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IRRIGATION REHABILITATION AND FARM ECONOMIC OUTCOMES: EVIDENCE FROM DIVERSE AGROECOLOGICAL TYPOLOGIES IN INDONESIA[1]

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Abstract

Irrigation systems in Indonesia face persistent challenges, including undermaintenance, sedimentation, and intersectoral competition for water, all of which undermine reliable water delivery to agriculture. To address these issues, the Strategic Irrigation Modernization and Urgent Rehabilitation Project rehabilitated canals across 14 irrigation schemes nationwide. Using inverse-probability-weighted regression adjustment (IPWRA) on data from approximately 1,600 farm-households, we estimate the impacts of these interventions on agricultural and dietary quality outcomes across two agroecologically distinct regions of Indonesia. The results reveal substantial heterogeneity in the impacts of irrigation rehabilitation, plausibly driven by differences in agroecological conditions across these regions. In tropical West Java, irrigation rehabilitation is associated with large increases in profitability, driven by higher productivity and the expansion of cultivated areas during the dry season. By contrast, in semi-arid Nusa Tenggara, irrigation rehabilitation is associated with modest improvements in profitability, due to operational efficiencies concentrated only during the rainy season. The study also documents a trade-off between improved irrigation and adoption of on-farm water-saving practices, particularly in West Java. The simultaneous increase in cultivated areas and the reduced uptake of water-saving practices suggest intensified water use at the farm level. Finally, irrigation investments do not translate into improved dietary quality, illustrating that infrastructure investment alone may be insufficient to improve nutrition outcomes. These results highlight the importance of tailoring irrigation programs to agroecological realities and bundling them with climate-smart, agronomic, and nutrition-sensitive interventions to simultaneously promote agricultural productivity, sustainable resource use, and broader household welfare.

Keywords: Irrigation Infrastructure; Agricultural Productivity; Water; Indonesia

JEL codes: O13, O18, Q12, Q15, Q25

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1. Introduction

Irrigation systems across Indonesia play a central role in sustaining agricultural production and rural livelihoods. However, these systems face several challenges, including undermaintenance, aging canals, and rising intersectoral water competition, which have eroded delivery reliability. Roughly half of Indonesia's 7.4 million irrigated hectares require rehabilitation, implying large efficiency losses in irrigation water service and foregone value added (World Bank, 2022). To improve irrigation services, the Government of Indonesia, with financing from the World Bank and the Asian Infrastructure Investment Bank (AIIB), implemented the Strategic Irrigation Modernization and Urgent Rehabilitation Project (SIMURP), a nationwide program aimed at restoring irrigation infrastructure and improving on-farm water delivery.

By stabilizing the water supply, investments in irrigation rehabilitation can influence agricultural production and household well-being through greater cropping intensity, higher yields, land use expansion and reduced exposure to climate-related production risk. Several studies have shown the positive impacts of irrigation infrastructure on agricultural production, climate adaptation, and household welfare outcomes in Indonesia (Aguilar et al., 2022; Gatti et al., 2021) and in other contexts (Duflo & Pande, 2007; Strobl & Strobl, 2011; Bardhan et al., 2012; Jacoby, 2017; Jones et al., 2022; Dyer & Shapiro, 2023; Blakeslee et al., 2023; Ahmed et al., 2026).[2] In addition, while modernizing irrigation infrastructure can reduce inefficiencies in water delivery systems, it can also incentivize farmers to use more water overall, constituting an agricultural water rebound effect (Pei et al., 2024; Wheeler et al., 2020; Song et al., 2018).

The literature extensively documents average returns on irrigation investments and their role in climate adaptation, yet few studies examine whether irrigation rehabilitation produces heterogeneous impacts and mechanisms across distinct agroecological contexts. Do these investments lead to higher farm profitability? And how do returns vary across agroecological regions? Do impacts occur through increases in land use (the extensive margin channel) or through increases in productivity of inputs (the intensive margin channel)? Does infrastructure provision affect farmer behavior regarding the uptake of on-farm water-saving strategies? Finally, given that many irrigation projects are justified on the grounds of food and nutrition security, it is crucial to assess whether these investments generate downstream benefits for the dietary quality of households. The study aims to answer these questions by evaluating the impacts of SIMURP on agricultural production and household food consumption in Indonesia's tropical West Java and semi-arid Nusa Tenggara.

To estimate the impacts of SIMURP investments, we collected data from West Java and Nusa Tenggara. The sampling for the ex-post evaluation is based on beneficiary water-user groups (WUGs) in which canals have already been built. The comparison group is selected in a step-by-step process. Initially, the evaluation team worked with SIMURP's Project Management Unit to narrow down a list of villages and sub-districts that did not receive any benefits (including any spillover benefits) from the irrigation rehabilitation investments. In the second step, the survey implementation team from the University of Indonesia validated these control

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[2] See Giordano et al. (2019) and Dillon and Fishman (2019) for a review of the impacts of irrigation.

villages to ensure that agricultural production systems and agroecological conditions were similar between the treatment and comparison households. Any comparison village that produced a different commodity or practiced different types of agriculture from the treatment areas in each agroecological zone was omitted from the sample and replaced with an appropriate control village. A total of 1,586 households (871 in West Java and 715 in Nusa Tenggara) were interviewed (see the Study Design section for more details).

Given that the treatment assignment is non-random and the impact estimates are based on an ex-post comparison between beneficiary and non-beneficiary groups, the estimates of SIMURP interventions may suffer from endogeneity bias due to farmers' selection and other unobserved characteristics correlated with the treatment assignment. To overcome these endogeneity issues, we use the "doubly robust" IPWRA method that relies on 'selection on observables' and controls for selection and confoundedness at the treatment and outcome model stage (Wooldridge, 2010). However, the identification assumption relies on a version of the Conditional Independence Assumption (CIA), specifically, the conditional mean independence assumption, to reduce selection bias, making it vulnerable to issues of heterogeneity due to unobservables (Wooldridge, 2010). Thus, our estimates should be interpreted as strong conditional correlations rather than causal estimates.

The results reveal marked regional differences in the relationship between irrigation rehabilitation and farm-economic outcomes, plausibly driven by variations in local agroecological conditions. In West Java, where the regional agroecology favors rice production, rehabilitation is associated with large and statistically significant increases in net value per hectare, driven by higher productivity and expansion of cultivated areas during the dry season. However, in semi-arid Nusa Tenggara, irrigation rehabilitation increases profitability only through operational efficiencies, concentrated in the rainy season. Second, the results reveal a trade-off between improved irrigation and adoption of on-farm water-saving practices (e.g., alternate wetting and drying, mulching, rainwater harvesting), particularly in West Java.[3] The combination of expanded land use and reduced adoption of water-saving practices highlights rebound-consistent behavior in this region.[4] Finally, irrigation investments do not translate into greater food consumption scores for men or women in the beneficiary households.

Taken together, the findings suggest that irrigation rehabilitation investments must be explicitly tailored to local agroecological conditions. In hydrologically favorable regions like West Java, while irrigation rehabilitation delivers sizable income gains, these gains are also associated with resource intensification. Therefore, irrigation investments should be paired with incentives and extension services that encourage the adoption of water-saving practices to mitigate rising water demand associated with agricultural output expansion. In contrast, in water-scarce regions such as Nusa Tenggara, irrigation rehabilitation alone offers limited returns outside the rainy season, indicating the need for integrated approaches that combine irrigation with drought-resilient crops, water storage, and demand-side management. Finally, the absence of

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[3] Alternate wetting and drying, rainwater harvesting, terracing and mulching are key climate-smart, water-saving practices in rice production (Das et al., 2024; Patle et al., 2020).

[4] It is worth noting that we only measure irrigation rehabilitation's impact on farm-level behavioral response and the extensive-margin response in terms of cultivated land. Therefore, our result is only suggestive of a rebound effect, and not a direct proof of it, given that we do not measure water withdrawals.

improvements in household food consumption highlights that higher farm profits do not automatically translate into nutritional gains, underscoring the importance of complementary interventions, such as market access or nutrition-sensitive agriculture, to translate production gains into broader nutrition improvements.

This study sits at the intersection of three closely related strands of literature on irrigation and agricultural productivity (Bravo-Ureta et al., 2020; Ahmed et al., 2026; Del Caprio et al., 2011; BenYishay et al., 2025), climate adaptation (Gatti et al., 2021; Wang et al., 2024), and irrigation efficiency rebound effects (Giordano & de Fraiture, 2014; Berbel et al., 2018; Li & Zhao, 2018; Meenakshi, 2026). Its central contribution is to demonstrate that similar irrigation rehabilitation investments can operate through different economic and behavioral margins across varying agroecological contexts. Furthermore, we contribute to the literature on the relationship between irrigation technologies and the climate-smart behavior of farmers by providing novel evidence on the trade-off between improved irrigation technology and the adoption of on-farm water-saving agricultural practices, illustrating that more efficient, cheaper water delivery to farms may disincentivize water-saving behavior.

2. Background and SIMURP Interventions

Indonesia’s irrigated agriculture is under increasing strain from deteriorating infrastructure, which limits the reliability of irrigation service delivery. Of the country’s 7.4 million hectares of irrigated land, around half require rehabilitation, including 16% that are heavily damaged and an additional 35% that are moderately or lightly degraded (World Bank, 2022). Given that irrigated agriculture employs over one-third of Indonesia’s labor force and remains the backbone of national rice production, these structural inefficiencies pose significant risks for both food security and rural livelihoods.

In response to these challenges, the Government of Indonesia has made irrigation rehabilitation and modernization a policy priority. The National Medium- and Long-Term Development Plans for 2025-2029 and 2025-2045, respectively, set a combined target of rehabilitating three million hectares of irrigated land. SIMURP, as part of this effort, aims to upgrade irrigation infrastructure in 14 irrigation schemes in Indonesia, covering a total land area of 276,000 hectares and reaching about 880,000 households.

SIMURP was implemented from July 2018 to July 2024, with loan closing in 2025, and had a total budget of approximately USD578 million. The program was organized into three interconnected components aligned with the government’s irrigation modernization framework. The first component focused on the urgent rehabilitation of approximately 100,000 hectares of national and lowland irrigation schemes. The second component supported the strategic modernization of 176,000 hectares within the Jatiluhur Irrigation Scheme in West Java, including major rehabilitation works along the East and North Tarum canals. The third component provided project management and capacity strengthening to support implementation at both the central and subnational levels.

Across components, investments primarily encompassed the rehabilitation and lining of canals, upgrades to hydraulic control and measurement structures, and the development of asset management and information systems. A key institutional innovation under SIMURP was the introduction of Irrigation Service Agreements (ISAs), which define service standards and operation and maintenance responsibilities across management tiers. As implementation of ISAs remained incomplete during the study period, the present analysis does not evaluate their performance and instead focuses on the impacts of completed physical rehabilitation and upgradation of canals.

While SIMURP spans 14 irrigation schemes, this study focuses on two representative irrigation regions in West Java and Nusa Tenggara. These regions capture distinct agroecological conditions and irrigation challenges, allowing us to examine how similar rehabilitation investments perform across heterogeneous contexts. Specifically, the analysis focuses on the Jatiluhur Irrigation Scheme in West Java and the Jurang Sate and Jurang Batu Irrigation Schemes in Nusa Tenggara.

West Java

The Jatiluhur Irrigation Scheme in West Java is among Indonesia’s most productive rice systems, covering approximately 240,000 hectares of predominantly paddy land cultivated under a double-cropping calendar. It contributes roughly 40% of West Java’s rice supply and 9.4% of national production. Rainfall averages 250-400 millimeters per month during the wet season (October-April) and 90-130 millimeters during the dry season (May-September), complementing surface irrigation supplied through regulated releases from the Jatiluhur Reservoir. This reservoir also serves Jakarta’s metropolitan area and surrounding industries within the Citarum Basin, creating increasing competition for water. Combined with sedimentation and aging conveyance infrastructure, such pressure has reduced delivery reliability and system efficiency.

Nusa Tenggara

The Jurang Sate and Jurang Batu schemes in Nusa Tenggara are located in one of Indonesia’s driest agricultural regions and are characterized by smallholder, largely subsistence farming. The region experiences a semi-arid monsoonal climate, with rainfall averaging 220-270 millimeters per month during the wet season and typically below 40 millimeters during the dry season. Agricultural production closely follows this seasonal pattern: Rice is grown during the rainy season, while a mix of rice, soybeans, and tobacco dominates the dry season. Irrigation infrastructure is limited, primarily relying on surface irrigation from small reservoirs and local water storage, which partially buffers against rainfall variability. Agricultural production remains highly dependent on hydrological conditions, leaving farmers vulnerable to monsoon variability and extended droughts.

Overall, the two regions capture two important agroecological systems of Indonesia’s irrigated agriculture. West Java represents a densely populated, commercially oriented rice economy supported by intensive surface irrigation, while Nusa Tenggara illustrates smallholder dependence on rainfall and vulnerability to drought.

3. Conceptual Framework

This section outlines a simple conceptual framework that links irrigation rehabilitation, agricultural production, and food consumption across sharply different agroecological contexts. The central role of irrigation infrastructure is to improve the reliability and timing of water delivery and may complement or substitute rainfall, depending on hydrological conditions. By reducing exposure to rainfall variability, irrigation rehabilitation has the potential to relax seasonal water constraints that limit agricultural production in many parts of Indonesia (Dillon & Fishman, 2019; Gatti et al., 2021).

Irrigation rehabilitation can influence agricultural outcomes through two broad channels. First, along the extensive margin, improved water reliability can enable farmers to cultivate land that would otherwise remain fallow during water-scarce periods, increase cropping intensity, or sustain cultivation across seasons (Duflo & Pande, 2007). These responses are most likely in settings where rainfall variability and seasonal water constraints hamper the production calendar or agricultural land use, and irrigation infrastructure can meaningfully expand the set of feasible cultivation choices. By contrast, in environments characterized by widespread market frictions or environmental stressors, including extreme aridity, improved conveyance alone may be insufficient to support large-scale land expansion, even when infrastructure quality improves (Jones et al., 2022; Connor et al., 2012). Second, along the intensive margin, irrigation rehabilitation can raise productivity on existing plots by improving control over water application. More predictable water delivery allows farmers to better time planting, apply complementary inputs more efficiently, and avoid yield losses (BenYishay et al., 2025; Bravo-Ureta et al., 2020).

By allowing growth in agricultural output through both intensive and extensive margins, irrigation infrastructure may improve household nutrition and food consumption, though the evidence remains mixed in the literature (Burney et al., 2010; Domènech, 2015; Balana et al., 2020).

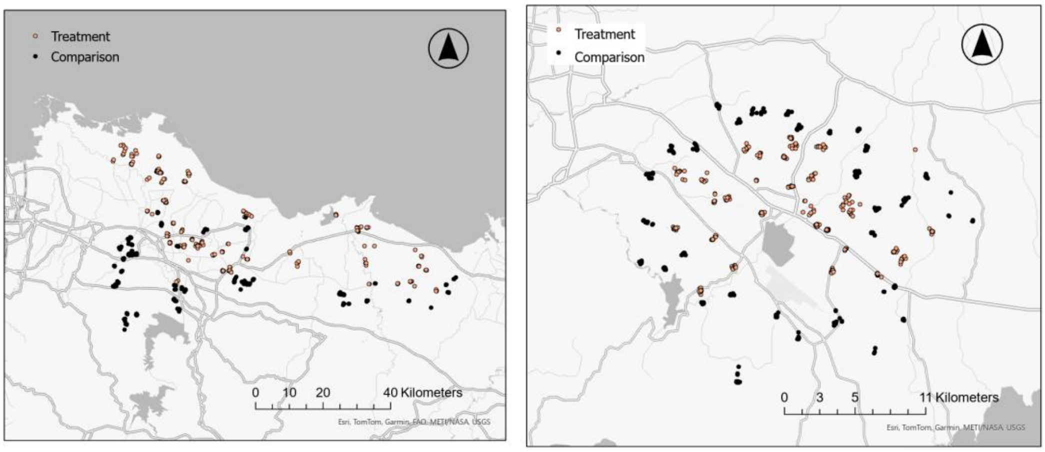
Crucially, agroecological conditions mediate both channels by determining whether additional water can be effectively delivered to crops and converted into output. In regions with favorable agroecological conditions, irrigation rehabilitation can substantially relax seasonal water constraints, generating gains through both expanded land use and higher productivity. However, gains achieved by intensifying water use at the plot level may trigger a rebound effect, in which increased efficiency of water delivery systems leads to greater overall water consumption, thereby exacerbating pressure on the reservoir (Wheeler et al., 2020; Song et al., 2018). In contrast, under several water-stress events during dry seasons, even substantial investments in irrigation infrastructure may fail to deliver reliable water at the plot level. In such contexts, a return to rehabilitation is likely to be muted or only complement the rainy season, as environmental constraints continue to dominate production outcomes.

This framework yields several implications for irrigation rehabilitation projects. First, the impacts of irrigation rehabilitation on farm profitability should be highly heterogeneous across agroecological zones. Second, gains should be strongest in regions and seasons where the hydrological conditions favor agricultural production. Third, observed impacts should operate through different combinations of extensive- and intensive-margin adjustments, governed by local hydrological and agronomic conditions. Finally, the increase in agricultural output associated with irrigation rehabilitation may be accompanied by intensified resource use.

4. Study Design

We conduct an ex-post evaluation exploiting cross-sectional variation between beneficiary and non-beneficiary WUGs to estimate the impact of irrigation rehabilitation under SIMURP. Primary household survey data were collected after project completion from three districts within the Jatiluhur Irrigation Scheme in West Java, and one district in the Jurang Sate and Jurang Batu schemes in Nusa Tenggara. Given the non-random placement of rehabilitation works, the sampling strategy was designed to enhance comparability between treated and comparison households by restricting the sample to WUGs operating under similar production conditions within each region.

Figure 1: Geographical Distribution of Beneficiary and Non-Beneficiary WUGs Across the Three Study Regions (from Left to Right: West Java and Nusa Tenggara)



Treatment Group: In West Java and Nusa Tenggara, treatment WUGs were randomly selected from a pre-existing list of beneficiary WUGs. Once the beneficiary WUG was identified, 10-12 households were randomly selected within each WUG to participate in the study. The treatment groups in West Java and Nusa Tenggara comprise 450 and 348 household observations, collected from 45 and 29 WUGs, respectively.

Comparison Group: The comparison WUGs were selected in a stepwise manner. First, in close coordination with SIMURP's Project Management Unit, we identified villages and WUGs that had not received rehabilitation investments and were not exposed to project spillovers, yet shared similar irrigation systems and production characteristics with treated WUGs. Second, these candidate comparison villages were validated by field survey teams to confirm similarities in terms of commodities produced and other conditions. The comparison groups in West Java and Nusa Tenggara consist of 449 and 372 household observations collected from 45 and 31 WUGs, respectively.

5. Empirical Strategy

Our objective is to estimate the impact of SIMURP investments on household-level agricultural and food consumption outcomes. The beneficiary selection in the project is non-random and is likely driven by both observable and unobservable factors correlated with outcomes, leading to potential selection bias in simple ordinary least squares (OLS) regressions. This could be the case despite efforts to ensure high comparability between the treatment and comparison groups during the data collection phase.

To address these issues, we employ the IPWRA estimator (Wooldridge, 2010), which offers a 'doubly-robust' approach to address problems of selection and generates a suitable counterfactual against which beneficiaries can be compared.[5] The identification is based on the CIA or selection on observables, which assumes that after controlling for observables that explain selection into treatment, the treatment assignment is independent of potential outcomes. To ensure a good overlap between treatment and comparison households, such that the CIA becomes plausible, we condition both the treatment and outcome equations on a rich set of observable covariates, which may help reduce selection bias due to observables (Imbens & Wooldridge, 2009). However, the threat from unobserved heterogeneity remains. Therefore, our results should be interpreted as associations that are suggestive but are not conclusive of causal effects.[6]

The IPWRA estimator is obtained by combining inverse probability weighting (IPW) in the treatment stage (using a logit regression) with regression adjustment (RA) in the second stage. The IPW stage reweights the data such that the treatment households are compared against a suitable counterfactual (treatment households under hypothetical non-treatment), reducing selection bias. Then, in the RA stage, weighted regressions are used with a rich set of covariates to control for confounding.

IPWRA estimation follows a three-step process. The first step estimates a logit regression of matching variables to obtain the inverse probability weights for each treatment arm. The selection of covariates is based on previous studies related to irrigation and household well-being (e.g., Bravo-Ureta et al., 2020; Gatti et al., 2021). These covariates include household demographics, characteristics of the household head, weather variables from satellite data, and land ownership.

In the second step, a weighted linear regression is estimated separately for the treatment and control arms, using weights based on the inverse probability weights calculated in the first step. In the third and final step, the IPWRA computes the average predicted outcomes for comparison and treatment groups using the generalized propensity scores and the conditional

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[5] IPWRA is 'doubly robust' because consistency of the average treatment effect requires only that one of the two models, the propensity-score model or the outcome regression, is correctly specified. Misspecification of one model can be compensated by correct specification of the other.

[6] This econometric approach does not mandate strict adherence to the Conditional Independence Assumption (CIA) for estimating the coefficients of interest; instead, it requires only that the conditional mean independence assumption restriction is satisfied, which allows for the conditional variance to depend on the treatment, unlike the CIA (Wooldridge, 2010).

means of predicted outcomes estimated in the first two steps. The estimates in the second step are obtained through weighted least squares, represented as:

$$y_{hj} = \alpha + \phi X_{hj} + \mu_j + \varepsilon_{hj} \quad \forall\, treat \in [0,1] \tag{1}$$

where, y_{hj} is the outcome of interest for household h in subdistrict j. X_{hj} are the set of covariates as described above. μ_j are subdistrict fixed effects that control for time-invariant, unobserved characteristics at the subdistrict level that could be correlated with outcomes. ε_{hj} are independent and identically distributed errors across subdistricts and households.

Then in the third step, the difference of the predicted outcome means from Eq (1) for $treat = 1$ and $treat = 0$ is estimated, producing the average treatment effects (ATE) of the beneficiary group:

$$ATE_{IPWRA} = n^{-1} \sum_{h=1}^{n} w_h [r_T(X, \delta_T) - r_C(X, \delta_C)] \tag{2}$$

where ATE_{IPWRA} are the average treatment effects for the irrigation treatment, estimated separately for West Java and Nusa Tenggara, respectively. In Eq 2, n is the number of observations, $w_h$is the inverse probability weight for each observation h, while $r_i(X)$ describes the regression model for beneficiary (T) and comparison group (C) with covariates X and estimated parameters δ_i, where δ_i are obtained from weighted regression procedures (as in Eq 1).

The estimation procedure is completed by bootstrapping the entire process 750 times since most of our regressions do not converge with the standard teffects package in Stata. For each bootstrap iteration, the standard errors are clustered at the subdistrict level to account for intra-cluster correlation in error terms.

An important assumption for identifying the impacts of irrigation infrastructure is the strict overlap assumption, which asserts that conditional probabilities are bounded away from zero and one. The overlap in propensity scores is verified in the graphs shown in Figure A1, which report the kernel density of the probability of being in any group after reweighting. No spikes are detected at the extremes of the distributions, meaning that all observations have a positive probability of belonging to each group. Finally, we calculate normalized differences for each covariate in each region and check their balance, as proposed by Imbens and Wooldridge (2009) (Table A1).

6. Data

The primary data come from the SIMURP Household Survey, which comprises 16 modules covering household demographics, agricultural production, input use, irrigation frequency and costs, land ownership, livestock and fishery activities, off-farm income, food consumption, health, drought coping, adoption of climate-smart practices, and women's empowerment in nutrition. Agricultural production information is recorded separately for each season and commodity, including cultivated area (hectares), harvested quantity (kg), quantity sold and consumed, unit prices (IDR/kg), and production costs. This detailed, season-specific information allows a comprehensive assessment of how irrigation infrastructure affects crop yields, input use, and food security during the dry and rainy seasons. The survey was administered in June 2025 across 1,600 households located in the project areas of West Java and Nusa Tenggara.

Prior to estimation, we screened the data for extreme values using a rule-based outlier detection procedure based on Tukey (1977).[7] After outlier removal, the final analytical sample consists of 1,586 households, including 776 treated households and 810 comparison households in total. Table 1 reports sample sizes by region and treatment status.

Table 1: Sample Sizes by Region and Treatment Status

Source: AIIB Staff

Region	Control	Treatment	Total
West Java	439	432	871
Nusa Tenggara	371	344	715
Total	810	776	1,586

Geographic coordinates for each household were also collected, enabling spatial linkages with climatic datasets. To capture environmental heterogeneity and exposure to weather shocks, we complement the household data with climatic variables derived from the Indonesian Meteorological, Climatological, and Geophysical Agency. These include annual averages, maxima, and minima of temperature and precipitation, which are matched to each household based on their georeferenced locations.

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[7] Observations with values lying outside the interquartile range (IQR), defined as below the 25th percentile minus 1.5 times the IQR or above the 75th percentile plus 1.5 times the IQR, were excluded for key continuous outcome variables within each region (Tukey, 1977).

7. Variables

7.1 Outcome Variables

Given the project's theory of change, the higher-level outcome variables include food consumption and agricultural production for each household. Household food consumption is measured using the World Food Programme's (WFP) Food Consumption Score (FCS) module, which is a standard measure of food security and nutritional adequacy. For each surveyed household, the FCS questionnaire was administered separately to one male and one female adult respondent. Following the official WFP weighting scheme, we construct male- and female-specific FCS indices (WFP, 2024).

Agricultural output is measured by calculating the net value of production per hectare for each household, which measures the profitability of agricultural production per unit of land. The net production value is defined as the total market value of all agricultural outputs produced by a household minus variable input costs, including seeds, fertilizer, agrochemicals, irrigation, hired labor, and transport. The net value per hectare is then obtained by dividing this value by the household's total cultivated area in the corresponding season or year. Variable descriptions are provided in Appendix B.

To further investigate the mechanisms driving variation in agricultural outcomes, we analyze four additional household-level variables. These include: rice yield, measured in kilograms per hectare, as an indicator of productivity; land use responses along the extensive margin, captured by both rice-cultivated area and total cultivated area (hectares); and labor input intensity, measured as hired labor expenditures per hectare (USD/ha). Rice-specific land area is included to assess whether households expand rice cultivation in response to improved irrigation services or adopt more diversified crops on additional cultivated areas. Table 2 reports summary statistics for these outcome variables used in the analysis. For each region, we present mean values separately for treatment and comparison households, along with pooled totals.

Table 2: Means of Outcome Variables Used in the Impact Assessment of Canal Rehabilitation in West Java and Nusa Tenggara

Source: AIIB Staff Estimations

	Unit	Total	Treat	Control
Panel A: West Java				
Food consumption score (male)	Index (0-112)	69.97	69.53	70.41
Food consumption score (female)	Index (0-112)	70.66	69.96	71.35
Net value per hectare	USD/ha	1,168	1,358	981.3
Total cultivated area	Ha	2.27	2.82	1.73
Rice-cultivated area	Ha	2.25	2.80	1.71
Rice yield	kg/ha	5,269	5,228	5,309
Labor input per hectare	USD/ha	742.1	661.5	821.6
Water-saving practices	%	0.17	0.06	0.28
Panel B: Nusa Tenggara				
Food consumption score (male)	Index (0-112)	67.82	67.24	68.36
Food consumption score (female)	Index (0-112)	68.11	68.50	67.75
Net value per hectare	USD/ha	1,561	1,565	1,558
Total cultivated area	Ha	0.67	0.68	0.66
Rice-cultivated area	Ha	0.47	0.47	0.47
Rice yield	kg/ha	5,918	5,942	5,894
Labor input per hectare	USD/ha	297.1	245.4	345.0
Water-saving practices	%	0.43	0.42	0.44

N = 871 for West Java and 715 for Nusa Tenggara.

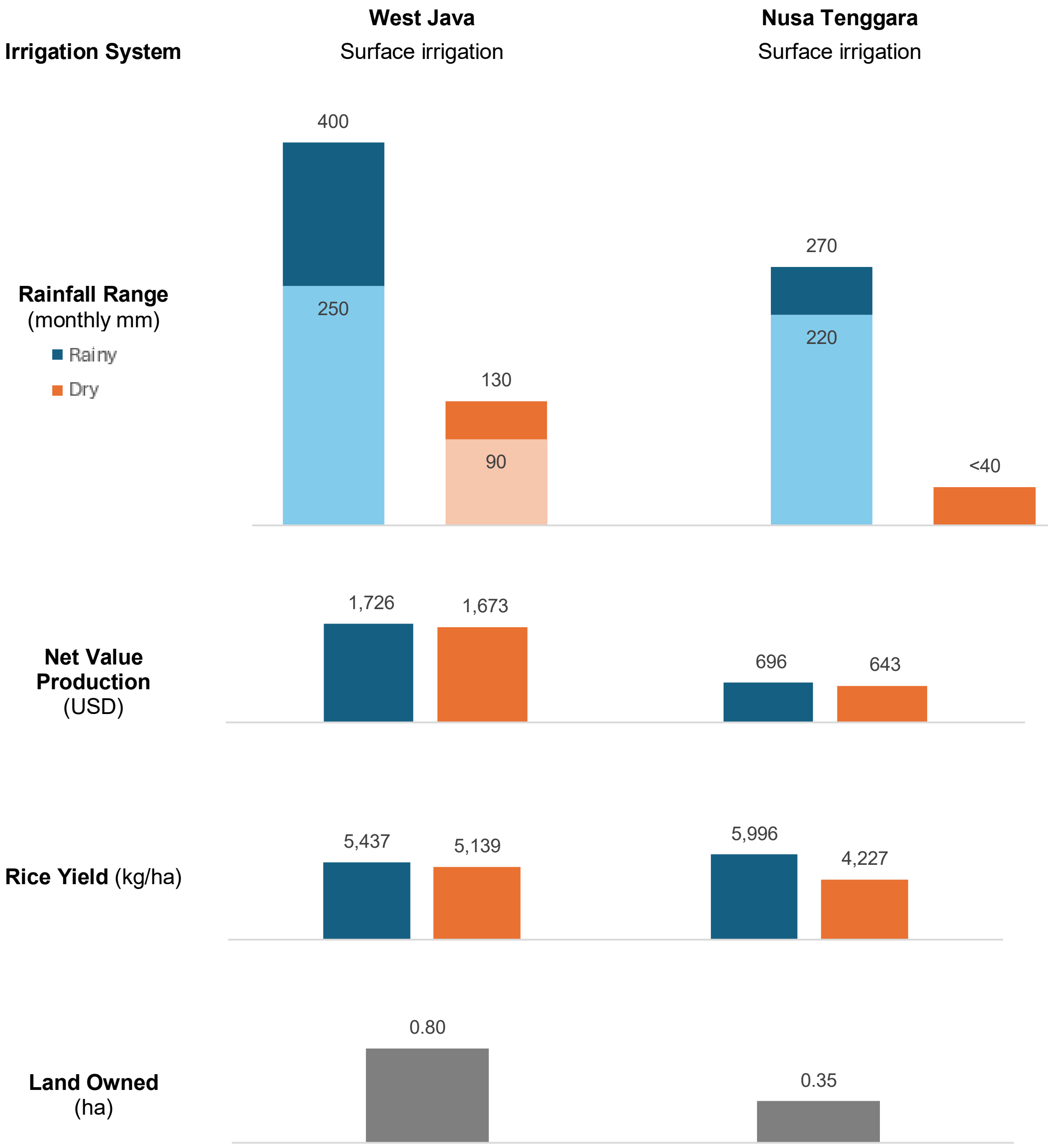
7.2 Production Characteristics Vary Across Agroecological Regions

Table 2 illustrates that production characteristics vary across these agroecological zones. In Table 3, we illustrate these changes clearly by (a) illustrating the different rainfall patterns across these regions, and (b) showing seasonal averages of production variables as well as land ownership.

West Java demonstrates strong rice production performance across the two cultivation seasons, with the net value of production for an average farm being USD1,708 during the rainy season and USD1,656 during the dry season (Table 3). Rice yields across the two seasons do not differ as much as in other regions because climatic conditions combined with an extensive irrigation system enable rice production throughout the year. The average landholding in the region is larger than in Nusa Tenggara.

In contrast, Nusa Tenggara exhibits a semi-arid production system, with production closely aligned with the monsoon cycle, reflecting marked wet and dry seasons. In the survey sample, paddy production dominates during the rainy months, while households predominantly produce a mix of rice, soybeans, and tobacco during the dry season (with typically <40 millimeters of precipitation per month). Agricultural production remains highly dependent on hydrological conditions, leaving farmers vulnerable to monsoon variability and extended droughts. Nusa Tenggara records lower total production values, USD689 (rainy season) and USD636 (dry season), due to smaller landholdings in the region (0.35 hectares on average).

Table 3: Production Diversity in Sample Sites



Source: AIIB staff calculations from survey data. 1 IDR = 0.000065 USD

Notes: mm = millimeter; kg = kilogram; ha = hectare.

7.3 Control Variables

The set of household-level covariates collected is based on the empirical literature on irrigation impacts in Asia (e.g., Bravo-Ureta et al., 2020; Ahmed et al., 2026). We include socio-demographic characteristics, such as household size, number of children, the gender and schooling level of the household head, the household head’s occupation, and owned land area. To capture climatic context and risk exposure, we also include precipitation and temperature indicators derived from data from the Indonesian Meteorological, Climatological, and Geophysical Agency.

Together, these covariates capture heterogeneity in productive assets, human capital, and climatic exposure that may jointly affect both participation in irrigation rehabilitation and agricultural outcomes. Table 4 presents the raw balance for these covariates by treatment status and region. As expected, there were key differences in the covariate balance that were addressed using inverse probability weighting.[8] Post-weighting statistics confirm that treatment and control groups achieve a satisfactory balance across all covariates after adjustment (Appendix A).

Table 4: Summary Statistics of Control Variables by Treatment Status and Region

Source AIIB Staff

	Control	Treated	P-value
Panel A: West Java			
Gender of household head	0.99	0.98	0.45
Age of household head (years)	56.32	54.04	0.002
No formal education	0.23	0.16	0.014
Primary education	0.44	0.48	0.301
Secondary education	0.3	0.31	0.706
Tertiary education	0.03	0.05	0.148
Farmer, full time	0.72	0.85	0.000
Farmer, part time	0.17	0.1	0.004
Off-farm employment/self-employed	0.03	0.03	0.966
Number of adults	3.47	3.46	0.913
Number of children	0.67	0.64	0.622
Owned land area (hectares)	0.56	0.77	0.001
Drought (months)	0.34	0.17	0.000
Observations = 871			
Panel B：Nusa Tenggara			
Gender of household head	0.97	0.98	0.613
Age of household head (years)	51.49	53.29	0.023
No formal education	0.18	0.15	0.251
Primary education	0.3	0.33	0.546
Secondary education	0.43	0.43	0.969
Tertiary education	0.09	0.1	0.653
Farmer, full time	0.78	0.75	0.318
Farmer, part time	0.19	0.23	0.284
Off-farm employment/self-employed	0.02	0.02	0.930
Household size (persons)	3.65	3.59	0.519
Owned land area (hectares)	0.35	0.36	0.829
Average temperature over the year (°C)	31.65	31.5	0.098
Observations = 715			

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[8] To ensure sufficient overlap in propensity scores, the specific control variables included in the logit models vary across the two regions. Nevertheless, all models consistently include variables from three broad categories: household demographics, land ownership, and climatic conditions.

8. Results and Discussion

8.1 Impacts of Irrigation Rehabilitation on Farm Profitability

The relationship between irrigation rehabilitation and farm profitability varies across agroecological regions. In tropical West Java (Panel A, Table 5), the impacts of rehabilitation are concentrated entirely in the dry season, where it is associated with an approximately 73% increase in net value per hectare.[9,10] This corresponds to about a 16% increase in the annual income of treatment households as compared to the comparison group. These estimates are in line with recent literature documenting substantial profitability gains from irrigation rehabilitation programs (e.g., Ahmed et al., 2026). In contrast, we observe a modest 10% increase in net profitability per hectare in Nusa Tenggara associated with rehabilitation, with gains concentrated in the rainy season (Panel B, Table 5). These results point to regionally differentiated responses to irrigation rehabilitation plausibly governed by agroecological conditions as well as irrigation and rainwater availability across seasons. Section 5.2 identifies the key mechanisms through which irrigation rehabilitation impacts agricultural output.

Table 5: The Impact of Irrigation Rehabilitation on Net Value Per Hectare (USD/ha) in West Java and Nusa Tenggara

Source: AIIB Staff Estimations

	Dry season	**Rainy season**
Panel A: West Java		
Net value per hectare	575.14***	26.29
	(74.14)	(124.29)
Comparison mean	783.35	1,130.02
Panel B: Nusa Tenggara Barat		
Net value per hectare	−359.61	169.71**
	(283.62)	(70.43)
Comparison mean	1,009.73	1,570.35

Number of observations for West Java and Nusa Tenggara are 871 and 715, respectively.
Standard errors are clustered at the sub-district level, reported in parentheses.
Significance levels are denoted as follows: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
Comparison means correspond to predicted counterfactual outcomes in the absence of rehabilitation.
Source: AIIB Staff Estimations

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[9] The ATE can be converted to percentages by dividing the each ATE by comparison mean and multiplying by 100. For example, the effect of rehabilitation on Net Value per Hectare in the dry season in percentages can be calculated as: (575.14/783.35)*100 = 73%

[10] Table C1 in Appendix C provides robustness of these results using alternative estimators.

8.2 Impact Channels

This section examines the mechanisms by which irrigation rehabilitation affects agricultural output, distinguishing between adjustments along the intensive margin (crop yields and labor input per hectare) and the extensive margin (cultivated land use).

In West Java, irrigation rehabilitation is associated with adjustments along both the intensive and extensive margins. On the intensive margin, dry-season rice yields increase by approximately 553 kilograms per hectare, an 11.5% gain relative to the comparison mean. Rehabilitation also enables the expansion of cultivated land by 34% and 25% relative to the comparison mean in the dry and rainy seasons, respectively. However, almost all of this increase in cultivated land is allocated to rice production, indicating that households do not move towards diversified or high-value non-staple crops.

Labor input per hectare also declines by roughly USD95, a decrease of 21% relative to the comparison group. First, this result arises because households may allocate the same amount of hired labor to additional cultivated land rather than hire additional labor. Second, better irrigation infrastructure can reduce the need for hired labor by reducing the frequency of repeated watering or making planting dates more predictable.

During the West Java rainy season, while the yield for the treatment group declines substantially, we do not see changes to the net value per hectare, likely due to cost savings associated with irrigation infrastructure. The yield in this case may have dropped due to a dilution of labor input, though the results are imprecisely measured.

Table 6: The Effect of Irrigation Infrastructure on Yield, Cultivated Land, and Input Costs in West Java

Source: AIIB Staff Calculations

	Dry season	**Rainy season**
Rice yield	553.06***	-493.46***
	(180.45)	(183.69)
Comparison mean	*4,798*	*5,716*
Rice-cultivated land	0.311***	0.245***
	(0.068)	(0.061)
Comparison mean	*0.878*	*0.989*
Total cultivated land	0.306***	0.245***
	(0.069)	(0.061)
Comparison mean	*0.889*	*0.993*
Labor input per ha	-94.68***	-64.77
	(21.24)	(67.49)
Comparison mean	*450.834*	*487.037*

N = 871

Standard errors are clustered at the sub-district level, reported in parentheses.

Significance levels are denoted as follows: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Comparison means correspond to predicted counterfactual outcomes in the absence of rehabilitation.

Responses to irrigation rehabilitation in Nusa Tenggara are moderate and operate primarily through improvements in cost efficiency. Labor expenditure for the treatment group is 32% and 29% lower in the dry and rainy seasons, respectively (Table 7). This result again indicates operational efficiency gains associated with better irrigation infrastructure.

Table 7: The Effect of Irrigation Infrastructure on Yield, Cultivated Land, and Input Costs in Nusa Tenggara

Source: AIIB Staff Calculations

	Dry season	**Rainy season**
Rice yield	-#	91.42
	-	(187.07)
Comparison mean	-	*5,877.16*
Rice-cultivated land	-	0.041
	-	(0.026)
Comparison mean	-	*0.401*
Total cultivated land	-0.040	0.033
	(0.030)	(0.026)
Comparison mean	*0.385*	*0.414*
Labor input per ha	-98.27***	-104.86***
	(22.68)	(0.58)
Comparison mean	*306.33*	*366.89*

N = 715
Standard errors are clustered at the sub-district level, reported in parentheses.
Significance levels are denoted as follows: * p < 0.10, ** p < 0.05, *** p < 0.01.
Comparison means correspond to predicted counterfactual outcomes in the absence of rehabilitation.
Estimates for rice yield and rice-cultivated land are not shown since rice is not the predominant crop grown in the dry season, and farmers grow various crops during this season in our sample.

Taken together, these results highlight the importance of regionally differentiated irrigation policies. In agroecologically favorable areas such as Jatiluhur, which also have better complementary infrastructure across agricultural value chains, irrigation rehabilitation can generate substantial gains on both the extensive and intensive margins, supporting the case for scaling such investments where dual-season rice cultivation is viable. In contrast, in Nusa Tenggara, where we do not see any meaningful increase in agricultural output, policy should focus on enhancing seasonal productivity through targeted support for crop diversification, adoption of drought- and salinity-tolerant varieties, and decentralized alternative water infrastructure, such as rainwater harvesting. Recognizing these regional differences is essential for maximizing the impact of irrigation investments and ensuring inclusive agricultural growth.

8.3 The Impacts of Irrigation Rehabilitation on Water-Saving Practices

In West Java, irrigation rehabilitation is associated with a 24-percentage-point decrease in the adoption of any water-saving practice on the farm or a 62% decrease in the number of water-saving practices adopted (Table 8). These results indicate that the water supply constraint was alleviated in this region, allowing farmers to shift away from conservation practices. By contrast, in Nusa Tenggara, we do not see this infrastructure-conservation trade-off, plausibly due to water supply constraints that are beyond the scope of small-scale infrastructure rehabilitation.

Table 8: The Effect of Irrigation Infrastructure on On-Farm Water-Saving Practices

	West Java	**Nusa Tenggara**
Adoption of water-saving practices (any)	-0.24***	-0.022
	(0.032)	(0.039)
Comparison mean	*0.28*	*0.44*
Number of water-saving practices	-0.20***	-0.085
	(0.026)	(0.064)
Comparison mean	*0.32*	*0.65*

The number of observations for West Java and Nusa Tenggara is 871 and 715, respectively.
Standard errors are clustered at the sub-district level, reported in parentheses.
Significance levels are denoted as follows: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
Comparison means correspond to predicted counterfactual outcomes in the absence of rehabilitation.

8.4 The Impacts of Irrigation Rehabilitation on Food Consumption

Indonesia continues to face substantial nutrition challenges despite sustained progress in agricultural and infrastructure development. The World Bank (2023) reports that child stunting declined from over 30% in 2018 to around 22% in 2022, yet remains high by international standards, while UNICEF (2022) documents a persistent “triple burden” of malnutrition, encompassing undernutrition, micronutrient deficiencies, and being overweight, driven in part by inadequate diets. Against this backdrop, examining whether irrigation rehabilitation translates into improvements in household food consumption, as measured by the FCS, is of clear policy relevance.

We find no statistically significant effects of irrigation rehabilitation on food consumption outcomes for either male or female household members across all regions (Table 9). Indeed, agricultural production and commercialization activities may not always improve food security or dietary diversity since other factors, such as market orientation or stickiness of habits, may play a key role in determining this relationship (Sibhatu & Qaim, 2018; Ahmed et al., 2026). Thus, interventions such as irrigation rehabilitation may need to be complemented with crop diversification strategies, market linkages, or nutrition education to improve household nutrition outcomes.

Table 9: The Effect of Irrigation Infrastructure on Food Consumption Scores

Source AIIB Staff

	West Java	**Nusa Tenggara**
FCS (male)	-0.170	-1.680
	(1.060)	(1.060)
Comparison mean	*70.405*	*68.364*
FCS (female)	-0.524	0.190
	(1.066)	(1.07)
Comparison mean	*71.345*	*67.753*
N	871	715

Standard errors are clustered at the sub-district level and reported in parentheses. Comparison means correspond to predicted counterfactual outcomes in the absence of rehabilitation.
FCS is constructed following the World Food Programme standard.
Significance levels are denoted as follows: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

9. Conclusions and Policy Implications

This study provides new evidence on both the potential and the limits of irrigation rehabilitation for improving agricultural and household welfare across Indonesia's diverse agroecological landscapes. Using IPWRA methods on household-level data from two contrasting regions, we show that the impacts of irrigation rehabilitation are highly context-specific. In tropical West Java, rehabilitation is associated with large gains in farm output. However, these gains are accompanied by an expansion in rice cultivation and a reduced adoption of water-saving practices, suggesting an increase in water demand. This implies that irrigation rehabilitation should be paired with water accounting, volumetric or incentive-compatible water governance where feasible, agricultural extension on climate-smart practices such as alternate wetting and drying, and monitoring of basic-level water use.

In contrast, in semi-arid Nusa Tenggara, canal rehabilitation alone may not sufficiently address water availability constraints, highlighting that rehabilitation may only work when water availability is not a binding constraint. Thus, complementary investments, including water storage, drought-resilient varieties, crop diversification, and value chain support, are needed to improve overall farm productivity and household welfare.

Finally, the absence of dietary impacts across both regions suggests that irrigation alone is unlikely to improve nutrition unless embedded within a broader development strategy that includes extension services, crop diversification, market integration, women's agency, and targeted behavioral change communication. In this sense, irrigation infrastructure may be a necessary but an insufficient condition for sustainable agricultural transformation, requiring careful integration with climate-smart and nutrition-oriented policies to simultaneously promote productivity, resource sustainability, and household well-being.

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Appendices

Appendix A: Overlap and Balance Assumptions

Figure A1: Overlap of Propensity Scores for West Java & Nusa Tenggara

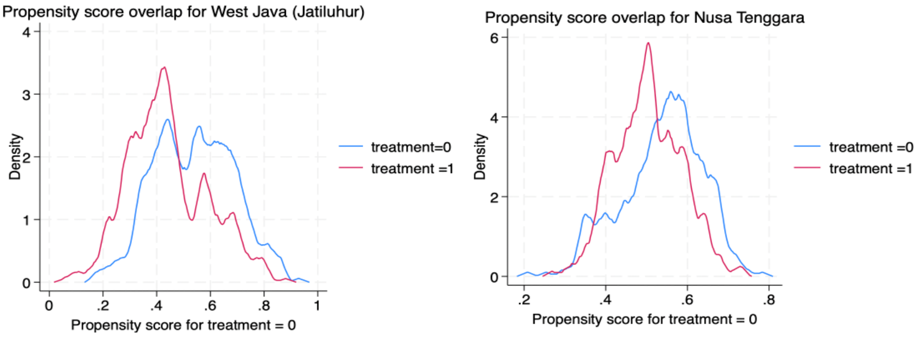

Table A1: Normalized Differences Among Covariates Between Beneficiaries and Non-Beneficiaries After IPW Stage

Source AIIB Staff

Normalized Difference Score	
Panel A: West Java	
Household head gender (1 = male)	-0.0042
Household head age (years)	-0.0184
Household head education level_2 (1 = primary education, 0 = otherwise)	-0.0094
Household head education level_3 (1 = secondary education, 0 = otherwise)	0.0103
Household head education level_4 (1 = tertiary education, 0 = otherwise)	-0.0102
Occupation_1 (1 = full-time farm, 0 = otherwise)	-0.0029
Occupation_2 (1 = part-time farm, 0 = otherwise)	0.0075
Household size (persons)	0.0077
Number of children (persons)	0.1804
Owned land area (hectares)	0.0125
Drought (months)	0.0101
Panel B: Nusa Tenggara	
Household head gender (1 = male)	-0.0011
Household head age (years)	-0.0101
Household head education level_2 (1 = Primary education, 0 = otherwise)	-0.0039
Household head education level_3 (1 = Secondary education, 0 = otherwise)	0.0017
Household head education level_4 (1 = Tertiary education, 0 = otherwise)	0.0010
Occupation_1 (1 = Full-time farm, 0 = otherwise)	-0.0054
Occupation_2 (1= Part-time farm, 0 = otherwise)	0.0012
Household size (persons)	0.0067
Owned land area (hectares)	0.0016
Min Temperature over the year (°C)	0.0104
Max Temperature over the year (°C)	-0.00226
Average Temperature over the year (°C)	-0.00229

Appendix B: Variable Definitions and Construction

Table B1: Description of Key Outcome Variables

Source AIIB Staff

Variable	Description	Unit
Net value per hectare	Net agricultural revenue per hectare, measured for the rainy and dry seasons.	USD/ha
Rice yield	Quantity of rice harvested per hectare (rainy and dry seasons).	kg/ha
Rice-cultivated area	Land area cultivated with rice (rainy and dry seasons).	hectares
Total cultivated area	Total agricultural land used by the household (rainy and dry seasons).	hectares
Labor input per hectare	Labor expenditures per hectare (rainy and dry seasons). Includes hired labor.	USD/ha
Water-saving practices	Number of water-saving practices (terracing, mulching, rainwater harvesting, alternate wetting and drying).	count
Food Consumption Score (FCS)	Household-level food consumption score computed following WFP methodology. Constructed separately for male and female dietary patterns.	index

Appendix C: Robustness Check: Net Value per Hectare Estimates Using Alternative Estimators

This appendix reports robustness checks for the estimated impacts of irrigation rehabilitation on net value per hectare using alternative estimators. In addition to the baseline IPWRA specification used in the main analysis, we report estimates based on ordinary least squares (OLS) and inverse probability weighting (IPW). The purpose is to assess whether the main findings are robust to different approaches for addressing observable differences between treatment and comparison households.

Table C1: Robustness Check: Net Value Per Hectare Estimates Using Alternative Estimators

Source AIIB Staff

Panel A: West Java			
	OLS	**IPW**	**RA**
Rainy Season	_254.31_	_47.64_	_-185.68_
	（313.27）	(103.79)	(245.02)
Comparison mean	1,130.02	1,130.02	1,130.02
Dry Season	_501.10_**	_576.56_***	_602.88_***
	（245.24）	(78.93)	(155.20)
Comparison mean	783.35	783.35	783.35
Panel B: Nusa Tenggara			
	OLS	**IPW**	**RA**
Rainy Season	50.02	115.71	91.14
	(163.90)	(73.66)	(114.38)
Comparison mean	1,570.35	1,570.35	1,570.35
Dry Season	_41.06_	_-168.87_	_-252.48_
	(404.19)	(246.64)	(310.40)
Comparison mean	1,009.73	1,009.73	1,009.73

Number of observations for West Java and Nusa Tenggara are 871 and 715.
OLS = Ordinary Least Squares; IPW = Inverse Probability Weighting; RA = Regression Adjustment.
Standard errors are clustered at the sub-district level, reported in parentheses.
Significance levels are denoted as follows: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
Comparison means correspond to predicted counterfactual outcomes in the absence of rehabilitation.