How Many Acres Do We Need to Fallow to Control Saltwater Intrusion in a Mega-Delta under Uncertainty?

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Selected Paper prepared for presentation at the 2024 Agricultural & Applied Economics Association Annual Meeting, New Orleans, LA; July 28-30, 2024

Abstract: Vietnam is the world's third-largest rice exporter. The country exports around seven million tons of milled rice annually, most of which originate from the Mekong Delta. The rice exported from the Delta accounts for about one-fifth of the total rice traded worldwide. Anthropogenic morphological activities intensify saltwater intrusion threatening rice production in this Delta. In response, the Vietnamese Government has implemented various strategies, including land use planning policies, e.g., land fallowing. We propose an integrated model that couples a hydro-statistical model with the Inventory Theory to evaluate the trade-offs between reducing saltwater intrusion intensity, and risks and agricultural productivity losses due to a potential land fallowing policy by 2050. The analysis reveals that the non-exceeding probability of saltwater intrusion level is approximately 0.8 at the optimal point. Under the baseline scenario, our proposed model indicates that fallowing of 123,552 acres could prevent saltwater intrusion-affected areas from surpassing 4.79 million acres, an average historical saltwater intrusion level in the Mekong Delta. However, with a sea-level rise of 22 cm factored in, 494,201 acres would need to be fallowed to maintain saltwater intrusion levels within historical limits. This adjustment would result in annual crop revenue losses of approximately $209.7 million. Under the combined effects of sea-level rise, land subsidence, and riverbed incision scenarios, the findings suggest that to sustain the saltwater intrusion level at the historical saltwater intrusion level, 247,105 acres would require fallowing. This would lead to estimated crop revenue losses of $104.8 million and significant construction costs – estimated at around eight billion US dollars – for implementing additional saltwater control engineering infrastructure within the Mekong Delta.

Keywords: Saltwater intrusion, Rice production, Mekong Delta, Uncertainty, Inventory Theory.

1. Introduction

Climate change has led to more prolonged and severe droughts worldwide in many major food production regions. One of the global policy concerns is to meet the growing demand for food with less water resources (UN, 2023). The world population is growing rapidly and is expected to reach 9.8 billion in 2050 and 11.2 billion in 2100 (Dinar, Tieu, & Huynh, 2019). About 10% of the world's population is estimated to live in lowland areas and river deltas (IPCC, 2023).

Anthropogenic morphological activities, such as sand mining, the construction of hydropower facilities, and rising sea levels caused by climate change, could hasten environmental transformations in river deltas globally. This could manifest as heightened erosion of riverbeds and banks, saltwater intrusion (SWI), and increased risks of land subsidence. Consequently, the well-being and food security of communities in these delta areas may face significant challenges (Eslami et al., 2021; Hackney et al., 2020; Kondolf et al., 2022; Schmitt et al., 2021; Tran et al., 2024).

Vietnam is the third-largest rice exporter in the world. It exports around seven million metric tons of milled rice annually, most of which come from the Mekong Delta (MKD). The rice exported from the Delta accounts for about one-fifth of the total rice traded worldwide. Rice encompasses more than 90 percent of the crop area planted in the MKD. Increased saltwater intrusion in dry years likely causes a significant reduction in rice production in this region. Recently, a series of large hydropower dams have been proposed and built upstream of the Mekong River. The total installed capacity of hydropower projects in the lower basin of the Mekong River Basin was 12,286 MW in 2020 and is expected to reach 30,344 MW in 2040 (MRC, 2024). Recent studies suggested that new and proposed dams in the upper Mekong River basin likely increase SWI intensity and risk in the Delta. These dams block water and sediment flow to the MKD, thus causing considerable land subsidence and riverbed incision. Also, coastal lowland rice-growing areas stand to be most impacted by sea-level rise (SLR), which is projected to rise by 0.2 inches per year (IPCC, 2023).

The Vietnamese Government has initiated various plans to tackle this problem, including land use control (e.g., reducing rice acreage) and better water management strategies by 2050. Fallowing and/or shifting low-productive land in the upper areas of the MKD toward less water-intensive crops could reduce the SWI in the coastal areas. The effects of the policy on optimal water management accounting uncertainty and costs are scant (Loc, Low Lixian, et al., 2021; Loc, Van Binh, et al., 2021; Thong & Tortajada, 2022). We develop a hydro-statistical-economic model integrating an economic model based on Inventory Theory with a crop yield, a statistical model, and a hydrologic model to assess the trade-offs between reducing SWI risk and agricultural losses.

2. Methodology

2.2.1. Study area

Our research focuses on the MKD, which comprises two natural floodplains. One floodplain spans across Vietnam, covering substantial areas of An Giang and Dong Thap provinces and significant portions of Kien Giang and Long An provinces (Fig. 1). The second floodplain is the Tonle Sap Lake in Cambodia. Both floodplains serve as natural reservoirs, storing water during wet seasons and redistributing it to the MKD during dry seasons.

Over the past thirty years, significant portions of these two floodplains have undergone conversion into agricultural and urban areas. In the VMD, the construction of dikes and flood control infrastructure has been implemented to manage flooding during the wet season, enabling the cultivation of two (or even three in certain areas) rice crops per year (Dung, vanHalsema, Hellegers, Hoang, & Ludwig, 2019; Käkönen, 2008; Triet et al., 2017). This floodplain in Vietnam contributes approximately one-third of the country's total rice production (GSO, 2023). Previous research has suggested that lowering the elevation of dikes could enhance the floodplain's capacity to retain greater volumes of floodwater for longer periods during the rainy season. Consequently, the stored water could then be gradually released downstream to mitigate the intensity and risks of saltwater intrusion during the dry season. However, the main drawbacks of this approach are primarily linked to a decrease in rice production, resulting in the cultivation of only one to two rice crops annually instead of two to three (Dung et al., 2019; Käkönen, 2008; Triet et al., 2017).

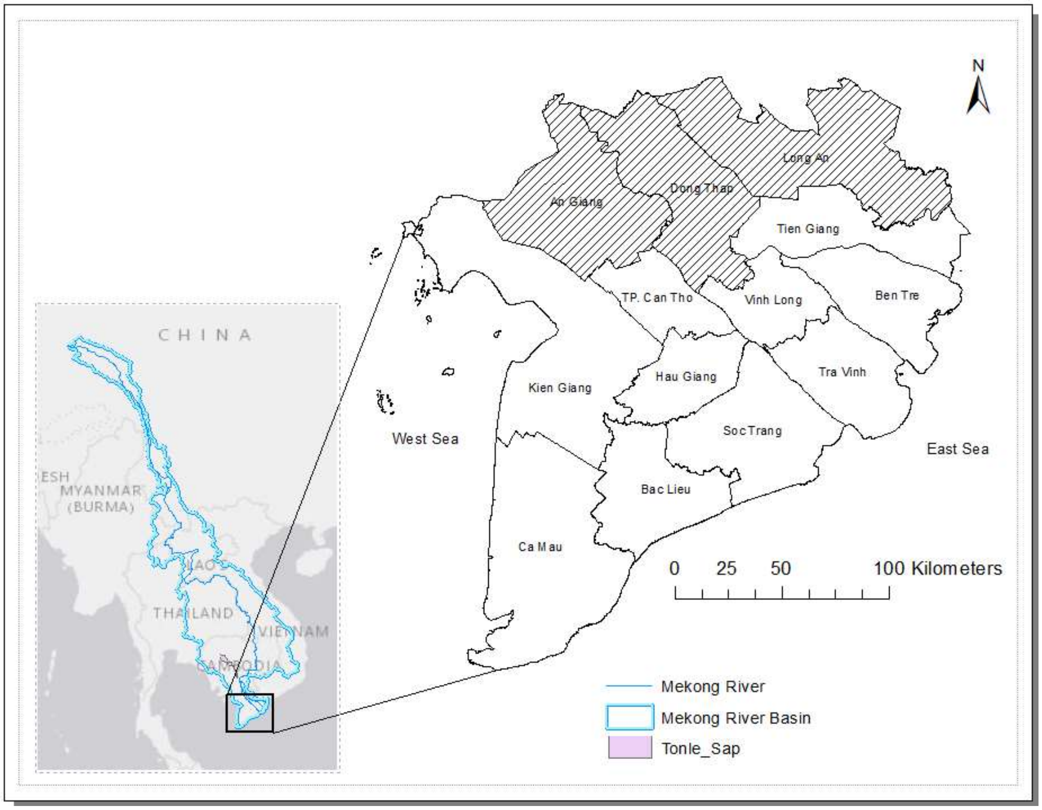

Figure 1. The study area, the Mekong Delta, with administrative province boundaries. We assess the change in agricultural land use for the crosshatched provinces. A large part of the crosshatched provinces are historically floodplain areas, locally known as the Long Xuyen Quadrangle and Plain of Reeds.

2.2.2. An economic model for optimizing land fallowing acres

Resolution 120, issued by the Vietnamese Government, provides a legal framework for policies that aim to develop and adopt climate-resilient sustainable practices (VNG, 2017). The Resolution highlights the need to incorporate nature-based adaptation approaches, e.g., flood-based farming systems in floodplain regions, rotating rice with shrimp in coastal areas, and land fallowing, which has yet to be used widely in the VMD. Suppose the land fallowing were to be used widely every year during the rainy season; policymakers need to decide on how many acres to fallow during the rainy season to increase water storage in the upper part of the MKD so that this stored water can be released to the coastal part of the MKD to control SWI during subsequent dry season. Our proposed economic model relies on the marginal decision rule presented in the figure below.

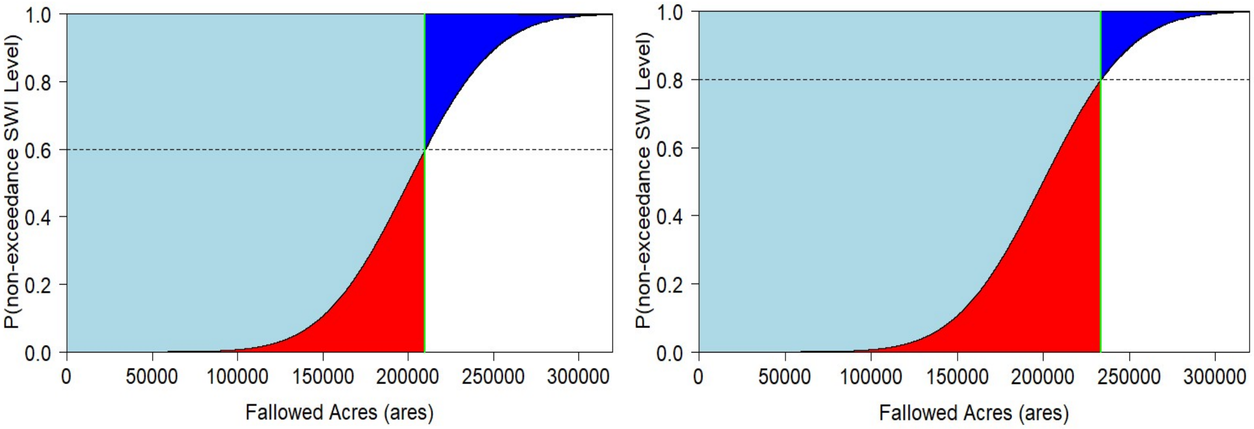

Figure 1. An illustration of optimal fallow areas given the cumulative distribution function representing the demand for annual fallowing areas for controlling saltwater intrusion

In the left panel, the curve represents the cumulative distribution function (CDF) of the annual fallowed acres distribution. The probability of non-exceedance SWI level, P(non-exceedance SWI level), is the probability of expected average saltwater-affected areas of less than or equal to a pre-determined SWI level, which is set by policymakers. This probability is also the probability of excess fallowing. The vertical green line represents the total fallowed acres required to achieve a pre-determined level of SWI risk. The light blue region represents expected acres needed to fallow, and the red and blue regions represent expected over- and under-fallowing acres, respectively. The figure in the right panel shows that if policymakers want to achieve a higher probability of non-exceedance SWI level, more acres need to fallow. The optimal number of fallow acres is determined where the probability of excess SWI risk (horizontal dash line) intersects the CDF. Thus, the optimal fallowed acres is where the expected marginal benefit of taking an additional acre out of production for controlling SWI is equal to its expected marginal cost, or the total costs of over- and under-fallowing are minimized.

Let X denote the random acres that need to fallow every rainy season to control SWI in the subsequent dry season, drawn from a known distribution with a density function (PDF), $f(x)$, and cumulative distribution function (CDF), $F(x)$. Let C_o denote the marginal cost of fallowing an additional acre (i.e., marginal loss of over-fallowing), and C_u, the marginal benefit of fallowing one fewer acre (i.e., marginal loss of under-fallowing). The objective is to find optimal fallowing acres, A^*, by minimizing the total expected loss for a given number of acres fallowed, A, and a given realization x of X. This decision rule is similar to the well-known inventory management problem that a decision maker balances the costs of below versus excess optimal inventory level for a stochastic demand of a perishable good (Arrow, Harris, & Marschak, 1951).

$$\min_A \mathrm{E}\left[C(X,A)\right]=\min_A\left(C_o\int_0^A (A-x)f(x)dx+C_u\int_A^\infty (x-A)f(x)dx\right) \tag{1}$$

We take the derivative of equation 1 and set the derivative equal to zero; then, we have

$$C_oF(A)= C_u(1-F(A)) \tag{2}$$

The left-hand side of equation 2 represents the expected marginal cost of over-fallowing. The right-hand side of the equation is the expected marginal benefit of under-fallowing. The optimal number of fallow acres is $F(A^*) = P(X \leq A^*) = \frac{C_u}{C_o + C_u}$, which is the $\left(\frac{C_u}{C_o + C_u}\right)$-th quantile of the *F(A)*.

For this research, we gather data from various sources. Key sources comprised the Mekong River Commission (MRC), Provincial Meteorological and Hydrological Departments (PMHDs) within the VMD, and the Southern Institute of Water Resources Research (SIWRR) in Vietnam. We utilize information from the General Statistics Office of Vietnam (GSO) and literature on production costs, rice yield, market prices, and other costs and benefits (e.g., benefits of land fallowing through fertilizer saving) to compute net returns from farming rice and shrimp to assess the trade-offs associated with managing SWI and food production.

2.2.3. A hydro-statistical model

The process of estimating the A^* includes two steps. First, we utilize the surface water flow MIKE 11 model to simulate the SWI for the MKD and examine the variability and uncertainty in historical and future estimates of the SWI. The model is a refined version used by Tran , Kanchit, Thares, and Nguyen (2011), which describes input data, parameters, calibration, and validation processes in great detail. In this study, we use the refined version of the model with all major saltwater control structures collected until 2018 to improve the model's performance. We re-validate the model with the data collected in 2018, observed SWI, and simulated SWI from previous studies (Tran et al., 2011). We run Monte Carlo simulations of SWI under all possible combinations of sea-level rise, river flow, land subsidence, riverbed incision, additional infrastructure, and land and water use scenarios.

Second, to infer the empirical CDFs, we use the Central Limit Theorem to estimate the probabilities of keeping the SWI in a normal year (define) as a baseline for different scenarios, assuming reductions in rice acreage and water use within the MKD (land use control scenarios). To estimate the CDFs, we apply the Central Limit Theorem to simulated saltwater-affected areas to estimate their means and variance. We assumed that each saltwater-affected area, denoted X_1, is an independent identically distributed (i.i.d) variable (i.e., SWI event). Thus, a sequence of i.i.d saltwater-affected areas, $X_1, X_2, \ldots, X_n$, has a mean, μ, and variance, σ^2, from any distribution, for all n, taken from a population with a replacement for sufficient large times ($n \geq 30$). Therefore, the sample mean, $\overline{X}$, is computed as, $\overline{X} = \frac{X_1 + X_2 + \ldots X_n}{n}$. The Central Limit Theorem states that the distribution of the sample means is approximately normally distributed (Ross, 2021). Sample means, $\mu_{\overline{X}}$, and its variance, $\sigma^2_{\overline{X}}$ for the random samples taken from the population can be computed as, $\mu_{\overline{X}} = \mu$ and $\sigma^2_{\overline{X}} = \frac{\sigma^2}{n}$, respectively (Ross, 2021). These estimates allow us to infer the CDFs associated with different levels of pre-determined SWI. We use equation 2 to estimate optimal fallow acres and the probability associated with each scenario considered. Then, we integrate a crop yield model developed by Nhan, Phap, Phuc, and Trung (2012) into our proposed economic model to estimate the crop revenue losses and quantify the trade-offs between controlling SWI and crop revenue losses through land fallowing policy.

3. Results and discussion

Our findings show that the probability of non-exceedance SWI level is approximately 0.8 at the optimal point. Depending on the scenario, this probability is associated with different acres that need to be fallowed. For the baseline, no SLR scenario, our model estimates that fallowing 123,552 acres is expected to prevent the SWI areas from exceeding 4.79 million acres, which is about the average historical SWI in the MKD. When an SLR of 22 cm is considered, 494,201 acres would need to fallow to prevent the SWI areas from exceeding 4.79 million acres. This translates to annual crop revenue losses of around $209.7 million. The findings reveal that 247,105 acres would need to fallow to maintain SWI level at its baseline under the combined effects of SLR, land subsidence, and riverbed incision scenario, with the estimated crop revenue losses of $104.8 million on top of around eight billion US dollars of construction costs for additional SWI control engineering infrastructure within the MKD.

4. Conclusions

We use an integration of a physical process-based, statistical, and economic model to quantify how a soft policy, i.e., land fallowing, can reduce the intensity and risk of SWI in the third largest delta in the world, the MKD. We find that SWI would be intensified and more uncertain – the distributions of future SWI are likely shifted leftward and wider, implying a greater risk to farmers in the MKD. We also find that the probability of non-exceedance SWI level is approximately 0.8 at the optimal point. The total acres that need to be fallowed range from 123,552- 494,201 to maintain the SWI at its historical average level. It is worth noting that under the combined effects of SLR, land subsidence, and riverbed incision scenario, the estimated fallowing acres are only 247,105, but with a substantial investment in additional SWI control engineering infrastructure within the MKD is likely required.

Our findings highlight the need for countries in the Mekong River Basin to have more sustainable and cooperative rather than competitive development plans, which serve better the whole basin's interest and those of countries that rely on rice exported from the VMD (Dunn & Minderhoud, 2022; Kondolf et al., 2022; Schmitt et al., 2021). Our analysis could help policymakers understand the SWI under uncertainty and the costs and benefits of a potential land fallowing policy for controlling SWI in the MKD.

5. Acknowledgments

The findings and conclusions should not be construed to represent any official Florida Legislative Office of Economic and Demographic Research (EDR) or US Government determination or policy. No official agency endorsement should be inferred.

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