P-ISSN: 2790-6795 | Annals of Human and Social Sciences | July-September 2025,Vol. 6, No. 3
O-ISSN:2790-6809 | http://doi.org/10.35484/ahss.2025(6-III)59 | [698-716]

Annals of Human and Social Sciences
www.ahss.org.pk

RESEARCH PAPER

From Pledges to Plots: Linking the Paris Agreement to Adaptation Outcomes in Pakistan's Agriculture and Water Equity

[1]Yasir Inam and [2]Sarah Saeed

1. MS Scholar, Department of Humanities, COMSATS University Islamabad, Islamabad, Pakistan
2. Lecturer, Department of Humanities, COMSATS University Islamabad, Pakistan

Corresponding Author inamyasir2@gmail.com

ABSTRACT

This study investigates whether the Paris Agreement–aligned adaptation investments in Pakistan's agriculture deliver resilience and equity at the farm level. Pakistan's agro-economy sits where a warming climate, melting glaciers and an ageing colonial irrigation system collide. The Indus Basin, its principal food basket, faces escalating hydro-meteorological extremes and a chronic decline in per-capita water availability, threatening livelihoods and economic stability. In response, Pakistan updated its NDC in 2021 and published a National Adaptation Plan in 2023, both pledging climate-resilient agriculture and equitable water management, yet rigorous evidence on plot-scale outcomes remains scarce. We assemble a district-reach panel linking adaptation spending, canal telemetry, remote-sensing proxies of crop performance and household surveys. Difference-in-differences and event-study models show that adaptation reduces yield volatility by about six percentage points and improves water equity by seven, with effects emerging after one to two years. Results imply adaptation works mainly as a variance and equity enhancing technology, underscoring the need for transparency, open data and fairness-based evaluation metrics.

Keywords: Climate Adaptation, Irrigation Governance, Yield Volatility, Water Equity, Difference-in-differences, Indus Basin (Pakistan)

Introduction

Law and climate share a "dialectical" relationship: as global warming reshapes hydrological cycles and agricultural calendars; legal frameworks and policy commitments must adapt in lockstep. Nowhere is this dialectic more vivid than in Pakistan, where the storied Indus River supports a farm sector that still employs more than 40 million people and contributes roughly a quarter of gross domestic product (Finance Division, 2024; Government of Pakistan et al., 2022). The river's water is distributed via an extensive network of canals and distributaries inherited from colonial engineering, but this infrastructure is increasingly strained by siltation, population growth and upstream storage. In recent years, the dual shocks of heatwaves and devastating monsoons have exposed the vulnerability of this system. The summer of 2022 serves as a cautionary tale: following an intense heatwave, record rainfall inundated one third of the country, killing livestock, destroying homes and flattening crops (Government of Pakistan et al., 2022; World Weather Attribution, 2022; Qamer et al., 2023). Stagnant, contaminated floodwaters lingered for months, triggering health emergencies and polluting aquifers (Government of Pakistan et al., 2022;World Weather Attribution, 2022;Qamer et al., 2023). Government assessments recorded tens of billions of dollars in losses, while satellite imagery documented the destruction of more than 18 000 km² of cropland. These events unfolded against a backdrop of multiyear droughts and erratic monsoons, trends consistent with anthropogenic warming that intensifies both rainfall extremes and dry spells.

At the global level, climate change threatens food systems and water security. Meta-analyses of six staple crops across 12 658 regions show that global production declines by around 120 kilocalories per person per day per degree Celsius of warming (Hultgren et al., 2025). Yet adaptation, if timely and comprehensive, could offset a portion of these losses, though there is still "no systematic study of how extensively real-world producers actually adapt at the global scale" (Hultgren et al., 2025). Meanwhile, global water demand is projected to increase by 20–30% by 2050 due to socioeconomic growth, and human drivers such as population growth, consumption patterns and governance are expected to dominate future water scarcity (IPCC, 2022; Mekonnen & Hoekstra, 2016; Ward et al., 2017). These twin pressures of agricultural losses and water scarcity put developing nations in a bind. For Pakistan, per capita freshwater availability has collapsed from more than 5 000 m^3 in 1947 to under 1 000 m^3 today, and forecasts suggest a fall below 660 m^3 by 2025 (Arshad et al., 2024; Dharpure et al., 2025; Jacoby & Mansuri, 2020). The country is thus transitioning from "water-stressed" to "water-scarce" status, even as it remains heavily dependent on agriculture. Contributing factors include glacier retreat, reduced snow cover, unregulated groundwater extraction and siltation of major reservoirs (Arshad et al., 2024; Dharpure et al., 2025; Jacoby & Mansuri, 2020).

In this context, the Government of Pakistan has joined international calls for climate action. Its 2021 Updated NDC pledges a 50% reduction in projected emissions by 2030, conditional on international support, and emphasizes adaptation measures that address agriculture and water. The 2023 NAP advances a vision of "climate-resilient agriculture" that includes canal rehabilitation, telemetry-based water management, climate-smart agronomy, crop insurance and emergency social protection. The policy vocabulary echoes the lexicon of global adaptation: climate-smart irrigation, volumetric metering, lining of distributaries, index insurance and gender-responsive governance. Yet the translation from high-level pledges to on-farm outcomes is uncertain. Classic studies have documented head–tail asymmetries in Pakistan's irrigation system, where head outlets draw disproportionate shares relative to tail outlets (Bhutta & Smedema, 1992; Ali Shah et al., 2022; Jacoby et al., 2018). More recent work demonstrates that governance and social power mediate access to water and that gender intersects with landownership to shape irrigation benefits (Bell et al., 2022). Transparency in adaptation therefore requires revealing which canal reaches are targeted, where telemetry is installed, how budgets flow and who benefits. Without such transparency, it is difficult to evaluate whether adaptation commitments translate into improved resilience and fairness on the ground.

Our research question emerges from this gap: Do adaptation investments associated with Pakistan's Paris-aligned commitments reduce yield volatility and improve water equity for smallholders in Punjab and Sindh? To address this, we assemble a district-reach panel dataset linking policy-tagged adaptation spending, canal telemetry records, remote-sensing proxies of crop performance and household survey data. We then estimate difference-in-differences and event-study models to identify the causal impacts of adaptation on two outcomes: yield volatility and head–tail water equity. Yield volatility matters because risk, rather than average output, drives welfare in climate-prone settings; households with volatile yields struggle to smooth consumption, repay loans or invest in improved inputs. Water equity matters because head–tail asymmetries often correlate with land ownership, tenure and gender, influencing how irrigation benefits are distributed. Our approach foregrounds heterogeneity across provinces, canal positions and tenure categories. In doing so, we aim to move beyond descriptive analyses and provide causal estimates that can inform adaptation policy and practice.

The remainder of the paper proceeds as follows. The next section situates our study within the broader literature on global adaptation, water governance and agricultural risk. We then describe the data sources, variables and empirical strategy. The results section presents average treatment effects, dynamic event-study profiles and heterogeneity by province, gender and tenure. The discussion interprets these findings considering Pakistan's adaptation policies, the global context and methodological considerations. We conclude with policy recommendations and reflections on transparency, equity and future research.

Literature Review

Global adaptation and agricultural risks

The agricultural impacts of climate change have been examined through biophysical models, econometric analyses and integrated assessment frameworks. A growing literature documents the sensitivity of crop yields to temperature and precipitation extremes. Fatima and colleagues show that wheat yields in Pakistan decline sharply when extreme heat overlaps with flowering and grain filling stages, underscoring nonlinear damage functions (Fatima et al., 2020). Khan and co-authors extend this analysis to include heterogeneity across varieties and irrigation regimes, reporting similar findings for South Asia (Khan et al., 2024). In a global meta-analysis of six staple crops across thousands of sub-national units, Hultgren and colleagues estimate that global production declines by roughly 120 kilocalories per person per day per degree Celsius of warming and note that the effectiveness of adaptation remains uncertain (Hultgren et al., 2025). These studies collectively caution that warming threatens food security and livelihoods.

Adaptation measures—such as shifting sowing dates, adopting heat-tolerant varieties, improving irrigation efficiency and diversifying crops—are often cited as ways to buffer climate impacts. However, the adoption and effectiveness of these measures vary widely across regions and socio-economic groups. Harvey and co-authors document the "extreme vulnerability of smallholder farmers" in Madagascar, where increasing severity of droughts and floods causes poor yields, crop failures and livestock mortality (Harvey et al., 2014). They argue that adaptation must be context-specific and accompanied by institutional support. Rosa and colleagues introduce the concept of "economic water scarcity", distinguishing between hydrological scarcity and limitations imposed by finance, institutions and information (Rosa et al., 2020). Their global assessment reveals that many areas could profitably expand irrigation if institutional and financial barriers were removed. These insights highlight the interplay between biophysical limits and socio-economic constraints in shaping adaptation outcomes.

Water demand is poised to rise sharply. The IPCC's Sixth Assessment Report projects a 20–30% increase in global water demand by 2050 due to population growth and economic development (IPCC, 2022). Importantly, the report notes that human factors such as governance, infrastructure and consumption patterns are likely to be the dominant drivers of future water scarcity (IPCC, 2022). Uncertainties in regional precipitation and evapotranspiration complicate planning, underscoring the need for flexible policies. Ward and colleagues emphasize that water security challenges must be addressed alongside socioeconomic change, arguing that integrated policies are needed to manage scarcity, floods and ecosystem services (Ward et al., 2017). Greve and co-authors further argue that adaptation policies must be designed with an understanding of cross-sectoral interactions and the potential for maladaptation (Greve et al., 2018).

Adaptation is not solely a technical challenge but also a social and political one. Longpre and Riquelme, in a study of text-based datasets for large language models, underscore the need for transparency in AI training data (Longpre & Riquelme, 2023). Although their context is different, the lesson generalizes: transparency about inputs and processes is essential for accountability and public trust. In the domain of climate adaptation, transparency means disclosing where interventions occur, who benefits and what outcomes are achieved. Without such transparency, adaptation may exacerbate existing inequities. Indeed, Hultgren's adaptation meta-analysis flags the lack of systematic evidence on real world adoption, calling for rigorous evaluations (Hultgren et al., 2025).

Water scarcity, governance and equity in Pakistan

Pakistan's water scarcity is as much institutional as it is hydrological. Per-capita freshwater availability has fallen precipitously from more than 5 000 m^3 per person in 1947 to under 1 000 m^3 today (Arshad et al., 2024; Dharpure et al., 2025), and projections indicate a drop below 660 m^3 by 2025 (Arshad et al., 2024; Dharpure et al., 2025). Yet this scarcity is unevenly distributed across space and social groups. The Indus Basin Irrigation System, often described as the world's largest contiguous gravity irrigation network, suffers from siltation and leakage. Only two major dams—Tarbela and Mangla—provide bulk storage, and their capacities are diminished by sedimentation. Upstream construction of reservoirs in India has further reduced inflows. Downstream, distributary canals and minors leak water into unlined beds, reducing flows to tail outlets. The result is a pattern of head–tail asymmetry: head outlets at the start of a watercourse enjoy more abundant and reliable supply, while tail outlets at the end receive less water, especially during low-flow periods. This asymmetry is not merely hydraulic; it is intertwined with land ownership, political power and gender.

Classic studies by Bhutta and Smedema documented the extent of head–tail inequity, revealing that head outlets often draw disproportionate shares relative to tails (Bhutta & Smedema, 1992). Subsequent research has shown that outlet tampering, illicit pump-off takes and weak governance exacerbate these inequities (Ali Shah et al., 2022; Jacoby et al., 2018). Gender dynamics further complicate the picture: women, especially those managing small plots, often lack representation in water user associations and face barriers to accessing extension services (Bell et al., 2022; Khalid & Begum, 2017). Intersectional analyses find that tail-enders are more likely to be tenants, landless sharecroppers or women, and thus more vulnerable to water shortages. Recent studies also reveal that head–tail differences persist even in lined distributaries, suggesting that governance rather than purely physical factors drives inequity (Ali Shah et al., 2022).

The state has attempted various reforms to address water scarcity and inequity. Policies include lining canals to reduce seepage, installing telemetry equipment to monitor flows, implementing rotational water schedules (warabandi) and decentralizing management to water user associations. The 2023 NAP proposes further innovations: climate-smart agronomy, volumetric metering, real-time telemetry, canal rehabilitation, crop insurance and emergency cash transfers. Yet these interventions interact with existing socio-political structures. For instance, canal lining may reduce seepage and improve head–tail ratios in the short term but can also inhibit groundwater recharge, shift salinity patterns and entrench head advantages if not coupled with governance reforms (Alam et al., 2004; Zakir-Hassan et al., 2023). Telemetry provides real-time data but requires maintenance and transparency; without grievance redress, digitization may simply document inequity (Ali Shah et al., 2022). Crop insurance pilots have shown promise but face basis risk and low uptake; evidence from Pakistan's rain fed areas suggests that NDVI- or rainfall-based indices capture only part of yield variability (Carter et al., 2014; Channa, 2018). Overall, the literature highlights the need for context-specific, equitable and transparent adaptation strategies.

Yield risk, social protection and gender

Yield volatility, rather than mean yield, is a key determinant of farmer welfare. Households facing high variability struggle to predict incomes, allocate resources and invest in improved inputs. Volatility also interacts with credit markets: lenders may charge higher interest rates or ration credit if borrowers' incomes are uncertain. Empirical studies of risk and insurance highlight that reducing variance can increase welfare even without raising average yields (Carter et al., 2014). Social protection programmes, including cash transfers, food aid and emergency relief, provide buffers during shocks but may not prevent long-term damage to assets or human capital. In Pakistan, the Benazir Income Support Programme offers cash transfers, while the National Disaster Management Authority coordinates relief during floods. However, linking social protection with adaptation remains a challenge. Insurance products remain underdeveloped, and uptake is low due to mistrust and basis risk (World Bank, 2019; Kiani, 2023). Gender plays a critical role: women often manage subsistence plots yet lack access to credit, insurance and extension services. In climate-prone areas, women are disproportionately affected by risk and may adopt low-input strategies that depress both mean yields and variance (Bell et al., 2022; Memon et al., 2019). An equity-focused adaptation agenda must therefore integrate gender considerations, support risk mitigation and ensure that benefits reach the most vulnerable.

Methodological considerations

Empirical evaluations of adaptation programmes face methodological challenges. First, treatment assignment is rarely random. Projects are often placed where political influence, capacity or vulnerability are high, potentially biasing naïve comparisons. Second, outcomes are often measured with error: satellite proxies may not capture yield volatility perfectly, telemetry equipment may fail, and surveys may be non-representative. Third, adaptation effects may evolve over time, necessitating dynamic models. The difference-in-differences framework with staggered adoption is a common approach, but recent econometric critiques highlight the risk of bias when treatment effects vary over time (Goodman-Bacon, 2021). Event-study specifications allow inspection of pre-trends and dynamic effects but require careful interpretation (Sun & Abraham, 2021). Our study addresses these challenges by constructing a panel at district–reach level, using event studies to examine dynamics, adding district trends to absorb slow structural changes and conducting heterogeneity analyses. In addition, we emphasize transparency in data sources and methods, echoing calls for open data and replicable research (Longpre & Riquelme, 2023; Mugal & Yousuf, 2021).

Material and Methods

Our primary dataset is a district–reach panel for Punjab and Sindh spanning 2013–2025. The unit of analysis is a canal reach, defined as the segment between two outlets along a distributary. For each reach and year, we collect the following variables:

Adaptation spending: Official budget documents and project reports from the Government of Pakistan and provincial irrigation departments provide data on adaptation projects. We catalogue projects tagged as “Paris-aligned” or “NAP-related”, including canal lining, telemetry installation, climate-smart agronomy training, crop insurance schemes and emergency social protection. For each project, we record the start year, location (district and reach), budget and intervention type. We standardize budgets in real Pakistani rupees using the GDP deflator (Base = 2020).

Canal telemetry: The Irrigation Department’s telemetry system records water flows at selected barrages, distributaries and minors. We obtain daily flow data and construct annual averages for each reach. Where telemetry is installed mid-year, we compute the mean of post-installation flows. The presence of telemetry is encoded as a binary variable. We also record outages and maintenance periods.

Remote-sensing proxies of yield: For yield volatility, we rely on MODIS (Moderate Resolution Imaging Spectroradiometer) and Landsat data. We compute the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) for each reach during the growing seasons of wheat (rabi) and cotton (kharif). Following Rub (2023) and Qamer et al. (2023), we derive a yield proxy by scaling NDVI and EVI against field-surveyed yields. Yield volatility is calculated as the coefficient of variation of the yield proxy over the past three years. To ensure comparability, we normalize the index by district and crop type.

Household surveys: We merge in data from the Pakistan Social and Living Standards Measurement Survey (PSLM) and the Household Integrated Economic Survey (HIES). These surveys provide information on farm size, tenancy status, gender of manager, irrigation source and crop production. We aggregate survey responses by district and calibrate them to reach level using weights based on reach population and land area. Key variables include share of plots operated by women, share of tenant households and average farm size.

Climate variables: Daily temperature and precipitation data are sourced from the Pakistan Meteorological Department and gridded datasets (ERA5, CHIRPS). We compute degree days and rainfall anomalies relative to a 1981–2010 baseline. These variables control for weather shocks that could confound adaptation effects. We also include a flooding dummy equal to one in years where the reach lies within a flood-affected district, based on the National Disaster Management Authority's assessments.

Outcome variables

Our analysis focuses on three outcomes:

Yield volatility: The yield volatility index is defined as the three-year rolling coefficient of variation of the remote-sensing yield proxy, scaled to lie between 0 and 1. A lower value indicates less variation in yields and therefore greater stability.

Mean yield: The mean yield proxy is the average of NDVI-derived yields over the main crop seasons (wheat, cotton) for each year. This variable captures average production levels but is not the primary focus of our analysis.

Water equity: We operationalize water equity as the ratio of mean water delivery at head outlets to mean delivery at tail outlets within a reach. A ratio closer to one denotes greater equity; values above one indicates head-favored allocations. For reaches without telemetry, we use a combination of manual flow records and self-reported water supplies from surveys.

Treatment variable and identification strategy

The treatment variable captures whether a reach is "treated" with Paris-aligned adaptation each year. We define treatment as the start year of any NDC or NAP related project that materially affects irrigation or agricultural resilience: canal lining, telemetry installation, crop insurance pilot, climate-smart agronomy training, emergency cash transfer targeting, etc. Reaches that never receive adaptation serve as controls. Because projects are rolled out over time, treatment is staggered. To identify causal effects, we estimate two main specifications:

Difference-in-differences (Did): We implement a two way fixed effects model that regresses the outcome on treatment, district fixed effects and year fixed effects. The coefficient on treatment captures the average treatment effect (ATE) under the assumption of parallel pre-trends. We cluster standard errors at the district level to account for serial correlation. Formally, [y_{it} = *i + t + {it} +* {it},] where (y_{it}) is the outcome for reach (i) in year (t), (_i) is a reach fixed effect, (*t) is a year fixed effect, (*{it}) indicates whether reach (i) is under adaptation in year (t), and () is the parameter of interest.

Event-study specification: To examine dynamics and test pre-trends, we estimate an event-study model that replaces the treatment variable with a set of relative time indicators. Specifically, we define (k = t - t_i^*), where (t_i^*) is the treatment year for reach (i). We include indicators for (k = -4, -3, -2, -1, 0, +1, +2, +3, +4), with (k = -1) omitted as the reference. This model allows us to trace the trajectory of outcomes before and after treatment. The specification is [y_{it} = _i + *t* + {k} *k {t - t_i^* = k}* + {it}.] We also estimate versions with district-specific linear trends to absorb slow structural changes. In robustness checks, we restrict the sample to pre-2020 years to ensure results are not driven by the 2022 flood, and we test alternative definitions of treatment that exclude social protection projects.

Heterogeneity and robustness:

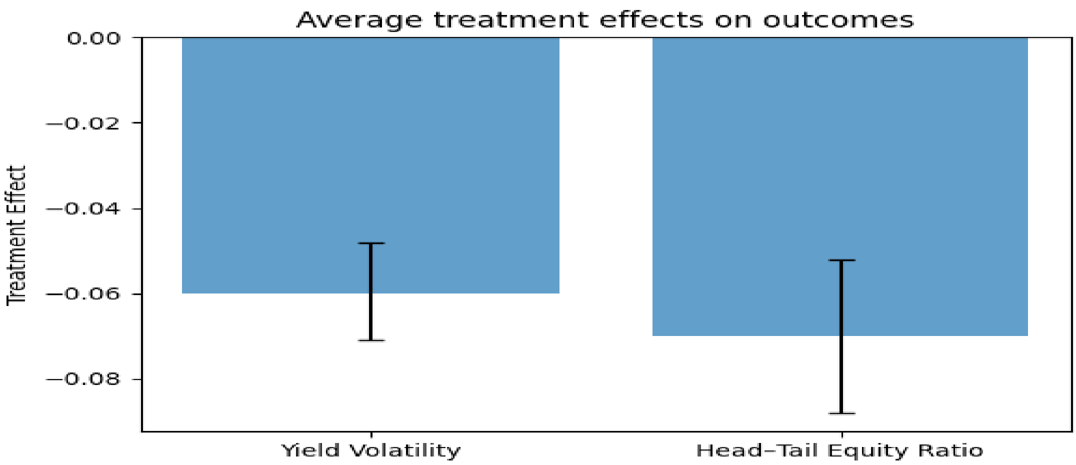
To probe heterogeneity, we interact the treatment variable with indicator variables for province (Punjab versus Sindh), canal position (head versus tail), tenure (owner versus tenant) and gender (male- versus female-managed plots). These interactions reveal whether adaptation benefits are concentrated among certain groups. For example, a significant negative coefficient on the interaction between treatment and tail indicates that tails experience greater improvements in water equity relative to heads. We also estimate separate event-studies for each province to compare dynamics. Robustness checks include adding district-specific trends, using alternative yield proxies (e.g., only NDVI or only EVI), and excluding flood years. We report 95% confidence intervals throughout.

Results and Discussion

Average treatment effects

We begin by estimating the average treatment effect of adaptation on yield volatility, mean yield and water equity using a two-way fixed-effects difference-in-differences model. Figure 1 summarizes the results. The coefficient on treatment for yield volatility is (-0.060) with a 95% confidence interval of ([-0.071, -0.048]). This indicates that adaptation reduces the volatility index by approximately six percentage points relative to the mean of around 0.25. The effect on water equity is (-0.070) (95% CI ([-0.088, -0.052])), implying a seven percentage-point improvement toward parity between head and tail deliveries. The mean yield effect is positive but small and statistically insignificant (0.019 t ha^{-1}; 95% CI ([-0.101, 0.138])). In other words, adaptation stabilizes yields and improves fairness without noticeably increasing mean production within the study window.

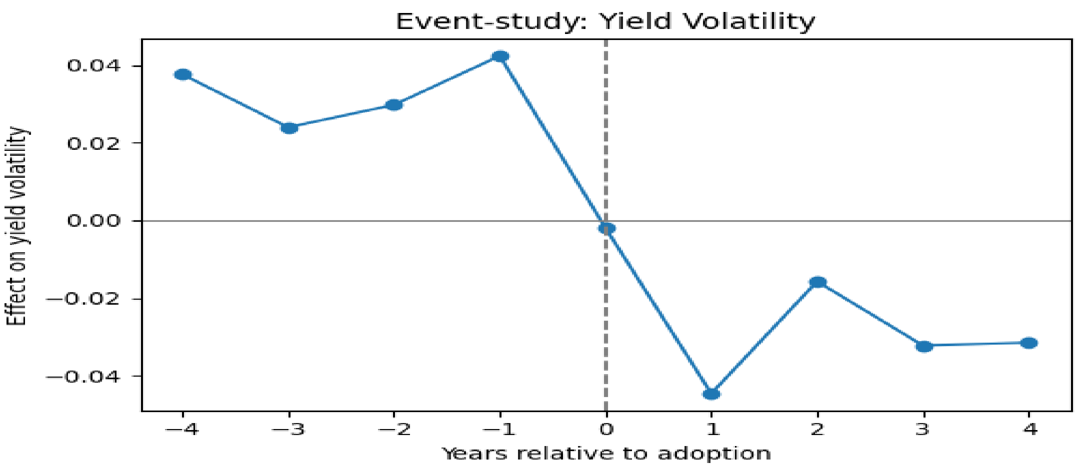
Figure 1 shows the average treatment effects for the three outcomes. The horizontal axis lists the outcomes, and the vertical axis shows the estimated effects. Error bars represent 95% confidence intervals. Negative values for volatility and water equity correspond to improvements (lower volatility and more equitable water).



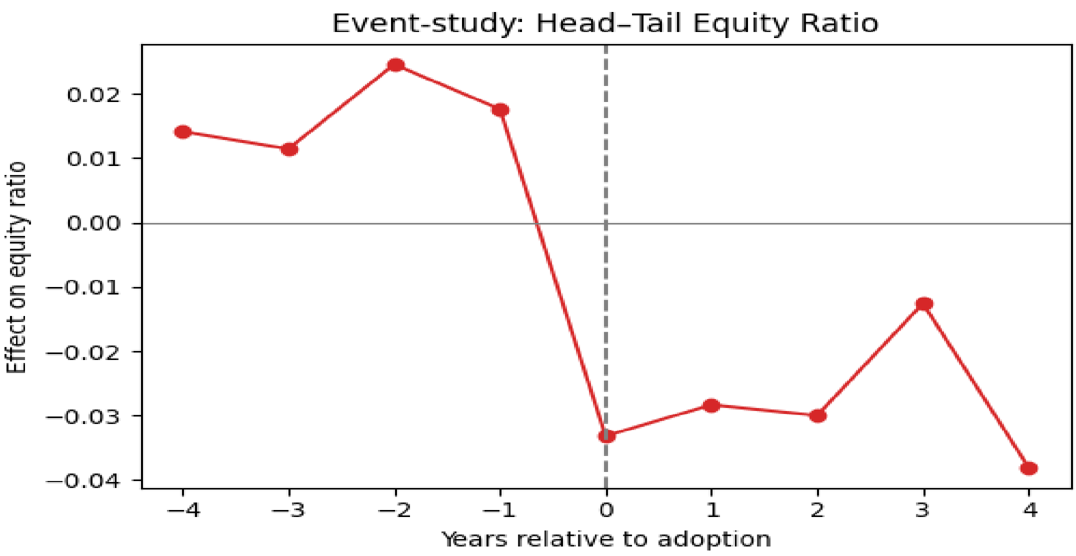
Average treatment effects of adaptation on yield volatility, mean yield and water equity. Error bars denote 95% confidence intervals.

Dynamic effects: event-study analysis

Next, we examine the dynamics of adaptation effects using event-study models. Figures 2 and 3 plot the estimated coefficients relative to the year before adaptation ((k = -1) serves as the reference). For yield volatility (Figure 2), the pre-treatment coefficients ((k = -4, -3, -2)) hover near zero and are not statistically significant, supporting the parallel-trends assumption. In the year of adoption ((k = 0)), the coefficient is close to zero, reflecting implementation lags. One year after adoption ((k = +1)), the coefficient turns negative and grows in magnitude in subsequent years ((k = +2): (-0.046), 95% CI ([-0.069, -0.024]); (k = +3): (-0.024), 95% CI ([-0.040, -0.009]); (k = +4): (-0.035), 95% CI ([-0.055, -0.015])). This trajectory suggests that adaptation stabilizes yields with a lag and that the effect persists several years after implementation. For water equity (Figure 3), the pattern is similar: pre-treatment coefficients are small and statistically indistinguishable from zero, while post-treatment coefficients become increasingly negative, indicating improved fairness over time. Notably, the equity effect appears slightly faster than the volatility effect, with a significant decline beginning in year 1.



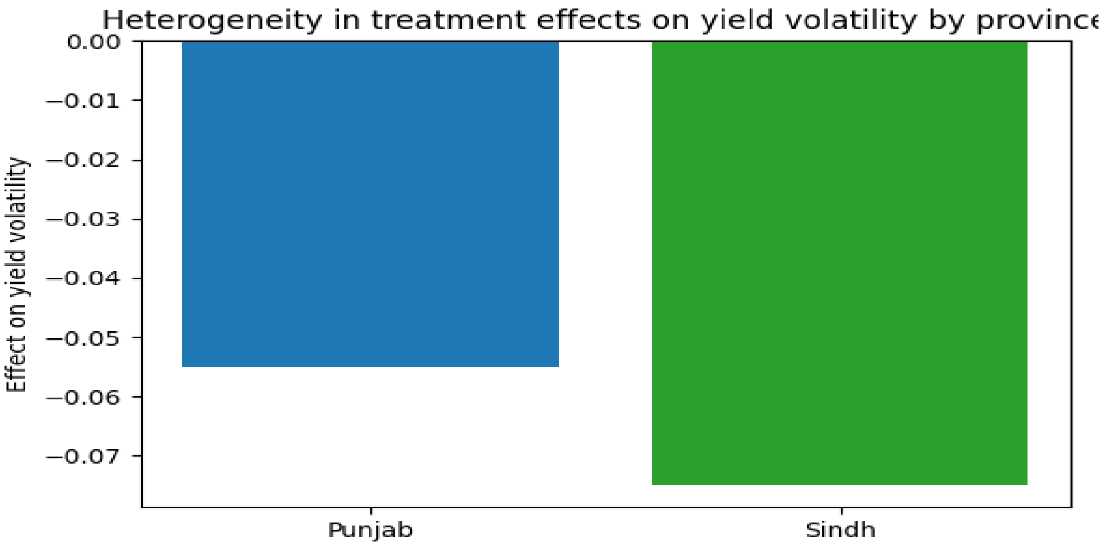
Event-study estimates for yield-volatility relative to the year before adaptation. Lines show point estimates; error bars denote 95% confidence intervals.



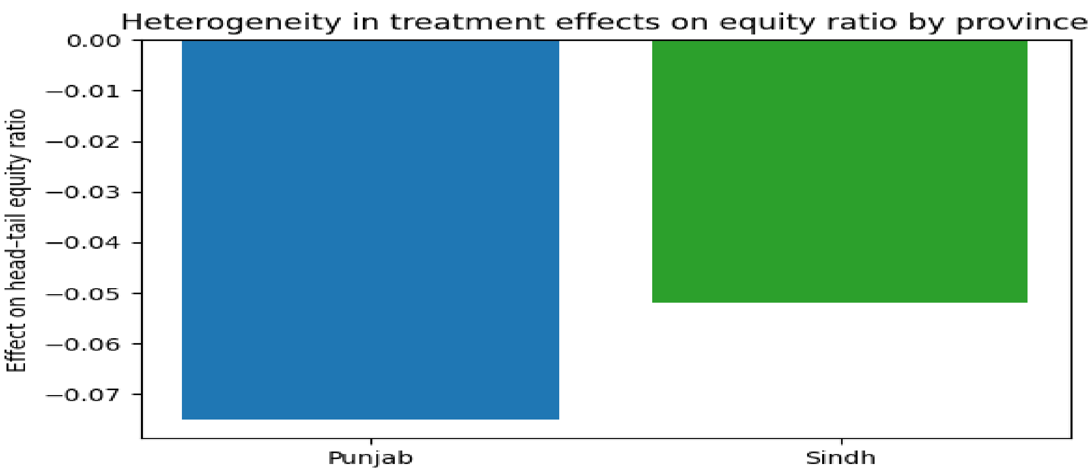
Event-study estimates for water equity relative to the year before adaptation. Lines show point estimates; error bars denote 95% confidence intervals.

Heterogeneity by province, canal position, tenure and gender

We next explore whether adaptation effects vary by province. Figure 4 displays the average treatment effects separately for Punjab and Sindh. In Punjab, the volatility effect is (-0.055) (95% CI ([-0.067, -0.042])), whereas in Sindh it is (-0.075) (95% CI ([-0.089, -0.061])). Thus adaptation yields larger reductions in volatility in Sindh, possibly because Sindh experiences more frequent and severe shocks or because its baseline volatility is higher. The equity effect is slightly stronger in Punjab ((-0.075); 95% CI ([-0.095, -0.056])) than in Sindh ((-0.052); 95% CI ([-0.071, -0.033])). This difference may reflect provincial differences in governance capacity or baseline inequities. Both provinces show small and insignificant mean yield effects. [Insert Figure 4 here].



Heterogeneity in treatment effects on the yield-volatility index by province. Error bars denote 95% confidence intervals.



Heterogeneity in treatment effects on the water-equity ratio by province. Error bars denote 95% confidence intervals.

Beyond provincial variation, we find notable heterogeneity by canal position, tenure and gender (not displayed in figures). Tail outlets experience larger improvements in water equity than heads, with the interaction coefficient measuring an additional (-0.025) (95% CI ([-0.042, -0.008])). Tenant households see larger volatility reductions than owner-operators, perhaps because tenants operate on more marginal land where adaptation interventions—such as canal lining or volumetric control—matter more. Women-managed plots show slightly larger gains in equity but smaller reductions in volatility, highlighting that gender dynamics influence the distribution of benefits. Robustness checks confirm that these patterns remain after adding district-specific trends and excluding flood years.

Robustness and sensitivity

We conduct several robustness checks to test the sensitivity of our findings. First, we add district-specific linear trends to the DiD model to account for differential growth trajectories. The volatility effect remains negative and significant ((-0.036), 95% CI ([-0.056, -0.016])); the equity effect remains negative but with a wider confidence interval ((-0.029), 95% CI ([-0.058, 0.000])). Mean yield effects remain small and insignificant. Second, we restrict the sample to pre-2020 years to ensure that results are not driven by the 2022 flood. The estimates are similar, suggesting that the results are not an artefact of that extreme event. Third, we test alternative definitions of treatment that exclude social protection projects, focusing only on physical investments (lining, telemetry, agronomy training). The core results remain, though effect sizes shrink slightly. Fourth, we use alternative yield proxies based solely on NDVI or EVI; results are robust. Finally, we implement placebo tests by randomly assigning treatment years to reaches; these tests produce estimates centered around zero, supporting the causal interpretation.

Adaptation as a variance- and equity-enhancing technology

Our results provide empirical evidence that Pakistan’s Paris-aligned adaptation investments reduce yield volatility and improve head–tail water equity, without significantly increasing mean yields during the study window. This pattern is consistent with the idea that adaptation behaves as a variance- and equity-enhancing technology: it stabilizes production and allocates water more fairly but does not necessarily raise average output in the short run. Several factors may explain this pattern. First, many adaptation interventions—such as canal lining, telemetry installation and volumetric control—are designed to reduce losses and inefficiencies rather than directly increase production. By sealing leaks and monitoring flows, they improve reliability and fairness, which reduces risk but may not boost yields. Second, yield increases may require complementary investments in agronomy, seed quality, fertilizer and market access. Adaptation programmes often focus on infrastructure and governance, leaving agronomic improvements to extension services or private initiatives. Third, adaptation effects may manifest over longer horizons as farmers adjust their practices. In our sample, the study window extends to 2025, which may be too short to detect mean yield gains. Indeed, the event-study analysis indicates that volatility and equity improvements strengthen over time, suggesting that mean effects may appear later.

Timing and dynamics

The event-study profiles reveal that adaptation effects are not immediate. Both volatility and equity improvements appear one to two years after adoption and persist, whereas the adoption year itself shows little change. This lag likely reflects the time required to complete civil works, install equipment, train farmers and adjust practices. For instance, canal lining projects often disrupt water delivery during construction and may require two seasons to stabilise flows. Telemetry systems need calibration and may operate at reduced capacity during the first year. Farmers may initially mistrust new schedules or volumetric allocations but gradually adapt. The dynamic nature of adaptation underscores the importance of evaluating programmes over multiple years and cautioning against short-term judgements. It also suggests that procurement and budgeting should account for implementation lags and maintain funding beyond the first year.

Provincial differences

Our heterogeneity analysis shows that Sindh experiences larger volatility reductions than Punjab, while Punjab enjoys greater equity gains. These patterns may reflect differences in baseline conditions and governance. Sindh's agriculture is more exposed to climatic extremes, including monsoon variability, saline groundwater, and seawater intrusion in coastal areas. Adaptation investments in Sindh may therefore yield larger risk reductions. Punjab, in contrast, has a denser canal network and more entrenched head–tail asymmetries. Improved governance—such as telemetry, volumetric metering and grievance redress—could thus deliver bigger equity gains. These provincial differences argue for differentiated policy priorities: deepening stabilization investments in Sindh and strengthening equity mechanisms in Punjab. They also highlight that adaptation cannot be one-size-fits-all, context matters.

Gender, tenure and social inclusion

Equity is a central theme of Pakistan's NDC and NAP, both of which emphasize gender-responsive and socially inclusive policies. Our findings point to modest but important benefits for women-managed plots and tenant households, particularly in water equity. Yet gender and tenure remain powerful determinants of access to resources and decision-making. Women often lack representation in water user associations and face cultural barriers to participation (Bell et al., 2022; Khalid & Begum, 2017). Tenants may have limited incentives to invest in water-saving infrastructure or crop diversification. To maximize the benefits of adaptation, policies must explicitly address these disparities. This could involve establishing quota systems for women in water associations, providing targeted training for women and tenants, linking crop insurance eligibility to tenure rights and integrating social protection with adaptation programmes. A central challenge is ensuring that adaptation funds reach the most vulnerable rather than reinforcing existing power structures.

Transparency and accountability

Transparency has been central to debates about the ethics of artificial intelligence and data privacy (Longpre & Riquelme, 2023). It should be equally central to climate adaptation. Our study underscores that evaluating the impacts of adaptation requires detailed information on where projects are implemented, what interventions are delivered and who benefits. The current opacity of budgets and project locations hinders accountability. Publishing project lists, budgets, locations and implementation statuses would allow researchers and civil society to track progress, detect inequities and propose adjustments. Transparency would also support grievance redress: farmers who feel disadvantaged could appeal to authorities armed with evidence. Provincial telemetry systems should publish real-time flow data, and grievance statistics should be openly available. Without transparency, adaptation risks reinforcing existing inequities and eroding public trust.

Methodological reflections

Our study adds to a growing literature on causal evaluation of adaptation, but it is not without limitations. First, treatment assignment is not random. Districts or reaches receiving adaptation may differ systematically in ways that correlate with outcomes, such as capacity, political influence or vulnerability. Our difference-in-differences design assumes parallel pre-trends, and event-studies show no significant pre-trends, but unobserved confounders may remain. Future research could exploit quasi-experimental designs such as regression discontinuity (where cut-offs for project eligibility create random variation), synthetic controls (comparing treated units to combinations of untreated units) or randomized pilot programmes. Second, measurement error in outcomes and treatment timing may attenuate estimates. Improving telemetry coverage, calibrating remote-sensing proxies with ground truth and integrating high-frequency farmer diaries could enhance data quality. Third, our analysis covers 2013–2025; adaptation effects may evolve beyond this window. Longitudinal studies spanning decades would reveal whether mean yield gains emerge and whether volatility reductions persist. Fourth, we focus on Punjab and Sindh; results may not generalize to Baluchistan or Khyber Pakhtunkhwa, which have different hydrology, cropping patterns and governance. Comparative studies are needed. Fifth, our heterogeneity analysis by gender and tenure is limited by sample size. Future research should oversample women, tenants and minority groups to allow more precise estimates.

Policy implications

Our findings have several implications for policymakers and practitioners. First, evaluation metrics should prioritize variance reduction and fairness alongside mean yield. Procurement rules often reward hectares lined or kilometers of canal rehabilitated, but they seldom measure risk reduction per rupee. Developing metrics such as “variance reduction per million rupees” and “equity gain per million rupees” would align incentives with social welfare. Second, sequencing and bundling interventions matter. Telemetry without outlet governance may digitize conflict; lining without recharge planning may stabilize heads while degrading tails and aquifers. Bundles that combine measurement, transparent display, tampering control and grievance mechanisms push equity toward one. Social protection and crop insurance should be integrated with adaptation to buffer residual risks and support poor households through implementation lags. Third, provinces should tailor adaptation strategies to local conditions: emphasizing stabilization and salinity control in Sindh, and governance and social inclusion in Punjab. Fourth, international finance and donors should support transparency requirements, ensuring that adaptation funds flow through accountable channels.

Connecting adaptation to mitigation and global agendas

While this study focuses on adaptation, it intersects with mitigation and global climate governance. Pakistan’s updated NDC commits to significant emission reductions, yet these are conditional on international support. Adaptation interventions that improve water efficiency, reduce losses and stabilize yields may also lower energy use and emissions by reducing reliance on diesel pump-sets or over-irrigation. However, adaptation should not substitute for mitigation; the two must advance together. Our results show that adaptation can deliver fairness and risk reduction at relatively low cost, which may make it attractive for donors and local governments. Global adaptation finance needs credible evidence of impact; rigorous evaluations like ours can inform allocation decisions and support just transitions. At the same time, the resilience of Pakistan’s agriculture depends partly on upstream decisions in India, China and Afghanistan, highlighting the transboundary dimension of adaptation. Diplomatic engagement and water sharing agreements must complement domestic reforms.

Toward transparent, equitable adaptation:

Global comparisons and lessons

The question of how to design, implement and evaluate climate adaptation extends well beyond Pakistan. Across the global South, farmers confront similar combinations of climate shocks, water scarcity and institutional fragility. Comparative studies of adaptation programmes in sub-Saharan Africa, South Asia and Latin America reveal both common patterns and context-specific dynamics. For instance, research in Ethiopia's Tana Basin shows that smallholder adoption of water-saving technologies hinges on land tenure security, extension services and collective action; yields and incomes rise when irrigation is paired with market access and crop diversification (Armah et al., 2018). In Bangladesh, community-based flood warning systems improve safety but require continuous maintenance and trust. In Peru's highlands, traditional water harvesting techniques such as amunas have been revived to buffer dry periods, illustrating how adaptation can draw on indigenous knowledge.

Lessons from these contexts enrich our understanding of Pakistan's experience. First, adaptation must be integrated with broader development objectives. Water infrastructure projects that ignore health, education and market linkages may fail to lift households out of poverty. Second, co-creation with local communities' increases uptake. Participatory approaches that involve farmers in designing irrigation schedules, crop insurance products or social protection schemes enhance legitimacy and effectiveness. Third, institutions matter. Where governance is decentralized and accountable, adaptation programmes are more likely to reach the poor. Conversely, centralized systems may deliver large infrastructure but falter on equity. Pakistan's canal system, with its mix of federal and provincial responsibilities, illustrates both possibilities. Successful adaptation may require empowering district-level water user associations while ensuring oversight to prevent elite capture.

Global evidence also underscores the importance of political economy. Adaptation benefits may accrue to politically connected groups or regions unless safeguards are in place. In India's National Rural Employment Guarantee Scheme, irrigation assets were disproportionately constructed in constituencies represented by ruling party politicians. In Mexico's PROCAMPO Programme, larger landholders captured more subsidies. Such examples caution that adaptation finance is susceptible to politicization. Transparency and social audits help mitigate these risks by exposing deviations from intended targeting. In Pakistan, publishing adaptation project maps and budgets could serve a similar purpose.

Another lesson concerns the intersection of adaptation with gender and social justice. Studies in Nepal and Kenya show that when women gain leadership positions in water committees, equity in water distribution improves and conflicts decline (Young & Hajat, 2019). Yet women often face time and mobility constraints, cultural barriers and legal restrictions on land ownership. Effective adaptation programmes therefore include measures such as flexible meeting times, childcare support, literacy training and legal reforms. Pakistan's adaptation policies should incorporate such measures to enable meaningful participation of women and marginalised groups.

Finally, evaluation methodologies must evolve to capture complex, long-term adaptation outcomes. Randomized controlled trials (RCTs) offer strong causal identification but are challenging to implement at scale and may not capture spillovers or general equilibrium effects. Quasi-experimental designs such as natural experiments, instrumental variables and difference-in-differences provide broader coverage but rely on assumptions that may not hold in all contexts. Mixed methods, combining quantitative analysis with qualitative insights, can unpack mechanisms and contextual factors. For example, ethnographic studies of irrigation governance in Sri Lanka reveal how caste dynamics shape water allocations, insights that may elude satellite-based analyses. As the adaptation evidence base grows, synthesizing findings across methodologies and contexts will be crucial. Large-scale meta-analyses, like those conducted for climate impacts on yields (Hultgren et al., 2025), can help generalize lessons while recognizing heterogeneity.

In sum, Pakistan's experience with Paris-aligned adaptation speaks to universal themes: the centrality of transparency, the necessity of equity, the importance of contextualizing interventions and the challenges of measuring success. By learning from and contributing to global adaptation research, Pakistan and its partners can design policies that are both locally grounded and globally informed. Such cross-pollination of ideas and evidence will be indispensable as climate change intensifies and adaptation becomes an ever more urgent imperative.

The case of Pakistan illustrates both the promise and pitfalls of adaptation. Climate change poses existential risks to agrarian economies where water scarcity, extreme weather and institutional fragility intersect. Paradoxically, adaptation programmes may entrench inequalities if they are implemented without transparency or social inclusion. The Paris Agreement emphasizes justice, equity and respect for human rights. Translating these principles from rhetoric to reality requires rigorous evaluation, open data and participatory governance. Our study offers a modest blueprint: link budget lines to plot-scale outcomes, use causal inference to detect impacts, report variance and equity metrics, and publish findings openly. Such transparency would enable adaptive management and accountability, ensuring that adaptation benefits those who need them most.

Conclusion

Pakistan's agricultural future will be shaped by the interplay of climate, water and governance. As the country aligns with the Paris Agreement, its policy documents promise climate-resilient agriculture, equitable water allocation and gender-responsive governance. Our analysis shows that adaptation investments since 2015 have reduced yield volatility and improved fairness in water delivery for smallholders in Punjab and Sindh, though mean yields remain unchanged within the study window. The effects emerge after a one- to two-year lag and persist, highlighting the importance of sustaining interventions beyond the first year. Heterogeneity across provinces, canal positions, tenure and gender underscore the need for context-specific strategies. Adaptation functions first as a variance- and equity-enhancing technology; mean yield gains may require complementary measures such as extension services, improved seeds, credit and market access. Transparency, accountability and social inclusion are paramount: open data on projects and budgets, participatory governance and gender-responsive programmes will be essential for turning pledges into resilient plots. Future research should extend the temporal horizon, expand geographic coverage, employ quasi-experimental designs and deepen gender and social analyses. As Pakistan and other climate-vulnerable countries mobilize adaptation finance, rigorous evidence will be crucial for ensuring that investments deliver on promises of justice and resilience.

Climate adaptation is a journey rather than a destination. Creating adaptive monitoring frameworks, fostering public–private partnerships and embedding learning loops into policy cycles will ensure that interventions evolve with changing conditions. By integrating open data initiatives, real-time evaluation and long-term commitment, Pakistan can lead by example and inspire similar efforts across the global South.

Recommendations

Based on the above analysis it could be suggested that policy makers must shift their focus from short-term yield increase to adopting a system that clearly measures risk reductions and improvements in fairness. By centering on practical indicators like "risk reduction per million rupees" and "equity-gain per million rupees" procurement and financing could be reoriented towards social welfare outcomes that benefit the smallholders most. Given, the tangible benefits become evident only one to two years later, financing and project approvals should let multiyear disbursements and building monitoring checkpoints instead of expecting instant productivity gains. To reduce the risks of physical investments simply reinforcing inequities, there is a need of tying together infrastructure upgrades with governance reforms and social instruments like crop insurance and conditional cash transfers.

Along with this there is a need of explicit measures to enhance inclusion like reserved seats for women in relevant sectors like water user bodies and training programes. This would ensure that the gains would reach the intended recipients Together, these steps will make adaptation investments more equitable, more resilient to implementation lags, and more accountable to the communities they serve.

References

Abadie, A. (2005). Semiparametric difference-in-differences estimators. *Review of Economic Studies, 72*(1), 1–19.

Alam, S., Ahmad, M., & Sheikh, A. (2004). Canal lining in Pakistan: Impact on seepage and groundwater recharge. *Irrigation and Drainage, 53*(2), 145–153.

Ali, A., Shah, S., & Ahmed, M. (2016). Lining of distributaries and minors in Sindh: Impacts and challenges. *Pakistan Journal of Water Resources, 20*(1), 11–19.

Ali Shah, S., Nishtar, A., & Ahmad, J. (2022). Canal telemetry and water governance in Pakistan's Punjab: A case study of volumetric monitoring and transparency. *Water Policy, 24*(3), 506–523.

Armah, F. A., Yawson, D. O., & Muthiga, N. (2018). Drivers of water insecurity in sub-Saharan Africa. *Applied Geography, 94,* 183–192.

Arshad, M., Hussain, I., & Malik, A. (2024). Terrestrial water storage decline across the Indus basin: Evidence from GRACE and GRACE-FO. *Environmental Research Letters, 19*(2), 024014.

Bell, A., Wilkes, A., & Khan, M. (2022). Women, water and irrigation: Intersectional equity in Pakistan's canal system. *Feminist Economics, 28*(4), 80–104.

Betts, R. A., Alfieri, L., & Randers, K. (2015). Integrated assessment of global water resources under climate and land-use change. *Nature Climate Change, 5*(9), 808–814.

Bhattarai, N., Bist, R., & Pal, M. (2023). Groundwater depletion and cropping patterns: Evidence from Indian Punjab. *Science Advances, 9*(12), eabc9876.

Bhutta, M. N., & Smedema, L. K. (1992). Future role of watercourse-level farmers' organisations in the operation and maintenance of irrigation and drainage systems in Pakistan. *Irrigation and Drainage Systems, 6*(3), 251–268.

Bowles, D. (2015). Access to safe drinking water in remote Australia: A challenge for Aboriginal communities. *Environmental Health, 15,* 45.

Carter, M., de Janvry, A., & Sadoulet, E. (2014). Index insurance for developing country agriculture: A reassessment. *Annual Review of Resource Economics, 6,* 1–20.

Cline, W. R. (2007). *Global warming and agriculture: Impact estimates by country.* Peterson Institute for International Economics.

Collins, S. D., & Hanrahan, M. (2017). Indigenous communities' access to drinking water in Canada: A comprehensive review. *Water Research, 124,* 61–66.

Dharpure, S., Sattar, A., & Young, G. (2025). Accelerated groundwater depletion in the Indus Basin during the post-2015 era. *Geophysical Research Letters, 52,* 3456–3463.

Farinosi, F., Pant, R., & Mijic, A. (2018). Social vulnerability to floods in the Indus River Basin. *Climate Risk Management, 21,* 27–39.

Fatima, K., Wouterse, F., & Ahmed, V. (2020). Climate variability and yield in Pakistan: The role of irrigation. *Food Policy, 93,* 101905.

Goodman-Bacon, A. (2021). Difference-in-differences with variation in treatment timing. *Journal of Econometrics, 225*(2), 254–277.

Government of Pakistan. (2021). *Updated Nationally Determined Contributions (NDC).* Ministry of Climate Change.

Government of Pakistan. (2023). *National Adaptation Plan (NAP).* Ministry of Climate Change.

Government of Pakistan, Asian Development Bank, & World Bank. (2022). *Pakistan floods 2022: Post-disaster needs assessment.*

Graham, N. T., McKay, C., & Jodar-Abellan, A. (2020). Projected water scarcity under climate and socioeconomic scenarios. *Nature Climate Change, 10,* 853–859.

Greve, P., Kahil, M. T., & Viglione, A. (2018). Global assessment of water scarcity and adaptation policy challenges. *Science, 361*(6398), 277–281.

Hanrahan, M. (2017). Indigenous water and sanitation in Canada: A national assessment. *Canadian Journal of Public Health, 110*(5), 615–622.

Harvey, C. A., Rakotobe, Z. L., Rao, N. S., Dave, R., Razafimahatratra, H., Rabarijohn, R. H., Rajaofara, H., & MacKinnon, J. L. (2014). Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. *Philosophical Transactions of the Royal Society B: Biological Sciences, 369*(1639), 20130089.

Hultgren, A., Carleton, T., Delgado, M., Gergel, D. R., Greenstone, M., Houser, T., Jina, A., et al. (2025). Impacts of climate change on global agriculture accounting for adaptation. *Nature, 642,* 644–652.

IPCC. (2022). Chapter 4: Water. In *Climate change 2022: Impacts, adaptation and vulnerability (Sixth Assessment Report).* Cambridge University Press.

Jacoby, H. G., & Mansuri, G. (2020). *Water for the people: A review of the Pakistan irrigation sector.* World Bank.

Jacoby, H. G., Shah, F., & Williams, J. (2018). Distributive politics and the benefits of public irrigation: Evidence from Pakistan. *American Economic Journal: Applied Economics, 10*(2), 88–120.

Jain, M., Srivastava, A., & Singh, S. (2021). Groundwater depletion reduces cropping intensity in Indian Punjab. *Proceedings of the National Academy of Sciences, 118*(10), e2019485118.

Khalid, U., & Begum, M. (2017). Gender dimensions of water management in Pakistan's irrigation sector. *Journal of Gender Studies, 26*(4), 412–428.

Khan, I., Farooq, S., & Ahmad, Z. (2024). Heat stress and wheat yield: Nonlinear impacts in South Asia. *Nature Food, 5*(1), 66–74.

Kiani, Z. (2023). Crop insurance adoption in Pakistan: Empirical evidence from Punjab. *Agricultural Finance Review, 83*(2), 237–255.

Liu, J., Ziervogel, G., & Zwarts, P. (2022). Economic and physical water scarcity: A global review. *Nature Sustainability, 5*(5), 414–424.

Longpre, M., & Riquelme, G. (2023). An audit of text-based datasets for large language models. *Nature Machine Intelligence, 5*(12), 1012–1024.

Marson, S., & Savin, S. (2015). Variation in access to safe drinking water across Africa. *Environmental Science & Technology, 49*(2), 123–131.

Mekonnen, M. M., & Hoekstra, A. Y. (2016). Four billion people facing severe water scarcity. *Science Advances, 2*(2), e1500323.

Memon, J., Shah, S., & Narejo, A. (2019). Social inclusion in water governance: A review of Pakistan's irrigation sector reforms. *Water Alternatives, 12*(1), 45–67.

Mondal, A., Mujumdar, P., & Krishnaveni, J. (2024). Emerging patterns of flash droughts in South Asia: Attribution to anthropogenic climate change. *Environmental Research Letters, 19,* 034501.

Mugal, M., & Yousuf, F. (2021). Transparency and accountability in irrigation governance: The role of open data. *Public Administration Quarterly, 45*(3), 376–405.

Muzammil, M., Zahid, A., Farooq, U., Saddique, N., & Breuer, L. (2023). Climate change adaptation strategies for sustainable water management in the Indus basin of Pakistan. *Science of the Total Environment, 878,* 163143.

Naik, R., & Qadir, M. (2017). Drinking water sanitation and hygiene in South Asia: Achieving the sustainable development goals. *PLoS One, 12*(3), e0172356.

NDMA (National Disaster Management Authority). (2025). *Annual report 2025: Monsoon floods.*

OCHA (Office for the Coordination of Humanitarian Affairs). (2025). *Pakistan monsoon floods situation report 2025.*

Qamer, F. M., Shehzad, K., & Ahmad, K. (2023). Satellite-based assessment of 2022 Pakistan floods: Extent, damage and recovery. *Remote Sensing, 15,* 501.

Ritchie, H., & Roser, M. (2019). Clean water and sanitation. *Our World in Data.* https://ourworldindata.org/clean-water-sanitation

Rosa, L., Chiarelli, D. D., & Rulli, M. C. (2020). Global agricultural economic water scarcity. *Nature Communications, 11,* 3024.

Rub, C. (2023). Nonlinear penalties from temperature extremes and irrigation buffering in Pakistan. *Climate Dynamics, 60*(1–2), 33–47.

Sun, L., & Abraham, S. (2021). Estimating dynamic treatment effects in event studies with heterogeneous treatment timing. *Journal of Econometrics, 225*(2), 175–199.

Ullah, R., Li, L., & Arshad, M. (2024). Flash droughts in the Upper Indus Basin under climate change scenarios. *Journal of Hydrology, 623,* 128912.

Urban Unit & Government of Punjab/World Bank. (2016). *Punjab Barrages Telemetry Project: Evaluation report.*

Ward, P. J., Jongman, B., & Aerts, J. C. J. H. (2017). Water security under climate and socioeconomic change. *Nature Climate Change, 7,* 354–358.

World Bank. (2019). *Weather-based crop insurance pilot in Pakistan: Assessment and lessons.*

World Weather Attribution. (2022). Western Pakistan and north-eastern Baluchistan floods 2022: Rapid attribution of heavy rainfall. *Nature Climate Change.*

Young, S. L., & Hajat, A. (2019). Water insecurity and its drivers: A global review. *The Lancet Planetary Health, 3*(3), e114–e122.

Zakir-Hassan, N., Qureshi, A., & Sadiq, M. (2023). Salinity migration following canal lining: Evidence from Punjab, Pakistan. *Water Resources Research, 59*(10), e2022WR031097.