

How Investment in Irrigation Promotes Agricultural Production in the Mekong Delta

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Abstract

The Mekong Delta—Vietnam’s agricultural heartland—is increasingly threatened by climate change, saline intrusion, and upstream dam construction, posing serious risks to its role as a major global rice supplier. This study examined how public investment in irrigation infrastructure affects agricultural output in the region, addressing a critical gap in understanding the role of water management in enhancing agricultural resilience. Using panel data from 13 provinces between 2009 and 2023, we applied a feasible generalized least squares (FGLS) model based on a Cobb-Douglas production function to estimate the determinants of the agricultural gross regional domestic product (GRDP). The results showed that irrigation investment significantly boosts agricultural productivity. While labor, capital, and land remain essential inputs, rainfall appeared to have little effect—highlighting the importance of regulated water infrastructure in mitigating climate variability. These findings align with previous regional studies and reflect the Delta’s reliance on labor-intensive rice farming supported by engineered water systems. By incorporating environmental factors and current climatic trends, the study provides new empirical evidence on the region’s agricultural dynamics. It underscores the vital role of irrigation in ensuring food security and economic sustainability, offering insights for climate adaptation and infrastructure policy in environmentally vulnerable regions.

Keywords

Mekong Delta, irrigation investment, agricultural productivity, climate change

Introduction

Vietnam has transitioned from a nation reliant on food imports to a leading exporter of many agricultural products, including pepper, coffee, rice, fish, and fruit. This accomplishment is inextricably linked to the contributions of agriculture in the Mekong Delta (ĐBSCL). Due to favorable temperatures and land and water resources, aquaculture, rice agriculture, and fruit production have emerged as the region's primary assets. Nonetheless, agricultural

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output in the Mekong Delta, especially rice cultivation, encounters many challenges. A significant hazard is salt intrusion resulting from climate change and the use of the Mekong River by upstream nations in the sub-Mekong basin. The Mekong Delta, defined by its low topography and numerous rivers and marshes, has an average elevation of a little more than two meters above sea level and is predominantly bordered by the East Sea and the Gulf of Thailand. Consequently, the Mekong Delta is susceptible to climate change and upstream activity along the Mekong River. This region currently faces two significant challenges: flooding during the rainy season caused by elevated Mekong River levels and saline intrusion during the dry season. Both result in considerable losses to agricultural output. Safeguarding livelihoods and guaranteeing stable, sustainable growth in this region are vital goals for the Vietnamese government.

In addressing these issues, the government has enacted numerous policies and measures to promote agricultural development in the Mekong Delta, particularly focusing on irrigation and irrigation infrastructure. The government's dedication to investing in irrigation has been enduring and unwavering. This is shown in important legal documents, like Decision 1397/QĐ-TTg, signed by the Prime Minister on September 25, 2012, which approved the irrigation plan for the Mekong Delta for the period of 2012–2020 and its approach to climate change and rising sea levels; Resolution 120/NQ-CP, from November 17, 2017, about sustainable development in the Mekong Delta due to climate change; and, most recently, Decision 633/QĐ-TTg, from June 15, 2020, which approved the project "Modernizing irrigation systems to support sustainable agricultural transformation and development in ecological sub-regions of the Mekong Delta." According to the theory of public investment in conjunction with the production function, government spending on infrastructure plays a crucial role in promoting economic growth (Fan *et al.*, 2004; Moguees *et al.*, 2012). Irrigation systems, as public goods, contribute to increased output by providing a reliable water supply, reducing drought risks, and

enabling multiple cropping seasons per year. Therefore, irrigation becomes essential for agricultural productivity, enabling farmers to alleviate water scarcity, stabilize yields, and adapt to environmental challenges. Investments in irrigation infrastructure are, thus, critical for enhancing agricultural production, particularly in regions like the Mekong Delta, where rice cultivation is vital for national food security (Barker *et al.*, 2004).

Prior to the construction of significant irrigation projects, the government undertakes environmental and social impact evaluations. A literature survey revealed scant studies assessing the impact of irrigation investments on agricultural output in the Mekong Delta. This study sought to examine the effects of governmental investments in irrigation on agricultural development in the Mekong Delta.

Methodology

Literature review

Irrigation is fundamental to agricultural productivity, allowing farmers to mitigate water scarcity, stabilize yields, and adjust to environmental problems. Investments in irrigation infrastructure are essential for improving agricultural productivity, especially in areas such as the Mekong Delta, where rice cultivation is vital for national food security (Barker *et al.*, 2004). This updated literature review consolidates the theoretical and empirical data about the effects of irrigation investment on agricultural production, incorporating fresh studies to address contemporary trends and deficiencies in the original framework. The review examines global and regional research to elucidate the mechanisms by which irrigation enhances productivity, its socio-economic ramifications, and the increasing concerns of sustainability and climate change. This section sought to establish a solid basis for examining the role of irrigation in the Mekong Delta by synthesizing research from the preceding five years.

The theoretical foundations of irrigation's influence on agriculture are based on the agricultural production function, particularly the

Cobb-Douglas model (Cobb & Douglas, 1928). Irrigation can be conceptualized as a capital input or a productivity enhancer, as it augments water supply, mitigates crop stress, and facilitates intensive agricultural methods. Recent research expanded this approach to incorporate environmental variables, such as rainfall variability, which affect the efficacy of irrigation (Hanjra & Qureshi, 2010; Wu *et al.*, 2023). Wu *et al.* (2023) contended that irrigation significantly enhances yield stability in areas with unpredictable rainfall, a situation particularly pertinent to the flood-prone and saline-impacted ecosystems of the Mekong Delta. The Cobb-Douglas model offers a versatile framework to measure the impact of irrigation on agricultural growth. The theory of public investment, alongside the production function, emphasizes the significance of government expenditures on infrastructure in fostering economic development (Fan *et al.*, 2004; Mogues *et al.*, 2012). Irrigation systems, classified as public goods, augment productivity by providing a dependable water supply, alleviating drought risks, and facilitating numerous cropping cycles. Fan *et al.* (2004) estimated that public irrigation investments in India generated returns of 10-15% through increased yields and poverty alleviation, a conclusion supported by findings in Vietnam's Mekong Delta (Barker *et al.*, 2004). Recent studies have highlighted the enduring advantages of irrigation, especially in locations susceptible to climate change. Burney *et al.* (2021) illustrated that irrigation investments mitigate 20–30% of yield losses due to drought, underscoring their significance in enhancing resilience. In the Mekong Delta, where salt intrusion and upstream damming jeopardize water supplies, public investment in irrigation is essential for maintaining agricultural productivity (Dang *et al.*, 2022).

This theory substantiates the emphasis on government-sponsored initiatives in this analysis. Environmental sustainability has become a crucial framework for assessing irrigation investments. Irrigation enhances production; yet, if mismanaged, it may deplete water supplies, deteriorate soil quality, and

disturb ecosystems (Micklin, 2016). Grafton *et al.* (2018) endorsed sustainable irrigation methods, including drip and precision systems, to enhance productivity while reducing environmental impacts. In the Mekong Delta, salinity intrusion intensifies water management difficulties, requiring expenditures that reconcile agricultural demands with ecological conservation (Dang *et al.*, 2022). Recent studies have emphasized the necessity of incorporating environmental variables, such as precipitation and soil salinity, into production models to precisely evaluate the net effects of irrigation (Wu *et al.*, 2023; Nguyen *et al.*, 2024). These observations highlight the necessity for a sophisticated strategy for irrigation investment, especially in ecologically delicate areas. Empirical research has repeatedly demonstrated that investment in irrigation improves agricultural output by augmenting crop yields and expanding arable land. Irrigation globally sustains roughly 270 million hectares of agricultural land, accounting for 40% of food production (Pascale *et al.*, 2011). Hussain and Hanjra (2020) performed a meta-analysis of 50 irrigation projects, revealing yield enhancements of 15-40%, particularly pronounced in water-scarce areas. Nhamo *et al.* (2019) revealed that smallholder irrigation projects in sub-Saharan Africa increased maize yields by 25% and household incomes by 30%, underscoring irrigation's dual function in enhancing productivity and alleviating poverty. Recent innovations in irrigation technology have enhanced these advantages. Wu *et al.* (2023) discovered that drip irrigation in China increased wheat and maize yields by 15% and enhanced water productivity by 10-20%, indicating possible implications for rice-based systems in the Mekong Delta.

Irrigation in the Mekong Delta has revolutionized agricultural methods, allowing farmers to go from single to double or triple plantings (Barker *et al.*, 2004). Investments on canals and sluice gates during the 1990s and 2000s mitigated soil acidity and flood threats, resulting in 20-30% increases in rice yields. Recent studies have emphasized climate adaptability and efficiency. Dang *et al.* (2022)

discovered that irrigation infrastructure in coastal provinces like Kien Giang mitigated saline intrusion, enhancing rice yields by 10-15%. The authors warn that excessive extraction jeopardizes long-term sustainability in the absence of comprehensive water management. Tran & Le (2021) examined panel data from 2005 to 2018, concluding that irrigation investment augmented the agricultural GRDP by 8% per province, with more pronounced effects in upstream regions less impacted by salt. Tran *et al.* (2024) investigated precision irrigation in An Giang, documenting a 12% increase in output and a 20% reduction in water usage, highlighting the potential of smart technology in the area.

The efficacy of irrigation investments is an increasing subject in contemporary literature. Bathla *et al.* (2021) evaluated public irrigation in India, discovering that canals functioned at 59% efficiency due to maintenance delays and inadequate governance. Tran & Le (2021) similarly observed that antiquated canal systems in the Mekong Delta diminish investment returns, highlighting the necessity for upgrading. Rebound effects, when water conservation results in heightened use, further complicate efficiency improvements. Berbel *et al.* (2020) noted that drip irrigation in Spain's Guadalquivir Basin led to increased water use as farmers enlarged irrigated regions, a concern pertinent to the intensification trends in the Mekong Delta. These findings underscore the significance of government and technology in optimizing the advantages of irrigation. Climate change intensifies the necessity for irrigation investment. Burney *et al.* (2021) predicted that irrigation can alleviate 20-30% of yield losses due to drought, rendering it an essential adaptation technique. In the Mekong Delta, elevated sea levels and diminished upstream flows jeopardize rice cultivation, requiring resilient irrigation systems (Dang *et al.*, 2022). Recent research investigated irrigation powered by renewable energy to improve sustainability. Hossain & Islam (2022) discovered that solar-powered irrigation in Bangladesh enhanced rice yields by 10% and diminished CO₂ emissions by 4-5 tons ha⁻¹ year⁻¹, presenting a viable model for the Mekong Delta. Grafton *et al.* (2018) indicated that precision

irrigation in Australia enhanced water use efficiency by 25%, implying scalable solutions for the coastal regions of Vietnam. Current trends in irrigation research emphasize intelligent and sustainable systems. Abioye *et al.* (2022) conducted a study of 170 papers on smart irrigation, revealing yield enhancements of 10-15% and water conservation enhancements of 20-30% facilitated by AI and IoT technologies. These systems have not been sufficiently investigated in the Mekong Delta, where conventional canals prevail (Nguyen *et al.*, 2024). The socio-economic repercussions also require consideration. Nhamo *et al.* (2019) discovered that irrigation schemes in Malawi diminished poverty by 20%, although the advantages were disproportionately allocated to affluent farmers due to discrepancies in land access. Tran & Le (2021) saw comparable disparities in Vietnam, where larger farms gained greater advantages from irrigation owing to superior access to technology. These findings underscore the necessity for inclusive policies to guarantee equitable outcomes.

Notwithstanding comprehensive study, numerous gaps remain. Long-term research on the resilience of irrigation systems in the context of climate change are limited, especially in the Mekong Delta, where salinity and flooding present persistent challenges (Burney *et al.*, 2021). Secondly, extensive cost-benefit evaluations that have incorporated environmental costs, such as soil deterioration, are constrained (Dang *et al.*, 2022). Third, the scalability of smart irrigation systems in resource-limited environments remains inadequately researched, despite its potential (Nguyen *et al.*, 2024). The distributional impacts of irrigation expenditures, particularly for smallholder farmers, necessitate additional investigation to address equity issues (Nhamo *et al.*, 2019). This paper fills existing gaps by delivering a contemporary econometric analysis of irrigation's effects in the Mekong Delta, utilizing panel data from 2009 to 2023 and integrating environmental factors to account for climate fluctuation.

The evidence confirms that irrigation investment improves production, resulting in

global yield improvements of 15-40% and Mekong Delta increases of 10-30% (Barker *et al.*, 2004; Hussain & Hanjra, 2020; Dang *et al.*, 2022). Recent research underscores sustainability and climate resilience; yet, inefficiencies and disparities reveal the necessity for innovation (Berbel *et al.*, 2020; Bathla *et al.*, 2021). This study addressed deficiencies in previous Mekong Delta studies. In contrast to previous research utilizing data up to 2018 (Tran & Le, 2021), this study encompassed the period from 2009 to 2023, highlighting increased salinity and damming effects. Incorporating rainfall fills a gap in research such as Dang *et al.* (2022), isolating the net effect of irrigation. The regional scale differentiates it from localized analyses (Nguyen *et al.*, 2019), and its emphasis on GRDP provides more comprehensive economic insights than yield-focused research (Barker *et al.*, 2004). These developments underscore the study's importance, offering contemporary, comprehensive evidence for sustainable agriculture practices.

Data and estimation model

The study utilized secondary data from the 13 provinces/cities in the Mekong Delta for the period of 2009-2023. The irrigation investment expenditure data for the Mekong Delta encompassed only investments in irrigation infrastructure, including costs for maintenance, upkeep, and dredging of operational irrigation canals, construction of new sluices and irrigation dams for water regulation in the Mekong Delta, and coastal embankment systems to prevent erosion in coastal areas. This excluded investments in roads, electricity, and other infrastructure for rural areas of the Mekong Delta. Meanwhile, K represented the general annual investment expenditures (allocated to and implemented by local authorities) for the agriculture and rural sectors of the Mekong Delta localities. The annual investment capital variable was included to avoid overestimation bias of the impact of irrigation investment on agricultural growth in the Mekong Delta. Both irrigation investments and general investments in agriculture and rural development in the Mekong

Delta constituted only public investments and excluded private investments due to data limitations. The cultivated land area included areas under perennial crops, annual crops, and aquaculture; encompassing both irrigated and non-irrigated areas. All monetary variables were adjusted to constant 2010 prices to eliminate the effects of inflation.

The feasible generalized least squares (FGLS) method was selected to estimate the Cobb-Douglas production model based on the panel data from the 13 provinces in the Mekong Delta during the period of 2009-2023, due to its ability to address common econometric issues in panel data, including heteroskedasticity and autocorrelation. The results of the modified Wald and Wooldridge tests confirmed the presence of both problems (**Table 4**), making methods such as ordinary least squares (OLS) inappropriate. Compared to the fixed effects model (FEM), FGLS was preferred because the Hausman test indicated that FEM was more suitable than the random effects model (REM), and FEM does not effectively handle heteroskedasticity and autocorrelation. REM was excluded because the assumption that errors are uncorrelated with the independent variables was not satisfied in this dataset. FGLS adjusts the error covariance matrix, ensuring efficient and unbiased estimates while maintaining the interpretability of elasticities for variables such as irrigation investment, capital, labor, and land. This method is particularly suitable for long panel data (T = 15) with a limited number of provinces (n = 13), providing reliable results for policy analysis (Tabak *et al.*, 2013).

Drawing on the Cobb-Douglas production function and the theory of public investment, the estimation model is specified as follows:

$$\begin{aligned} \ln(GRDP_{it}) = & \alpha + \beta_1 \ln(Irriga_{it}) + \beta_2 \ln(K_{it}) \\ & + \beta_3 \ln(Labour_{it}) \\ & + \beta_4 \ln(Land_{it}) \\ & + \beta_5 \ln(Rain_{it}) + \gamma_i + \delta_t + \varepsilon_{it} \end{aligned}$$

where:

$GRDP_{it}$: Agricultural GRDP of province i at time t (billion VND, constant 2010 prices),

$Irriga_{it}$: Public investment in irrigation projects (billion VND, constant 2010 prices),

K_{it} : Agricultural investment capital, excluding irrigation (billion VND, constant 2010 prices),

$Labour_{it}$: Number of agricultural laborers aged 16-60 (thousand people),

$Land_{it}$: Agricultural land area (thousand m²),

$Rain_{it}$: Average annual rainfall (mm),

ε_{it} : Error term,

α : Constant term, and

$\beta_1; \beta_2, \beta_3, \beta_4, \beta_5$: Coefficients representing the elasticities of GRDP with respect to each input.

The log-linear specification was chosen for several reasons. First, it aligns with the Cobb-Douglas production function, allowing for the estimation of input elasticities. Second, it mitigates heteroskedasticity commonly observed in economic data. Third, it facilitates the interpretation of coefficients as percentage changes, which is intuitive for policy analysis (Fan *et al.*, 2004).

The variables in the estimation model are summarized and described in **Table 1**.

Results and Discussion

The current status of irrigation and agricultural production in the Mekong Delta

The Mekong Delta (MD) features a low-lying, flat terrain directly influenced by the Mekong River's hydrological regime and the East-West Sea tidal patterns. Consequently, irrigation plays a pivotal role in agricultural production and the livelihoods of the nearly 18

million inhabitants in the region. Over the past two decades, the government has invested substantially in large-scale irrigation infrastructure, combined with internal canal networks, creating a multifunctional irrigation system that serves both agricultural production and disaster prevention. As of 2023, the entire region encompassed over 23,000km of main canals and primary and secondary channels, connected to approximately 75,000km of internal field canals and ditches, ensuring water supply and drainage for most cultivated areas. Additionally, the irrigation system included more than 1,100 major and minor headwork structures alongside thousands of commune and district-level regulatory gates, with a total capacity for salinity control, freshwater retention, and flood drainage covering over 2 million hectares of agricultural land. The flood control dike systems in Dong Thap Muoi, the Quadrangle of Long Xuyen, and along the Tien and Hau Rivers span thousands of kilometers, playing a crucial role in expanding the third-season rice cultivation area. Notable inter-regional key projects include the Cai Lon-Cai Be Sluice in Kien Giang, which controls salinity and freshwater for over 384,000 hectares of agricultural land while providing domestic water for approximately 1.5 million residents; the O Mon-Xa No system in Can Tho-Hau Giang, serving as a water supplier and drainage system for over 300,000 hectares of agricultural land; the Nam Mang Thit system in Vinh Long-Tra Vinh, protecting approximately 130,000 hectares of agricultural land from saline

Table 1. Variables of the estimation model

Variables	Unit	Description	Source of data
GRDP	Billion VND	Agricultural GRDP at constant 2010 prices	Statistical Yearbooks for the 13 Mekong Delta provinces
K	Billion VND	Annual investment capital in agriculture in the Mekong Delta (at constant 2010 prices)	Statistical Yearbooks for the 13 Mekong Delta provinces
Irriga	Billion VND	Annual investment in irrigation projects in the Mekong Delta (at constant 2010 prices)	Ministry of Agriculture and Rural Development, Vietnam
Land	Thousands of hectares	Land area used for agricultural production in the Mekong Delta	Statistical Yearbooks for the 13 Mekong Delta provinces
Labor	Thousands of people	Number of agricultural laborers aged 16-60 years old	Statistical Yearbooks for the 13 Mekong Delta provinces
Rain	mm	Average annual rainfall	Statistical Yearbooks for the 13 Mekong Delta provinces

intrusion; and the Go Cong system in Tien Giang, safeguarding over 54,000 hectares of coastal cultivated land.

This irrigation infrastructure has yielded substantial benefits, notably the capability for proactive water supply and drainage management, flood mitigation during the rainy season, and salinity prevention with freshwater retention during the dry season, thereby ensuring rice, fruit, and aquaculture production. Simultaneously, irrigation has facilitated the promotion of seasonal structural transformation and the development of diverse farming models such as rice-shrimp and rice-fish systems, contributing to enhanced farm household incomes. Furthermore, these facilities ensure domestic water supply for millions of rural residents and play a vital role in national food security. Overall, the MD irrigation system has established a multi-tiered network, from major headworks to internal field canals and ditches, serving both water control functions and socio-economic development support. However, facing mounting challenges from climate change, saline intrusion, and alterations in Mekong River flow patterns, the need for upgrading, modernizing, and efficiently managing the irrigation system's operations has become an urgent task toward achieving sustainable and adaptive agriculture in the future.

Analysis of coefficient correlation

To test the multicollinearity issue of the dependent variables, this study employed the correlation matrix described in **Table 2**. The results showed that the absolute value of the correlation coefficients was less than 0.8. This means the model does not suffer from serious multicollinearity.

Tests for selecting panel data regression models

Firstly, the research tested the stationarity of the data to ensure the most reliable results. The results of the Maddala-Wu test (Maddala & Wu, 1999) and the Pesaran test (Pesaran, 2007) indicated that all the series were stationary either at their levels or at their first difference. This ensures the validity of the regression estimation

results. The outcomes of the stationarity tests for the data used in the study are presented in **Table 3**.

To assess the appropriateness of the estimation model, the Hausman test was conducted with the null hypothesis that the differences in the coefficients were not systematic. The probability of the Hausman test was 0.0000, less than the significance level of 1%, meaning that the fixed effect model was appropriate with the characteristics of the data.

The results of modified Wald test indicated that there was heteroskedasticity as well as first order autocorrelation issues based on the result of the Wooldridge test (**Table 4**). Consequently, the FGLS method was applied to solve the above problems (Tabak *et al.*, 2011).

Feasible generalized least square results

The FGLS estimation results of the impact of irrigation investment and other factors on agricultural production in the Mekong Delta are presented in **Table 5**. The feasible generalized least squares (FGLS) regression, performed on the panel data from the 13 provinces in the Mekong Delta (2009-2023), estimated a Cobb-Douglas production function with $\ln(\text{GRDP})$ as the dependent variables, namely irrigation investment, agricultural capital, labor, land area, and rainfall, and fixed effects for province and time. This model adjusts for heteroskedasticity and autocorrelation, guaranteeing reliable outcomes. The coefficients indicated substantial effects for the majority of the variables: irrigation (0.0212, $P = 0.029$), capital (0.1161, $P < 0.01$), labor (0.2369, $P < 0.01$), and land (0.1114, $P < 0.01$), although rainfall (0.0634, $P = 0.418$) was deemed negligible. These findings underscore the essential contributions of labor, capital, and land to agricultural productivity, with irrigation serving a supplementary function in bolstering resilience. This section examines the results, assesses their economic ramifications, and juxtaposes them with regional and worldwide research to contextualize their importance.

The irrigation investment coefficient of 0.0212 ($P = 0.029$) signifies that a 1% increase in public irrigation expenditure would elevate the agricultural GRDP by 0.0212%, all else being equal. In a province with an average GRDP of 50

Table 2. Matrix of the correlation coefficient between variables

Variables	GRDP	K	Labor	Land	Irriga	Rain
GRDP	1.0000	0.5543	0.6834	0.4709	0.2854	0.1297
K	0.5543	1.0000	0.1415	0.0603	0.1242	0.2332
Labor	0.6834	0.1415	1.0000	0.5430	0.1203	-0.0759
Land	0.4709	0.0603	0.5430	1.0000	0.2184	0.3623
Irriga	0.2854	0.1242	0.1203	0.2184	1.0000	0.1607
Rain	0.1297	0.2332	-0.0759	0.3623	0.1607	1.0000

Table 3. The results of the unit root test

Variables	Maddala-Wu test		Pesaran test	
	Level	First difference	Level	First difference
GRDP				-66.623*** (0.000)
K		44.559** (0.013)		-2.230** (0.013)
Labor		67.086*** (0.000)		-2.244**
Land	47.384*** (0.006)			
Irriga	40.215** (0.037)			
Rain	-2.244** (0.012)			

Note: (***): statistically significant at the 1% level, (**): statistically significant at the 5% level, (*): statistically significant at the 10% level, (ns): not statistically significant.

Table 4. Regression model appropriation test.

The null hypotheses	Probability	Decision
Difference in coefficients not systematic	0.0000	Reject
There is the absence of heteroskedasticity	0.0000	Reject
No first order autocorrelation	0.0000	Reject

Table 5. Results from the FGLS

Variables	Coef.	Std. Err	Prob.
lnIrriga	0.0212	0.0096	0.029**
lnK	0.1161	0.0222	0.000***
lnLabor	0.2369	0.0558	0.000***
lnLand	0.1114	0.0338	0.001***
lnRain	0.0634	0.0783	0.418 ^{ns}

Note: (***): statistically significant at the 1% level, (**): statistically significant at the 5% level, (*): statistically significant at the 10% level, (ns): not statistically significant.

trillion VND, a 1% increase in irrigation spending (from 500 billion VND to 505 billion VND) would contribute an additional 1.06

billion VND, culminating in a total of 13.78 billion VND across the 13 provinces annually. This modest, yet substantial, effect corroborates

the concept that irrigation improves productivity by securing water availability, alleviating flooding, and combating saline intrusion—critical issues in the Mekong Delta. Barker *et al.* (2004) discovered that irrigation investments in the 1990s facilitated double-cropping, resulting in a 20-30% increase in rice yields, with an inferred elasticity of 0.03-0.05. The lower elasticity of 0.0212 indicates the region's developed irrigation system, where marginal improvements are diminished due to saturation, as evidenced by province fixed effects. Regional analyses further substantiate these findings. Tran & Le (2021) projected an 8% increase in the GRDP per province with elasticity values ranging from 0.03 to 0.04. Similarly, Dang *et al.* (2022) documented yield enhancements of 10-15% in salinity-impacted regions, including Kien Giang, with elasticity values between 0.015 and 0.025. Nguyen *et al.* (2019) observed a 10-12% yield enhancement via alternating wetting and drying (AWD) in An Giang (elasticity 0.02-0.03), while Tran *et al.* (2024) reported a 12% yield gain using precision irrigation in the same region, indicating that technology can augment the efficacy of irrigation. Hussain and Hanjra (2020) claimed global yield gains of 15-40% (elasticity 0.05-0.12), while Wu *et al.* (2023) noted a 15% increase in China (elasticity 0.05-0.10). The Mekong Delta's reduced elasticity is reasonable due to its emphasis on resilience rather than growth, in contrast to less irrigated areas such as sub-Saharan Africa (Nhamo *et al.*, 2019).

The coefficient of agricultural capital, 0.1161 ($P < 0.01$), indicates that a 1% increase in non-irrigation capital (such as machines and fertilizers) would result in a 0.1161% rise in the GRDP. For a province with a GRDP of 50 trillion VND, this would equate to an increase of 5.805 billion VND for each 1% rise in capital (e.g., from 1 trillion VND to 1.01 trillion VND), totaling 75.465 billion VND regionally. This highlights the connection between capital and irrigation, particularly as mechanization advances in the Mekong Delta. Nguyen *et al.* (2019) discovered that automation in An Giang increased rice yields by 10%, enhancing alternate wetting and drying (AWD), but Tran and Le (2021) indicated a diminished capital elasticity of

0.07-0.09, presumably attributable to their earlier study period (2005-2018) lacking modern mechanized developments. Fan *et al.* (2004) projected a global return on capital of 8-12% in India (elasticity 0.07-0.09), while Nhamo *et al.* (2019) reported a 20% increase in maize yield in sub-Saharan Africa (elasticity 0.08-0.10). The increased elasticity seen indicates the Mekong Delta's transition to modern inputs, a tendency not as apparent in previous research such as Barker *et al.* (2004).

The labor coefficient of 0.2369 ($P < 0.01$) was the highest, signifying that a 1% increase in labor would result in a 0.2369% rise in the GRDP. In a province with a GRDP of 50 trillion VND, a 1% increase in labor (from 500,000 to 505,000 laborers) would contribute an additional 11.845 billion VND, resulting in a regional total of 154.085 billion VND. This underscores the labor-intensive characteristics of rice farming in the Mekong Delta, where manual activities such as transplanting are essential. Tran & Le (2021) predicted a diminished labor elasticity of 0.06-0.08, potentially attributable to their abbreviated timeframe or absence of rainfall controls, which were incorporated in our model. Nhamo *et al.* (2019) identified an elasticity of 0.06-0.08 in Malawi, which is lower than our findings, indicating the Mekong Delta's heightened need for labor for rice production systems. Mechanization in regions such as An Giang (Nguyen *et al.*, 2019) may diminish this reliance over time.

The land coefficient of 0.1114 ($P < 0.01$) indicates that a 1% increase in cultivated land would result in a 0.1114% rise in GRDP. For a province with a GRDP of 50 trillion VND, this would indicate an increase of 5.57 billion VND for each 1% extension of land, totaling 72.41 billion VND regionally. This underscores the significance of land despite challenges such as salinity and development. Tran & Le (2021) documented a comparable land elasticity of 0.10-0.12, but Hussain & Hanjra (2020) observed a 10-20% global augmentation in cultivated land (elasticity 0.10-0.15), corroborating our results. Barker *et al.* (2004) noted a 15% expansion of cultivable area due to irrigation in the 1990s, which our research quantifies in economic terms.

The rainfall coefficient of 0.0634 ($P = 0.418$) was insignificant, indicating that yearly rainfall changes do not significantly influence the GRDP. The tropical monsoon climate of the Mekong Delta, characterized by annual precipitation of 1,400-2,400mm predominantly from May to November, saw variations from 2009 to 2022 as a result of climate change and El Niño/La Niña phenomena, including floods in 2010 and 2016 and droughts in 2015 and 2019 (Smajgl *et al.*, 2015). Nonetheless, irrigation infrastructure, bolstered by policies like Decision 1397/QĐ-TTg (2012), alleviated these effects by guaranteeing a consistent water supply and drainage. Upstream damming, such as the Nuozhadu Dam in 2012, diminished dry-season flows by 20-30%, while sea levels increases of 3-4mm annually exacerbated salinity, impacting 600,000 hectares in 2016 and 2020 (Dang *et al.*, 2022). Initiatives such as the Cai Lon-Cai Be sluice (2020) addressed these concerns by diminishing reliance on rainfall. The precise water requirements for rice production, satisfied through irrigation, reduce the significance of rainfall (Tran *et al.*, 2024). Rosegrant *et al.* (2009) observed the minimal influence of rainfall in well-irrigated tropical areas, corroborating our conclusion.

Input interactions disclose essential dynamics. The high elasticity of labor (0.2369) relative to irrigation (0.0212) and capital (0.1161) highlights its preeminence in rice production, whereas the role of capital indicates that mechanization amplifies the advantages of irrigation, as evidenced in India (Fan *et al.*, 2004). The contribution of land (0.1114) underscores resource limitations, whereas the insignificance of rainfall (0.0634) accentuates the stabilizing function of irrigation (Rosegrant *et al.*, 2009). These results correspond with regional studies (Nguyen *et al.*, 2019; Dang *et al.*, 2022) and international research (Fan *et al.*, 2004; Hussain & Hanjra, 2020), hence affirming the model's resilience. They emphasize labor and capital as fundamental drivers of prosperity, with irrigation bolstering resilience in the climate-sensitive Mekong Delta.

Beyond these economic impacts, irrigation systems in the Mekong Delta have considerable environmental effects that necessitate meticulous

attention for sustainable management. The extensive application of irrigation has led to soil deterioration by salinization, especially in coastal provinces like Kien Giang and Ben Tre, where saltwater intrusion impacted 600,000 hectares of agricultural land in 2016 and 2020 (Dang *et al.*, 2022). Intensive groundwater extraction for irrigation in the dry season, together with inadequately managed canal systems, has intensified soil sinking, averaging 1-2cm annually throughout the region (Minderhoud *et al.*, 2017). The Delta's wetland ecosystems, essential for biodiversity and water regulation, have been jeopardized by modified natural flow regimes due to irrigation infrastructure, exemplified by the Cai Lon-Cai Be sluice completed in 2020, which, although effective in salinity management, diminishes sediment deposition and disturbs the soil nutrient equilibrium (Smajgl *et al.*, 2015). The extension of irrigated areas has induced a rebound effect, wherein enhanced water access leads to greater consumption, further exhausting surface and groundwater resources, particularly in light of a 20–30% decrease in upstream flows caused by dams such as Nuozhadu (Dang *et al.*, 2022). The environmental concerns underscore the necessity for sustainable approaches, such drip irrigation and integrated water management, to reconcile agricultural productivity with ecological conservation in the Mekong Delta.

Conclusions

The FGLS estimation results indicated that labor, capital, and land continue to play decisive roles in agricultural growth in the Mekong Delta, reflecting the labor-intensive nature of the region's agriculture. Notably, the elasticity coefficient of irrigation investment (0.0212), though smaller than those of capital (0.1161) and labor (0.2369), remains both statistically and economically significant. This finding confirms that irrigation serves as an essential complementary factor in stabilizing production under conditions of climate change, salinity intrusion, and upstream flow fluctuations. Rainfall was found to have no significant effect, reinforcing the notion that the current irrigation system has largely substituted the natural role of

rainfall in ensuring water availability for production. These findings suggest that policies for sustainable agricultural development in the Mekong Delta should focus on three pillars: (i) maintaining and improving the efficiency of labor and land use; (ii) promoting investment and technological advancement, including mechanization; and (iii) continuing selective investment in irrigation systems, not merely to expand irrigated areas but, more importantly, to enhance resilience against drought, salinity intrusion, and climate risks. In this sense, the future goal of irrigation development should move beyond simply increasing output to strengthening sustainability and adaptive capacity for the entire regional agricultural system.

Despite providing empirical evidence on the role of irrigation in agricultural growth in the Mekong Delta, this study had several limitations. First, the provincial-level data employed may not have fully captured the heterogeneity in the structure and efficiency of irrigation systems at the district or household levels. Second, the analysis focused mainly on economic outcomes (agricultural GRDP) while not fully accounting for the social and environmental benefits of irrigation, such as improved livelihoods, disaster risk reduction, or ecosystem services. Third, the model primarily incorporated traditional variables (capital, labor, land, irrigation, and rainfall) and did not consider emerging factors, such as the impact of digital transformation in irrigation management or fluctuations in agricultural trade policies. Moreover, this study did not explicitly address the institutional and governance dimensions that shape agricultural outcomes. Khan *et al.* (2024) demonstrated that weak governance—manifested in corruption, smuggling, and institutional inefficiencies—can undermine household food security, while Khan *et al.* (2025) highlighted the importance of infrastructure knowledge and climate-resilient technologies in enhancing resilience and long-term food security. These insights suggest that irrigation's contributions should not be evaluated solely in economic terms but also within broader institutional and technological contexts. Future research should therefore adopt more disaggregated data and integrate institutional,

governance, and technological variables, potentially combining quantitative and qualitative approaches, to provide a more comprehensive understanding of irrigation's role in sustainable agricultural development and food security.

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