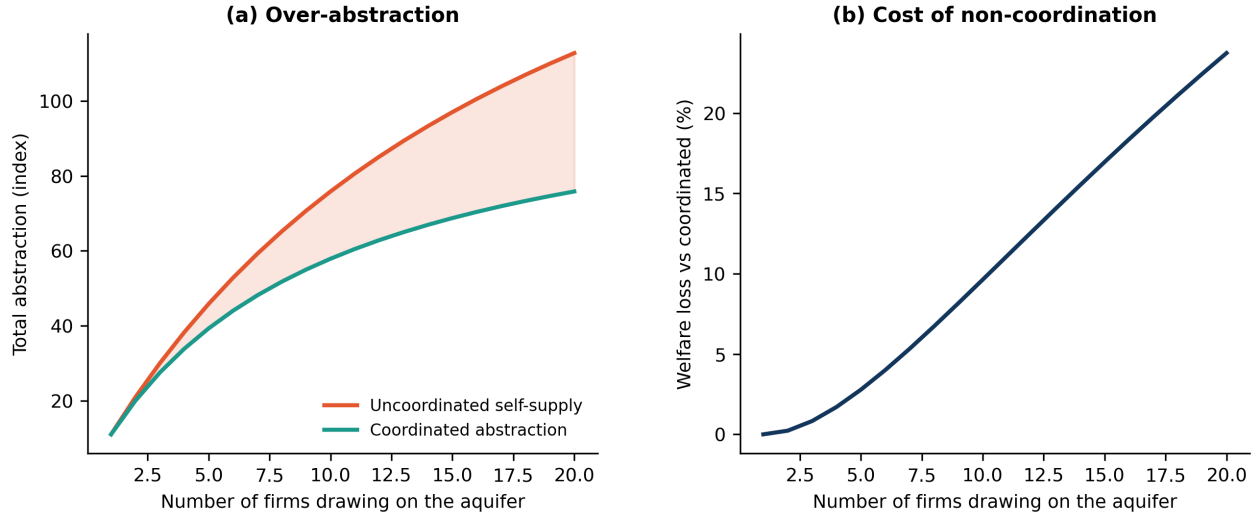


Figure 7. (a) total abstraction under uncoordinated self-supply and under coordination, and (b) the welfare loss from non-coordination. Parameters are assumed: $v = 12$, $b = 0.9$, $c_0 = 1$, $c_1 = 0.5$, $R = 10$.

Table 3. Constructs, Indicators, and Candidate Data for Plant Level Research

Construct	Symbol	Example indicators	Unit	Candidate data source
Productivity	ω	Estimated total factor productivity; value added per worker; capacity utilization	Log index; ratio	Plant accounts; production records
Shortage frequency and depth	p, d	Days or months below need; share of need unmet; supply interruptions	Share	Plant logs; utility records; enterprise surveys
Basin stress	S	Basin water stress indicator; drought index; groundwater level	Index; meters	Basin risk tools; hydrological records
Reuse share	r	Recycled water as share of process need	Share	Meters; effluent treatment records
Storage	β	Days of on-site storage relative to typical shortage length	Days; share	Plant survey
Capability	WSCI	Four component scores; geometric index	Score (1–100)	Plant survey; audit and certification records
Water price	π	Tariff, abstraction charge, tanker price	USD per m ³	Utility bills; invoices
Controls	X	Size, age, sector, ownership, capital intensity, financing access	Various	Survey; administrative data

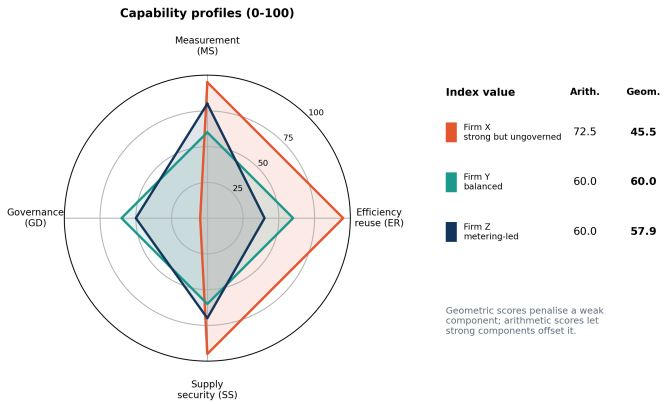


Figure 8. Capability profiles of three hypothetical firms on the four WSCI components.

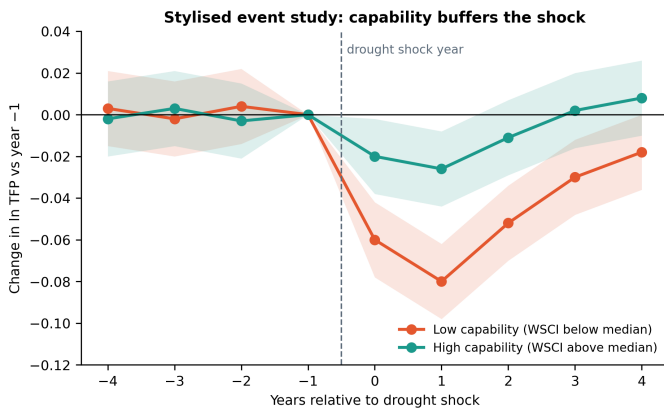


Figure 9. Stylised event study of log productivity around a drought shock for plants with low and high water stewardship capability.

4.6 Validation

The WSCI should be validated by expert review of content, confirmatory factor analysis of dimensions, tests of invariance across sectors and sizes, and reliability checks. The model should be validated by comparing predicted and observed shortage losses, by reporting results under alternative productivity estimators and alternative definitions of shortage, and by checking whether the estimated kink agrees with the threshold implied by plant level data.

5. Evidence Synthesis and Context

5.1 What the Pre 2023 Evidence Shows

Figure 10 classifies the reported findings of the reviewed studies by level and by channel, and four patterns emerge. First, scarcity is documented extensively at global and basin scale, with a growing emphasis on monthly variability and groundwater (Mekonnen and Hoekstra, 2016; Rodell et al., 2018; Kummu et al., 2016). Second, aggregate studies link rainfall variability and water security to output and growth (Brown and Lall, 2006; Damania et al., 2017; Berrittella et al., 2007). Third, the clearest plant level evidence on reliability concerns electricity rather than water (Allcott et al., 2016; Fisher-Vanden et al., 2015), with a synthesis that includes water outages (Rentschler et al., 2019). Fourth, the management literature links environmental performance to financial outcomes without isolating water (Klassen and McLaughlin, 1996; Russo and Fouts, 1997; Konar and Cohen, 2001). Within the sources reviewed here, direct plant level evidence that ties corporate water management to productivity in emerging economies is thin. The pattern of blanks in Figure 10 is therefore informative: the cells where a firm level study would report scarcity and management together are empty.

5.2 Sector Exposure

Vulnerability to scarcity varies across sectors, because water intensity, location, and capability differ. Define an illustrative vulnerability score

$$V_s = I_s \times E_s \times (1 - c), \quad (14)$$

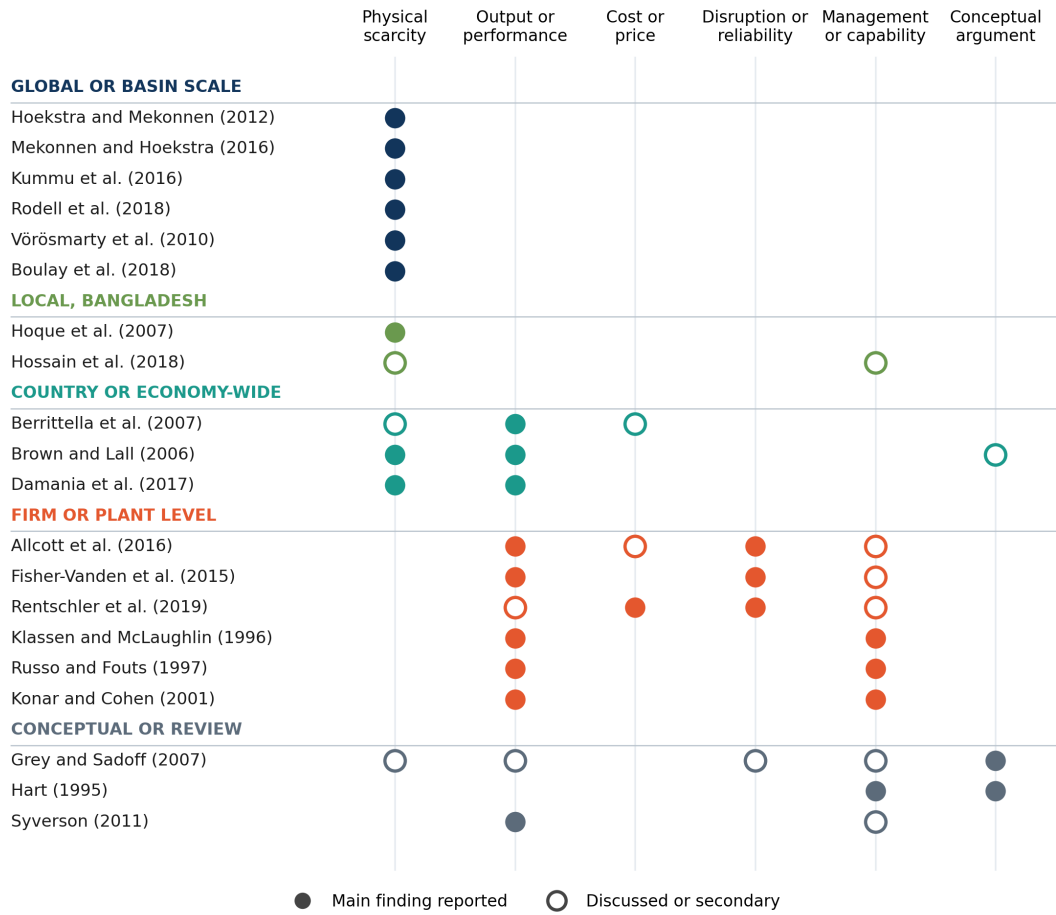


Figure 10. Findings reported in selected pre 2023 studies, by level of analysis and channel.

where I_s is a water intensity index, E_s is the share of capacity in stressed basins, and $c = \text{WSCl}/100$ is capability. Figure 11 uses assumed values for ten sectors. Textile wet processing and leather tanning rank highest at low capability ($V = 0.42$ and 0.34 at $c = 0.30$), and electronics assembly ranks lowest (0.07). Raising capability from 0.30 to 0.70 lowers every score by 57% , so rankings are unchanged, but the absolute gain is largest where exposure is highest: 0.24 for textile wet processing against 0.04 for electronics assembly. The implication is that capability programs return the most in the sectors with the greatest intensity and exposure, and that a uniform program wastes effort in sectors with little water at risk. The values are assumed and should be replaced with measured intensities and exposures.

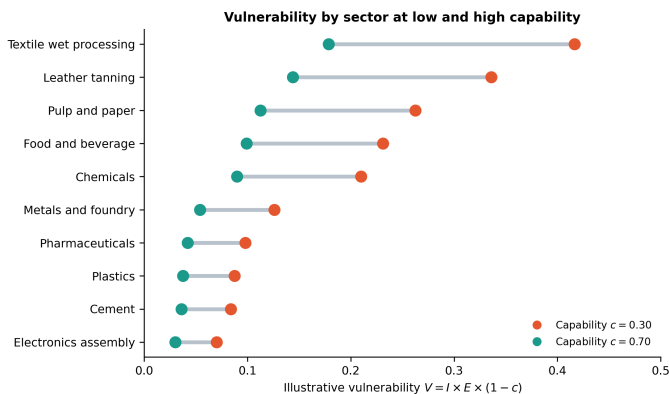


Figure 11. Vulnerability by sector at low ($c = 0.30$) and high ($c = 0.70$) capability, using assumed intensity and exposure values.

5.3 Country and Sector Context

The evidence cited is drawn mainly from global assessments, the United States, India, and China, and should not be transferred to Bangladesh or other emerging economies without testing. Differences in tariffs, groundwater governance, effluent regulation, the share of firms with captive water sources, and access to finance mean that thresholds and payback periods will differ. In Bangladesh, textile wet processing com-

bines high water intensity with a concentration of plants near stressed urban aquifers and rivers, which suggests a high exposure score, but this must be measured at the plant.

5.4 Research Propositions

The synthesis and the model support five propositions, stated with their tests in Table 4.

6. Discussion

The central implication is that the economic case for corporate water management rests on reliability. A manager who compares the cost of a recycling plant with the water bill will often conclude that it does not pay, since the bill is small. The comparison that matters is with the expected shortage loss, which in the high stress case of the illustration is more than twice the bill and which grows with the margin earned per unit of water. The case is weakest where stress is low: reuse yields a few hundred USD per year at low stress, and the optimum is an interior choice below the resilience threshold. This explains why firms in water-rich locations do not invest and why the same practices are urgent elsewhere. It also explains why measurement matters. Without logs of shortage frequency and depth, a firm cannot compute Λ and will treat reliability as a cost of doing business.

Two further points follow from the model. The resilience threshold gives a concrete target: a plant that recycles at least the share of its water that it loses in a typical shortage is insulated from that shortage. This target is not a universal efficiency goal, and exceeding it is justified only by the water bill. Second, the complementarity built into the WSCI means that capability should be developed in balance. A firm that invests heavily in metering and reuse but leaves governance weak is likely to have large dashboards and little change in outcomes.

6.1 Managerial Implications

Manufacturers should log shortage frequency and depth, compute the expected loss and the shadow value of water, and compare investment with the loss rather than with the bill. They should aim for the resilience threshold through reuse before adding storage, because the two are sub-

Table 4. Research Propositions and Their Empirical Tests

No.	Proposition	Test	Expected sign	Key data
P1	Water stress lowers realized plant productivity, and the loss rises with shortage frequency and depth and is larger in water intensive sectors	Eq. (12): α_1	—	Plant panel; shortage logs
P2	Water stewardship capability buffers the productivity loss from stress, and balanced capability matters more than any single component	Eq. (12): α_3 ; geometric vs arithmetic WSCI	+	WSCI components
P3	Productivity gains from reuse are concentrated below the resilience threshold $r = d$ and are small above it	Eq. (13): γ_1 vs γ_2	$\gamma_1 > \gamma_2 \approx 0$	Reuse; shortage depth
P4	Returns to water investment rise with stress, but upfront capital and financing constraints delay adoption among high stress plants	Adoption timing and payback; interaction with credit access	Varies	Capex; financing access
P5	Where plants share a source, private self-supply raises aggregate abstraction and shortage risk for neighbors	$\ln D_{br}$ on $\ln N_{br}$; κ_1	+	Groundwater records; plant counts

stitutes for loss reduction. They should develop capability components together, appoint an owner for water performance, and coordinate with neighbors on shared sources. Lenders can assess projects using the avoided loss, which is often larger than the water bill, and can provide capital for high stress sites where upfront needs are largest. Table 5 links actions to mechanisms and indicators.

6.2 Policy Implications

Policy makers influence the problem through price, supply, rules, and information. Tariffs that reflect scarcity and cost recovery raise the incentive for reuse, but they act on the bill, which is the smaller part of the cost, so reliability programs and information are complements to pricing. Clusters sharing a source can benefit from abstraction rules and monitoring that internalize the commons externality (Ostrom, 1990), from shared treatment facilities that make reuse affordable for small firms, and from disclosure standards that make water risk visible to lenders. Because the largest capital needs fall on high stress plants, targeted credit or blended finance can address financing constraints. Programs should be evaluated using productivity and shortage indicators, not only adoption counts.

6.3 Implications for Bangladesh and Emerging Economies

Industrial output in emerging economies is growing while urban aquifers decline and effluent rules tighten (Hoque et al., 2007; Hossain et al., 2018). Water-intensive export sectors are exposed to buyer expectations on water as well as to physical risk. A Bangladesh study should measure the three quantities that the model identifies as decisive: how often and how deeply plants are short of water, how much of the process water is reused, and the margin earned per unit of water. It should also separate plants that depend on public supply from those with their own wells, because the commons externality operates through the latter.

7. Limitations and Future Research

The study has several limitations. First, it is a structured evidence synthesis and a theoretical model, not a causal plant level study, and it is not a systematic review with a registered protocol. Second, direct evidence on corporate water management and productivity in emerging economies is thin in the sources reviewed, so the model relies on analogies to electricity and to the management literature. Third, the model simplifies shortages into frequency and depth, treats capacity as fixed, ignores demand response and price pass-through, and uses a reduced form cost of reuse; real plants can ration water across lines, shift schedules, or buy tanker water at a premium, which would lower the loss. Fourth, all numbers in Sections 3–5 are assumed for exposition. The ratios of loss to bill and the payback periods depend on assumed margins, tariffs, and costs, and they are not estimates. Fifth, the evidence classification in Figure 10 reports directions and does not weight studies by quality. Table 6 pairs limitations with responses.

Priority questions for future work include how large p and d are in practice for different sectors and basins, whether the kink at the resilience threshold appears in data, how much price pass-through and rationing reduce the loss, how effective coordination arrangements are in clusters, and how reuse affects energy use and effluent compliance.

8. Conclusion

This study examines the economic consequences of corporate water-resource management for industrial productivity under conditions of water scarcity. Evidence available before 2023 indicates that scarcity

is widespread and often seasonal, that water-supply variability is associated with lower output at the aggregate level, and that unreliable utilities impose substantial operating costs on industrial plants. Nevertheless, direct plant-level evidence on the relationship between corporate water-management practices and productivity in emerging economies remains limited. The findings and implications of this study should therefore be interpreted as conditional on the assumptions of the proposed model rather than as definitive empirical estimates.

The model provides a compact economic explanation of how water scarcity affects industrial production. Its central mechanism is reliability rather than price alone. When water becomes unavailable, committed capital, production equipment, and labor may remain idle, reducing the productive use of resources that firms have already paid for. The expected share of capacity lost is represented by

$$\Lambda = p(1 - \beta) \frac{(d - r)^+}{1 - r},$$

where p denotes shortage frequency, β represents the share of capacity protected through available buffers, d measures shortage depth, and r denotes the reuse share. The positive-part operator captures the fact that shortages exceeding the effective protection provided by reuse generate production losses. This formulation highlights why two plants facing similar water prices may experience substantially different economic outcomes: their exposure depends on the frequency and severity of shortages and their ability to maintain operations during disruptions.

The distinction between the market price of water and its economic value to production is particularly important. The shadow value of water, m/w , can substantially exceed the price paid to utilities when water unavailability constrains production. In such circumstances, investments in recycling, storage, and alternative supply can generate benefits beyond direct reductions in freshwater purchases. These benefits include avoided production interruptions, improved utilization of labor and machinery, more predictable delivery schedules, and reduced exposure to emergency procurement. Consequently, evaluating water-management investments exclusively through water-bill savings may underestimate their contribution to operational performance.

Corporate water management can reduce expected production losses by increasing the reuse share and improving the plant's capacity to withstand supply disruptions. The resilience threshold, $r \geq d$, identifies the point at which reuse is sufficient to eliminate modeled shortage-related losses under the stated assumptions. However, achieving this threshold does not necessarily maximize profit. The profit-maximizing reuse share, r^* , reflects a trade-off between the marginal benefits of additional reuse and its associated treatment, operating, and capital costs. Where scarcity is relatively mild, the incremental benefits of further investment may not justify the additional expenditure. Under more severe water stress, the avoided losses may be substantially greater, making higher levels of reuse economically attractive. The optimal decision therefore depends on local scarcity conditions, production requirements, technology costs, and the firm's financial capacity.

The illustrative investment analysis further suggests that the economic attractiveness of reuse varies across stress tiers. Under the assumed parameters, payback periods are approximately four to five years, indicating that some reuse investments may be financially viable over a medium-term planning horizon. These results should not be interpreted as universal benchmarks because actual returns depend on water tariffs, shortage probabilities, treatment efficiency, energy prices, financing costs, equipment lifetimes, and the extent of production losses avoided. In addition, the plants facing the greatest scarcity may require

Table 5. Implications for Actors: Actions, Targeted Mechanisms, and Monitoring Indicators

Actor	Recommended action	Mechanism targeted	Indicator to monitor
Manufacturers	Log shortage frequency and depth; target the resilience threshold through reuse; assign an owner	Measurement; reuse; governance	$\hat{p}$, $\hat{d}$, Λ ; reuse share r
Lenders and investors	Underwrite avoided shortage loss; finance high stress sites; require disclosure	Financing; governance	Avoided loss per USD invested; disclosure coverage
Utilities and regulators	Reliability standards; scarcity reflecting tariffs; abstraction monitoring	Supply security	Interruption days; groundwater level
Industrial cluster managers	Shared treatment and storage; coordinated abstraction	Reuse; commons	Cluster abstraction; reuse share
Statistical agencies	Publish plant level water use and reliability data that can be linked to productivity	Measurement	Linked data availability
Researchers	Report shortage frequency, depth, and productivity together, with sensitivity of the WSCI to aggregation	Measurement	Λ ; α_3 ; γ_1 , γ_2

Table 6. Limitations and Proposed Responses

Limitation	Proposed response
No new causal estimate	Test P1–P5 with plant panels, event studies, and instruments
Thin direct water evidence	Collect plant level logs of shortage, reuse, and output
Simplified shortage process	Extend to rationing across lines, rescheduling, and tanker purchases
Assumed parameters	Replace with measured margins, tariffs, and costs
Shared-source data gaps	Link plant locations to groundwater and basin records
Index not validated	Validate WSCI with factor analysis and observed outcomes

the largest initial investments precisely because they need more extensive treatment, storage, or supply infrastructure. This creates a potential financing constraint: the firms with the greatest potential gains may not always have the resources necessary to capture them.

The framework also clarifies the relationship between different adaptation strategies. Reuse and storage can act as substitutes in protecting production reliability because both can reduce exposure to shortages, although their relative effectiveness depends on the timing and duration of disruptions. Reuse can provide a continuing alternative source of process water, whereas storage can bridge temporary interruptions when sufficient water has been collected in advance. Their effectiveness may therefore differ across industries and operating environments. By contrast, the components of organizational capability may be complementary: weaknesses in monitoring, planning, maintenance, or operational coordination can limit the benefits of otherwise effective technical investments. This complementarity provides an economic rationale for constructing the Water Security Capability Index (WSCI) using geometric aggregation, which penalizes unbalanced capability profiles more strongly than a simple arithmetic average.

These relationships have practical implications for industrial managers. Water-risk assessments should incorporate not only average annual consumption and expenditure but also shortage frequency, shortage depth, disruption duration, and the consequences of interrupted production. Firms should identify critical processes, estimate the output at risk during water interruptions, and compare the lifecycle costs of reuse, storage, alternative supply, and operational adjustments. Investment decisions should also account for maintenance requirements, energy consumption, treatment performance, and the quality standards necessary for reusing water in different production processes. A phased investment strategy may be appropriate where capital is constrained, beginning with measures that provide the greatest reduction in expected losses relative to their cost.

The implications extend beyond individual plants. When firms draw from a shared water source, private adaptation may improve the reliability of an individual facility while increasing aggregate abstraction. For example, independent investment in self-supply infrastructure can intensify competition for groundwater or other shared resources if extraction is not effectively governed. As a result, private resilience does not automatically translate into collective water security. Firm-level investments should therefore be accompanied by source-level monitoring, transparent allocation rules, abstraction controls, and coordination among industrial users and relevant public authorities. Where appropriate, shared treatment facilities, water-reuse networks, and collective storage infrastructure may help reduce duplication and distribute investment costs across participating firms.

Policy makers can use this framework to distinguish between measures that lower the cost of water and those that improve its reliability. Appropriate interventions may include incentives for efficient

reuse technologies, support for industrial water audits, improved utility infrastructure, access to financing for capital-intensive upgrades, and stronger monitoring of shared water resources. However, subsidies should be designed carefully to avoid encouraging excessive consumption or shifting environmental costs to other users. Policies that reward verified reductions in freshwater abstraction and improvements in production resilience may provide a better alignment between private incentives and broader resource-management objectives.

Several limitations qualify these conclusions. First, the model is illustrative and depends on assumed parameter values rather than estimates derived from a representative plant-level dataset. The resulting optimal reuse shares, expected losses, and payback periods are therefore scenario outcomes, not causal estimates or forecasts for a specific industry. Second, the model simplifies differences in water quality, treatment technologies, production processes, and the timing of shortages. In practice, reuse may be limited by contamination, regulatory requirements, or process-specific quality standards. Third, firms may face uncertainty about future water availability, technology costs, and regulation, making investment decisions dynamic rather than static. Finally, firms that adopt advanced water-management practices may differ systematically from those that do not, so observed productivity differences cannot automatically be attributed to management capability.

Future empirical research should test the framework using plant-level panel data that record shortage frequency and depth, freshwater withdrawals, reuse shares, storage capacity, water-management expenditure, output, and relevant capability measures. Such data would help establish whether the predicted resilience threshold corresponds to a measurable change in production losses and whether the relationship between reuse and performance varies systematically across industries and scarcity conditions. Researchers should also investigate heterogeneity by plant size, capital intensity, export orientation, water dependence, and access to finance. These differences may help explain why similar water-management investments generate different returns across firms.

Identification remains a central challenge. Droughts and other plausibly exogenous water-supply shocks could provide opportunities to examine how plants with different pre-existing capabilities respond to disruptions. Event-study designs and other robust panel estimators could help separate the effects of water-management practices from selection into adoption, provided that their identifying assumptions are carefully assessed. Additional analysis could evaluate whether the marginal productivity benefit of reuse declines after the resilience threshold, whether reuse and storage are substitutes in practice, and whether complementary organizational capabilities improve the returns to technical investment. Linking plant-level outcomes to watershed-level abstraction and allocation data would further allow researchers to assess whether private adaptation generates net social benefits or transfers scarcity costs to other users.

Overall, the study provides a conditional framework for understanding the economic consequences of industrial water scarcity and the potential value of corporate water-resource management. Its central message is that water risk cannot be assessed adequately through prices or annual consumption alone. The frequency and severity of interruptions, the productive capacity exposed to those interruptions, and the firm's ability to maintain operations jointly determine the economic consequences of scarcity. For managers, the relevant question is which combination of reuse, storage, and organizational capability provides reliable production at an acceptable lifecycle cost. For policy makers,

the challenge is to support industrial resilience without undermining the sustainability of shared water resources. Answering these questions with plant-level evidence will be essential for determining when corporate water-management investments improve productivity, when they provide insufficient protection, and when coordinated action is necessary to achieve both economic and environmental objectives.

Data Availability

No new primary dataset was collected for this study. All numerical values in the model illustrations are assumed. The code used to produce the figures and the numerical illustration (`make_figures.py`) is available from the authors on request.

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