The Economics of Climate Change in the Dong Nai Delta: Adapting Agriculture to Changes in Hydrologic Extremes[1]

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Abstract

The effects of climate change will be particularly felt in the Dong Nai river delta of Vietnam due to its hydrologic and economic characteristics. Climate change projections suggest that the delta may be subject to an increasing magnitude of salinity concentration due to changes in seasonal rainfall patterns. We study the economics of climate change impacts and adaptation in the delta, with particular attention to changes in hydrologic extremes. Reduction in river flows during low-flow periods will result in increased salinity levels which will significantly affect agricultural production in the downstream areas of the delta that are already constrained by salinity intrusion in the dry season. We integrate these agronomic, hydrologic and economic aspects of climate change in the delta into a framework that examines optimal cropping patterns adjustment as well as the optimal timing and location of water infrastructure investments as a response to increased salinity in the delta. Our results suggest that salinity damages to agriculture can be alleviated through adjustments in the farming system for a certain range of salinity. Our analysis also suggests that earlier construction is preferred under scenarios of faster salinity increases. Finally we find a tradeoff between protecting upstream versus downstream areas in the delta. For some cases, protecting regions closer to the sea is not economically viable given the delta's hydrologic characteristics.

Keywords: climate change adaptation, agriculture, water, cost-benefit analysis, dynamic programming, Vietnam.

JEL codes: Q54, Q25, Q15.

1.- Introduction

Climate change impacts in the water cycle will be strongly felt in the Dong Nai river delta of Vietnam due to its hydrologic and economic characteristics. We present a study of climate change impacts and adaptation in the Lower Dong Nai Delta. From an economic perspective the study area is characterized by its significant contribution to agricultural production in the region. Rice, sugarcane and vegetables are among the most relevant crops cultivated in the area and contribute to almost 50 percent of regional GDP. From a hydrologic perspective, the delta is characterized by having a six month low flow season when rainfall is very scarce and a flooding season when extreme precipitation and tropical cyclones occur. Seawater intrusion occurs during the dry season given the relatively flat topography and the low elevation of the delta's land with respect to sea level. As a result of this, the accumulation of salinity in the soils during the dry season is the main limiting factor for agriculture production in the areas located downstream of the Dong Nai river delta.

The assessment of some the physical impacts of climate change in the delta suggests that salinity concentration levels will increase due to a combination of higher sea tides and lower upstream flows in the dry season (Dung Do Duc, 2010). These impacts can have an important effect on the sustainability of production from agricultural land in the long term. Adapting to increased salinity may involve changing cropping patterns, adjusting the crop input mix, constructing new water infrastructure or abandoning land.

We integrate agronomic and hydrologic aspects of climate change in the delta into a hydro-economic framework that examines the economic desirability and tradeoffs between available adaptation options in the districts located downstream in the delta. The main research questions that we try to address can be summarized as follows:

- How can agricultural production and cropping patterns adapt to increased salinity from an agro-economic point of view?
- What is the interplay between softer adaptation options such as adjustments in cropping patterns and hard options such as infrastructure investments (sluice gates)?
- What is the optimal timing to build protective water infrastructure under different climate change scenarios?
- Where should water infrastructure be built to respond to increasing salinity given the characteristics of the delta?

Our framework for analysis has two components, a model for agricultural land use, and a model for water infrastructure investment analysis.

An economic model of agricultural land use is constructed using data available from crop cost and return studies and land use observations for the area. The model structure and calibration is similar to the one introduced by Howitt (1995) and later on by Merel and Bucaram (2010). Our model aims at maximizing the net annual benefit from agricultural production in each of the delta’s districts taking into account biophysical and economic constraints. An agronomic function is also incorporated in the model to relate crop yield and salinity levels following the work by Van Genuchten, M. T., and G. J. Hoffman (1984). When this yield-salinity relation is introduced in the model the overall impacts of salinity in agricultural production can be studied in a more robust manner where both agronomic and economic aspects are integrated. Using mathematical programming techniques the model is able to identify economically feasible adjustments of crop (agriculture land use) and input changes that can reduce the impact of increased salinity on production. Our model simulations allow us to parameterize a relationship between the value of annual agricultural production and different salinity concentration levels.

Secondly, we construct a model for analyzing investments in water infrastructure. The implicit objective of the model is to minimize land value loss due to salinity in a district by choosing when and where to invest in water infrastructure. The economic value of agriculture land is derived using our agriculture model, which relates annual net benefits from agricultural production to salinity concentration levels. In other words, our model treats agricultural land as an asset that generates annual profits whose value is depreciating over time due to increased salinity. Our water infrastructure model has an inter-temporal structure to study investment planning in a context of long-term climate change adaptation. This allows us to study the optimal timing profile for building protective structures that can prevent land from loosing value.

The model maximizes the expected net present value of agricultural land, i.e. the discounted streams of annual agricultural production profits. We formulate the problem as a dynamic program with one state and one control variable and solve it using the Bellman equation. Our state variable is salinity level which is based on hydrological simulation results. Our control variable is a binary variable that represents whether or not a given water infrastructure is built. The formulation of this problem as a dynamic discrete choice program is similar to a class of problems that aim to study optimal stopping rules (Dixit and Pindyck, 1994), i.e. the optimal timing for investment. Using our dynamic model we also study how the optimal timing for infrastructure investment differs for two climate scenarios that reflect the range of possible future climate outcomes. Finally, we study the economic tradeoffs between protecting upstream areas versus areas closer to the sea.

This paper begins with a review of the literature related to climate change adaptation in agriculture and water. Next, we describe the hydrological, agronomic and economic conditions of the study area in the Dong Nai Delta. The two models and preliminary results are presented in the following sections. First, we present the mathematical programming model used to study the effects of salinity in regional agricultural production. Second, we explain the structure of our dynamic programming model used to evaluate the timing and location of water infrastructure investments in the delta. We conclude our paper with an interpretation of the results obtained and possibilities for further extension.

2.- Literature Review

The vast majority of studies on the economics of climate change in agriculture and water have centered on changes in precipitation, temperature or runoff. Most of these studies have considered changes in average climate characteristics, leaving aside changes in the extremes. Given the specific characteristics of the Dong Nai delta, i.e., two clearly distinct seasons that differ greatly, we believe that changes in hydrologic extremes are the most relevant aspects to be considered for adaptation planning. A reduction in rainfall and consequently upstream freshwater runoff in the dry-season will exacerbate the current salinity problems caused by seawater intrusion in the area. Salinity concentration levels in the delta are therefore the proxy that we will use to study climate changes in seasonal hydrologic extremes. Our study about the economics of climate change in the delta will focus both on agriculture production and water infrastructure investments related to the agriculture sector. We review previous approaches used to study these two aspects of climate change.

2.1.- Agriculture and Climate Change

Our first strand of analysis is the economic study of climate change impacts and adaptation in agriculture production within the delta. Agricultural production models can be used for this purpose. Two types of modeling approaches exist, inductive and deductive. We summarize these two types of approaches below.

Inductive model approaches rely more heavily on a rich data set to provide the data with which most or all of the parameter values in the model can be estimated from observed behavior using econometric techniques. Econometric models have been widely used to study how changes in precipitation and temperature affect the value of agriculture production. Earlier models such as the Ricardian model (Mendelsohn et al. 1994) use a cross-sectional data set to explore how farm values and net revenues vary across climatic zones. These studies estimate response functions that are assumed to incorporate optimal adaptation, however there is no clear estimation of behavioral or operational responses at the farm level. Multinomial logit models have been used to explicitly estimate adaptation responses such as changes in crop choices or the adoption of irrigation, see for example Haneman et al. (2005), Seo and Mendelsohn (2006) and Howitt et al. (2009).

In general, econometric models tend to underestimate the future positive effects of adaptation. The main reason for this is that the adaptation responses to future climate change outcomes that lie outside the observed ranges can only be inferred, but not observed. Hence, adaptation responses having to do with technological improvements cannot be properly studied in an econometric framework (Adams, 2006).

Deductive models operate with much smaller data sets and use previously estimated parameters. They involve mathematical programming and assume optimizing behavior that is calibrated using minimal data. These models can accommodate various types of constraints such as resource limitations (e.g., land, water), nutrient balance constraints, and other policy relevant constraints. They can also easily accommodate exogenous information on yields and soil processes from biophysical models. Previous studies on agriculture and climate change using this technique have analyzed the effect of climate related crop yield changes (Howitt and Pienaar, 2006) and climate related changes in salinity (Howitt et al., 2009). These studies estimate adaptation responses such as adjusting irrigation, the combination of crops to be grown and the input mix in response to climate change.

The assumptions made in the construction of these models tend to overestimate the level of adaptation. In particular, the assumption of no transaction costs or institutional barriers for reallocating inputs or crops and the assumption of perfect foresight with respect to future climate conditions can significantly overestimate the mitigation of negative climate impacts.

Given the lack of a sufficiently rich data set for the area of study we will adopt a deductive approach to study climate change impacts on agricultural production in the delta. We will also use this approach given its flexibility to incorporate technological improvements on salt-tolerant crops that are not currently observed in the past but are in the process of being tested.

2.2.- Water Infrastructure Investments and Climate Change

The second objective of this paper is to study the economic implications of climate change with respect to water infrastructure investments that are related to agriculture production in the delta. The main aspects to be considered are the optimal timing of infrastructure construction as an adaptation investment, taking into account the fixed costs, uncertainty and irreversibility related to these decisions. In addition to dynamic aspects, spatial considerations of infrastructure investments are analyzed in order to capture the hydrological complexity of the delta. In this section we will review previous approaches to studying water infrastructure investments in the context of climate change and will also give an overview about the literature on uncertainty and irreversibility.

Water infrastructure investments and climate change have previously been studied using simulation and optimization models. Callaway et al. (2007) explicitly model the expansion of the water infrastructure system in the context of climate change. Their empirical model considers structural adaptation measures such as building a dam and non structural measures such as changes in operations and introducing efficient water market allocations. Their modeling approach allows them to study the optimal capacity of a reservoir and other structural works such as water pumps. Even though they consider the interplay between structural and non-structural measures, the optimal timing and location of the dam as well as uncertainty aspects are not fully considered in their study.

Fisher and Rubio (1997) consider uncertainty and irreversibility in a theoretical framework applied to investments in infrastructure related to water storage capacity. They find that increases optimal water storage capacity increases with greater variance of water resource availability. Their study also finds that there is a range of inaction for investments in infrastructure when there is a high cost for reversing investments.

Block and Strzepek (2007) develop a model to assess investments in dam development for hydropower and irrigation purposes in a context of future climate change. They consider the implications of climate extremes for the analysis of the potential net benefits of infrastructure development. Another important aspect of their modeling framework is the sequential nature of various dam constructions along the Nile River. However, their model objective is to simulate future conditions, i.e., their focus is to assess the economic performance of a given infrastructure investment plan along the river under climate change conditions. The authors do not attempt to study what would be the optimal number and size of dams in the river given climate change conditions.

Lund et al. (2006) and Medellin et al. (2008) develop an optimization model that can evaluate the additional needs and value of increased water storage or infrastructure expansion under prolonged drought conditions due to climate change. The model optimizes both water allocations and the operation of water facilities to study different adaptation options given a set of infrastructure and physical constraints. The model considers broad mix of adaptation options such as system re-operation, conjunctive use, water reuse and desalination, water markets and water conservation. Although the model does not explicitly address the optimal timing of infrastructure investment, it does have the potential to size optimal investments in infrastructure as well as their location.

Zhu et al. (2007) address the optimal timing of infrastructure investment in a study flood protection and adaptation of floodplains to climate change and urbanization. The authors use an optimization model. The focus is on levee design in a river basin as a long term adaptation option. The dynamic programming model maximizes the value of the floodplain by choosing levee setback and height, taking into account the costs and the benefits associated with those decisions as well as the probability of flooding. The authors find the optimal timing profile of changes in levee height and setback for a given set of climate change scenarios.

Finally, the theoretical literature on uncertainty, irreversibility and investment timing is summarized by Dixit and Pyndick (1994). Wright and Erickson (2003) review this literature and consider its application to climate change adaptation. The authors develop an option value framework to study the optimal timing for adaptation responses using an optimal stopping model. Their modeling study is not based on empirically estimated parameters; however their work constitutes a good illustration of the additional aspects to be considered when it comes to water infrastructure investments and climate change uncertainty.

The water infrastructure investment model developed in this paper uses an optimization framework as opposed to simulation. The optimization model uses dynamic programming to find the optimal timing and location of infrastructure construction. The initial model specification considers a range of extreme hydrologic scenarios under a closed loop.

2.- The Dong Nai Delta: Hydrology, Agriculture and Climate Change.

The Dong Nai River Basin (DNRB) is the largest national river basin and the economic center of the country in southern Vietnam. The delta is situated in the lowland areas of the basin. The Lower Dong Nai Delta includes 4 provinces and Ho Chi Minh City as can be seen in table 1. Both HCMC and BR-VT are important urban and industrial centers respectively whereas Long An and Tay Ninh have important agricultural production areas. Total population in the area amounts to more than 9 million inhabitants. Agriculture production is highly diversified, with products ranging from staple crops like rice, to raw materials for the local industry such as sugarcane, to high-valued crops like vegetables and fruits.

Table 1: Economic Indicators for the Provinces in the Lower Dong Nai River Delta

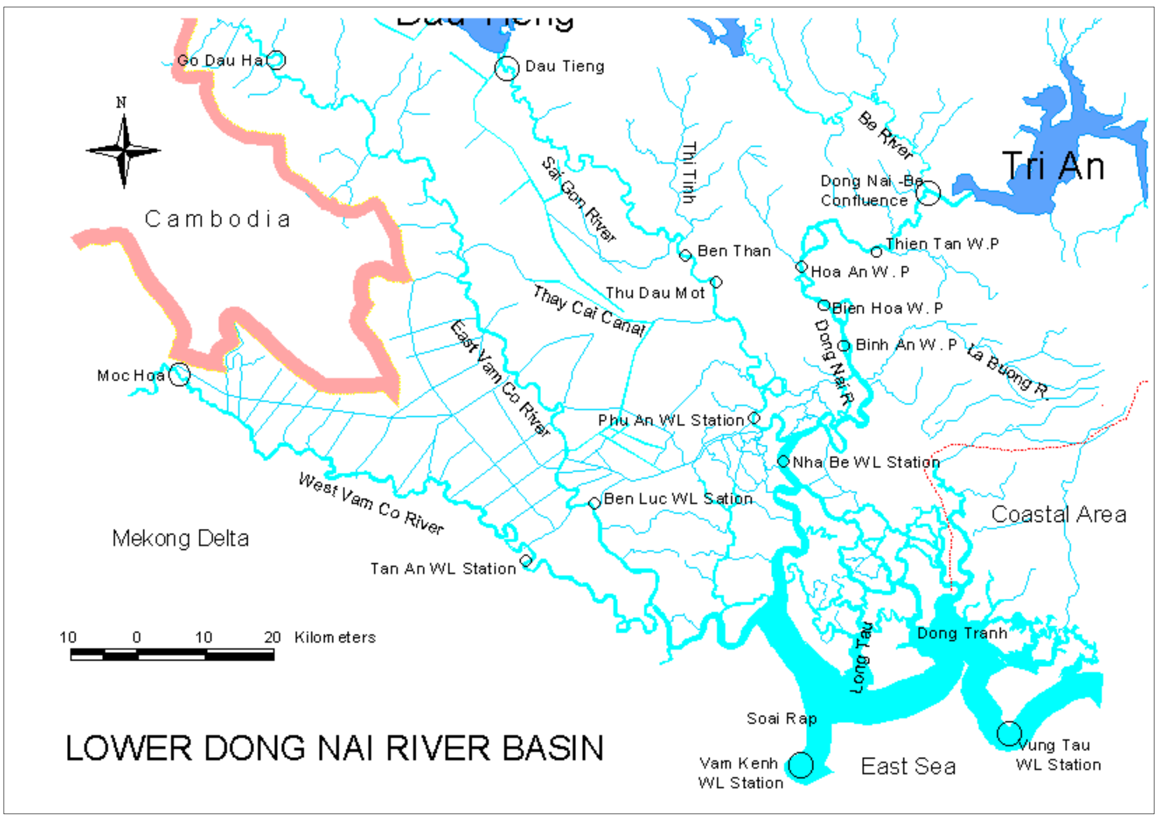
Province	Land Area 2007	Gross Irrigated Area 2007	Population 2007	GDP 2007	Share Agriculture GDP 2007
	(ha)	(ha)	(‘000)	(M USD)	(%)
HCMC	209,505	72,482	6,347	6254	4
Long An	188,153	151,246	1,430	724	54
Tay Ninh	402,812	220,635	1,053	413	46
BR-VT	190,000	30,057	947	4456	5
TOTAL	990,470	474,420	9,777		

Reference: Land area: Sub-NIAPP; Gross irrigated area: adjusted from SIWRP; Population and GDP: various statistical yearbooks from GSO.

The Lower Dong Nai Delta has 3 major rivers: the Dong Nai mainstream, the Sai Gon, and the Vam Co Dong system that joins the Dong Nai just before the outlet into the East Sea (figure 1). Two reservoirs are located upstream of the Sai Gon and Dong Nai rivers, Dau Tieng and Tri An. Dau Tieng is actually the largest irrigation reservoir in Vietnam.

The delta area possesses abundant water resources; however, the delta is subject to annual flooding in the wet season and salinity intrusion in the dry season (Ringler and Huy 2004). The area is therefore more vulnerable to hydrologic extremes than to changes in average hydrology.

Figure 1: Lower Dong Nai Delta



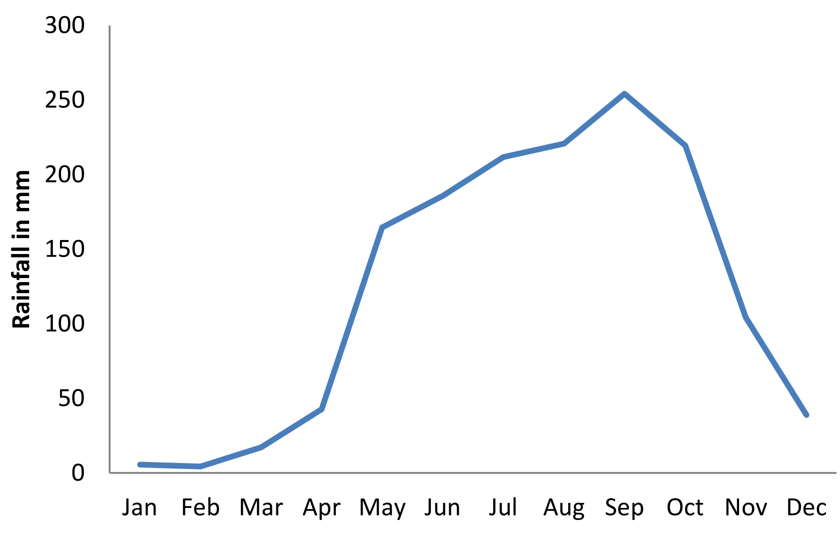
Source: SIWRP (2009)

2.1.- Current Hydrology.

There are two clearly distinct seasons in the delta area, the rainy season and the dry season. Rainfall and runoff patterns follow accordingly. The tidal regime and discharge patterns produce a similar pattern of salinity accumulation in the area.

Rainfall is normally greater in the upstream area of the delta or the central area of DNRB (ranging from 2,200 to 2,800 mm) while low rainfall stretches along the coast (from 800 to 1,400 mm). The average annual rainfall in the basin is about 2,000 mm in the Dong Nai River and about 1,500 mm in the coastal area. Rainfall is divided into two seasons; the rainy season represents approximately 87-93% of the annual total while the dry season is only 7-13%. The rainy season begins in May and ends in October, lasting approximately 6 months (see figure 2)

Figure 2: Monthly Rainfall (average 1990-2006)

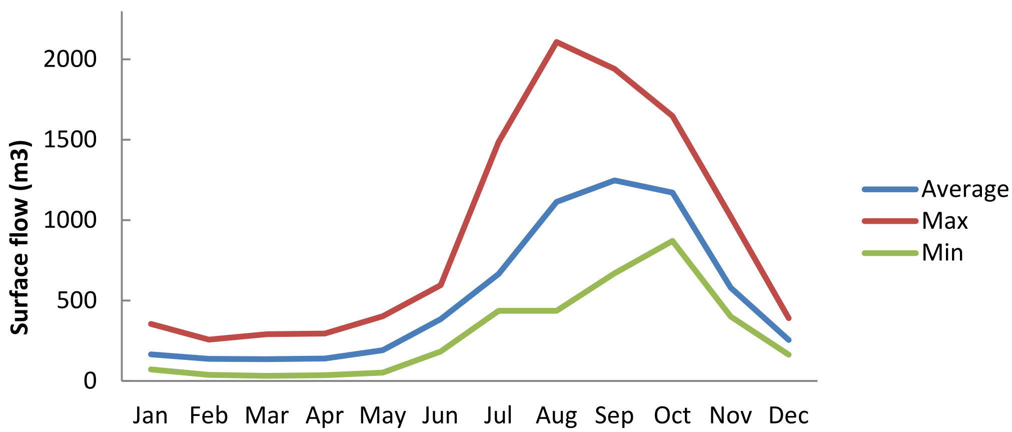


Source: SIWRP (2009)

Flow in the Dong Nai river basin is dominated mainly by rainfall regime and therefore it varies accordingly in terms of in space and time. The flood season, which occurs from June to November, begins approximately one to two months after the rainy season, and constitutes 80%

of the total annual flow. The dry season lasts over six months from December to May, with lowest flow in March or April or even in May. Monthly flow records indicate highest totals in the July-September months (see figure 3).

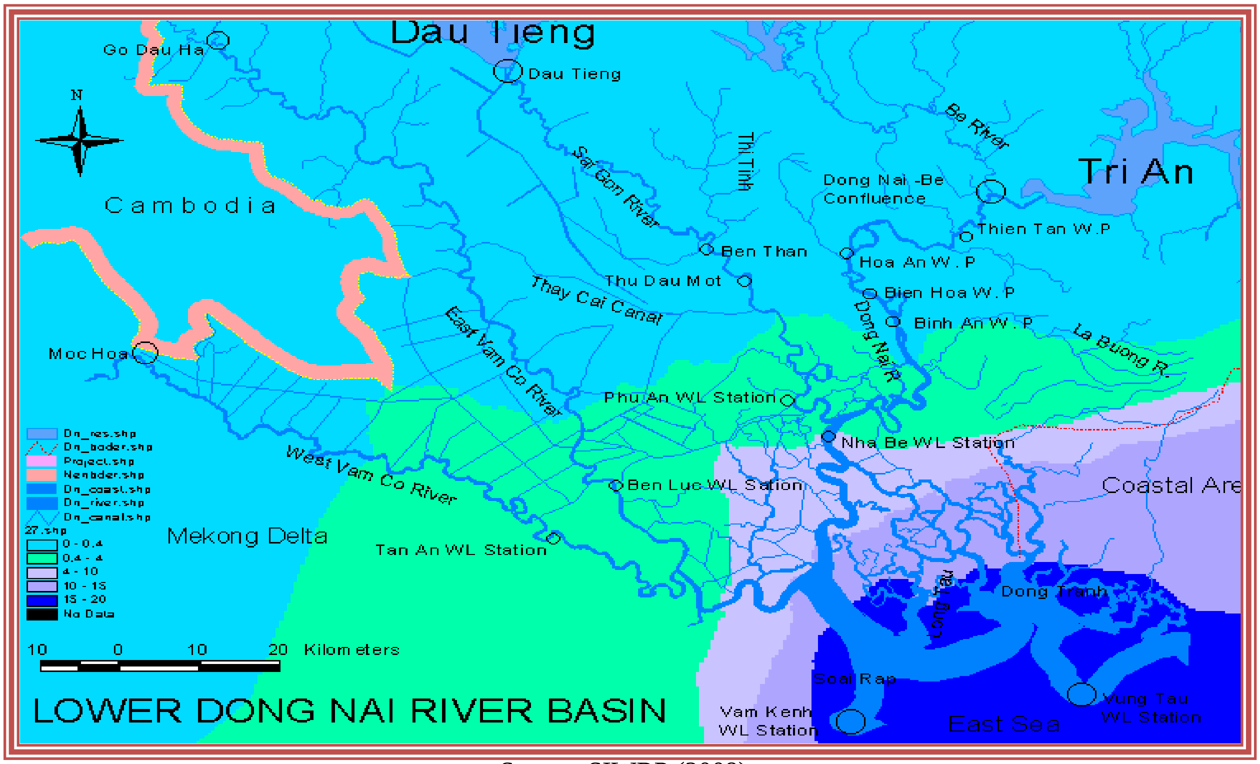
Figure 3: Monthly Runoff (1990-2006)



Source: SIWRP (2009)

Salinity is already a problem due to the delta's hydrologic and geomorphologic characteristics (see figure 4). The lower Dong Nai delta is a low-lying area with a complex branched and looped river network and is strongly affected by tides from the East Sea in the Pacific Ocean. The tidal amplitude is very large, and may reach up to 3.5-4.0 m along the coast. Due to the large amplitudes of the tide and the low riverbed slopes, the tide propagates from the sea to the river mouth and then further into the rivers and canals. Under natural conditions, the tide affects the water level up to the Tri An waterfall foot in the Dong Nai River, 132.8 km from the sea, to the Dau Tieng dam site in the Sai Gon River, 184.4 km from the sea, and to the Cambodia border in the East Vam Co River, 208 km from the sea.

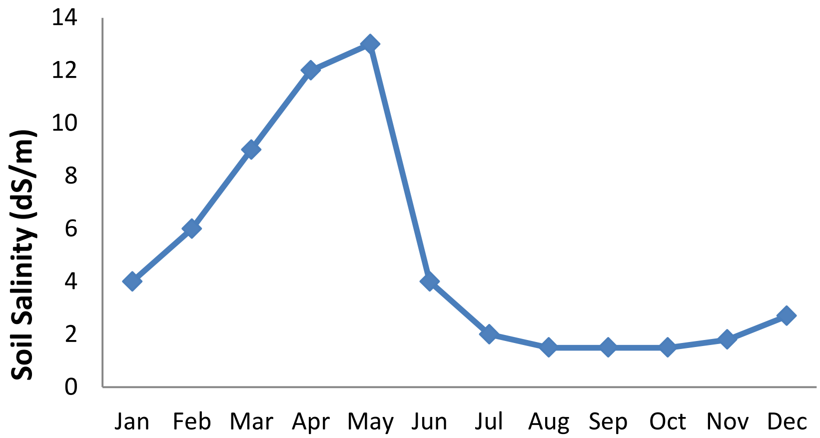
Figure 4: Current Salinity Area Map



Source: SIWRP (2008)

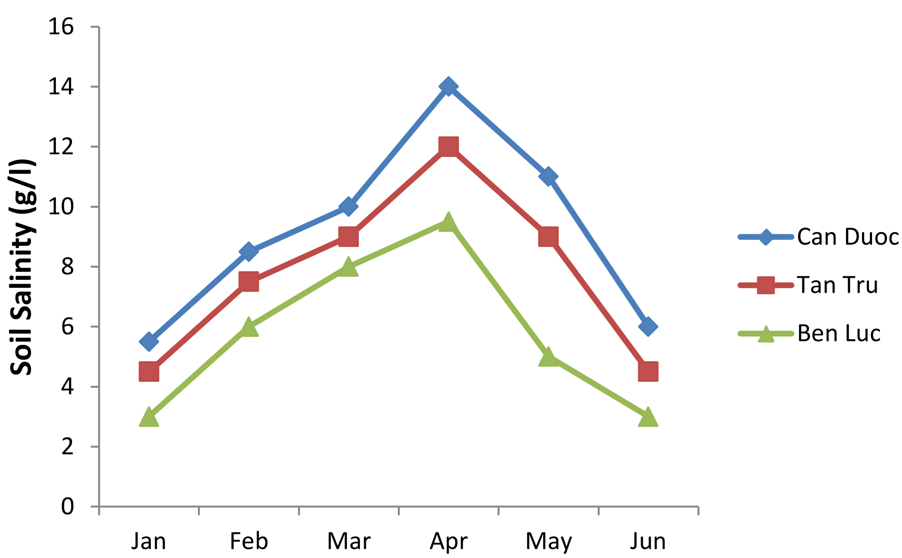
Salinity dynamics follow from rainfall and river flow patterns. Salinity levels reach their peak during the last months of the dry season which coincide with the periods of lowest flow, normally in April or even in May. The rainy season decreases salinity build-up in the delta’s land for almost six months (see figure 5).

Figure 5: Seasonal Salinity Dynamics



The spatial distribution of salinity concentration in lands follows from the delta's morphologic characteristics. Downstream areas that are closer to the sea such as the Can Duoc districts are subject to higher salinity concentrations throughout the dry season (see figure 6)

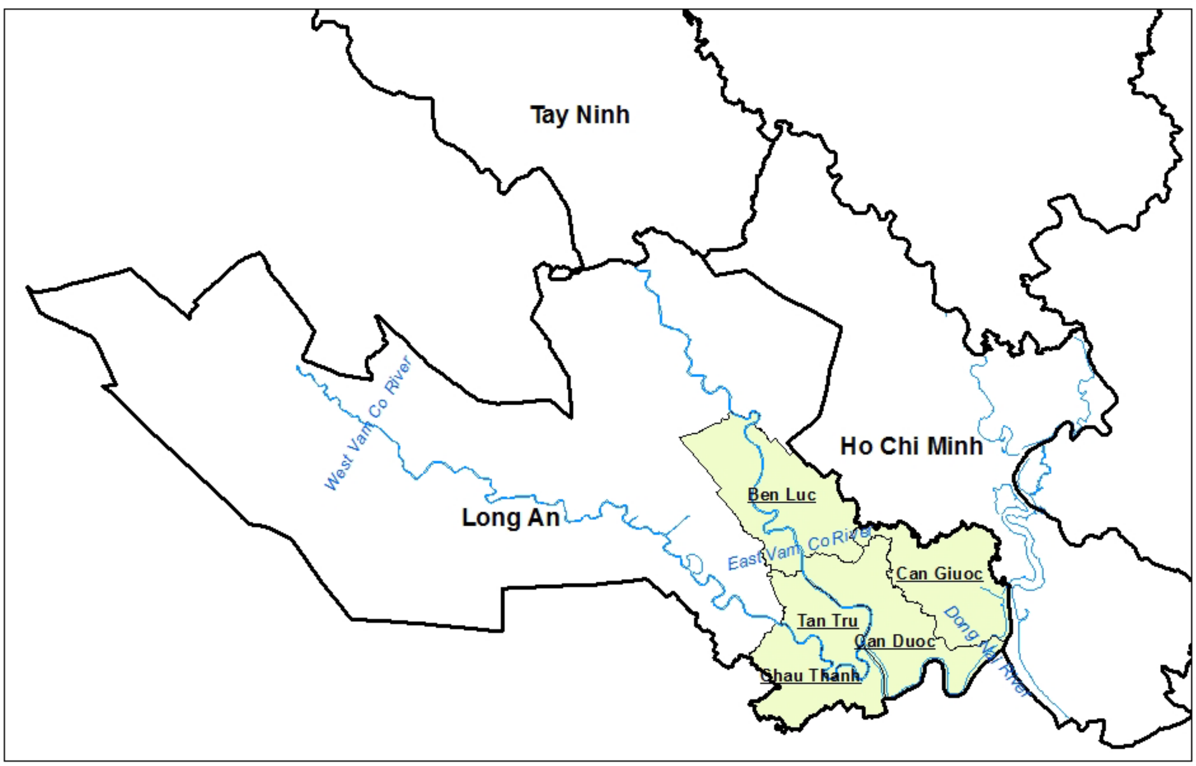
Figure 6: Spatial Salinity Dynamics



2.2.- Agriculture in the study area.

The area of study has been selected based on two factors, the projections on the spatial extent of future salinity increases and the relative importance of agriculture in the regional economy. Five downstream districts belonging to Long An province have been selected (see figure 7). The districts selected are Ben Luc, Tan Tru, Can Guioc, Can Duoc and Chau Thanh. These study area is smaller than Lower Dong Nai Delta area; however, it covers more than 85 percent of the area and agricultural production affected by seawater intrusion. We believe that it is also a good representation for the water infrastructure model developed later on since more than 70 percent of the infrastructure investment plans refer to that area.

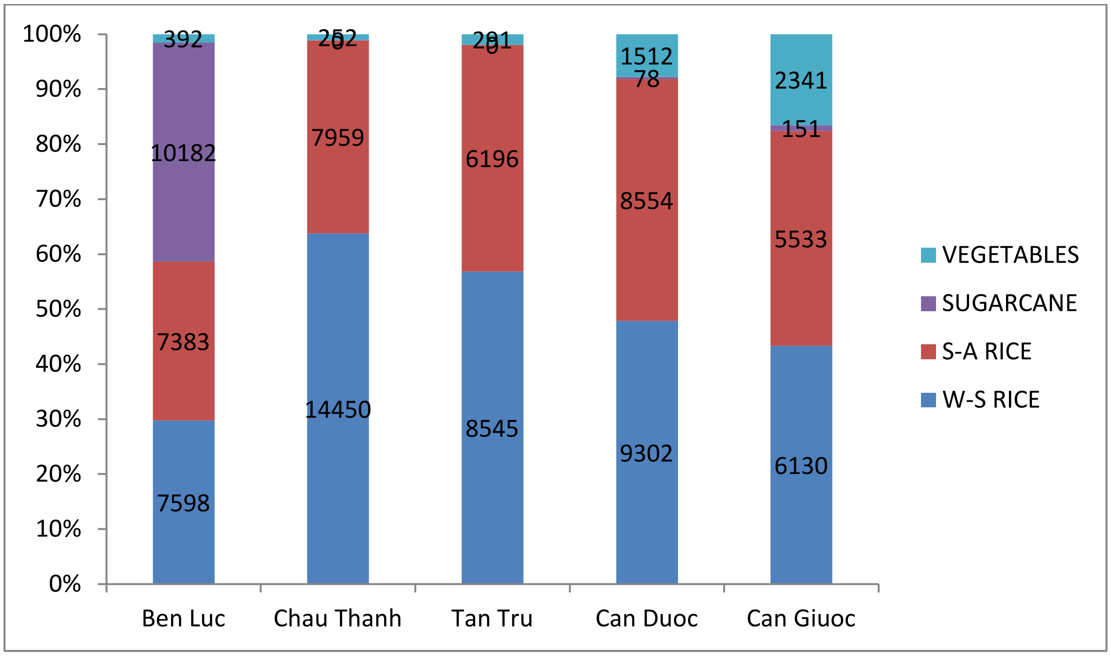
Figure 7: Map of Administrative Boundaries for Selected Districts of Study



Agricultural production is one of the main economic activities in the district selected. More than 70 percent of land is dedicated to agriculture. Annual crops are separated by season

(Winter-Spring, Summer-Autumn, and Rainy Season). Rice is one of the main crops in the districts and is planted throughout the year. Vegetables and sugarcane are the other crops planted in the area (see figure 8).

Figure 8: Agricultural Land Use in the Districts (average from 2001- 2007)



Source: GSO (2007)

Data on yields, inputs, prices and production costs have been gathered from cost and return studies. Table 2 summarizes the main relevant data on crop production for this area. Land cost includes seeds, fertilizer, machinery, pesticide and other cost not included in labor or water. The input variables incorporated are in USD/ha. Family labor is valued at the prevailing wage rate stipulated by the farm households. Water includes both estimated irrigation water applied and effective rainfall. Water costs are derived from input intensity and irrigation services fees (ISF). ISF are area-based and can vary by crop, season, and type of irrigation water supply (gravity or pump irrigation). Currently, ISF only partially reflect the scarcity value of water; fees are typically higher for pump irrigation, but also typically lower for rice, which consumes relatively more water (Ringler, 2004). It is also worth noting that districts located downstream have on average a higher cost of production due to salinity conditions.

Table 2: Crop Prices, Input Use and Yields

Crop	Price	Yield	Land Cost	Irrigation Water	Labor
	(USD/mt)	(mt/ha)	(USD/ha)	(mm)	(USD/ha)
W-S Rice	135	3.78	69 (112)	1102 (1203)	38 (71)
S-A Rice	130	3.3	79 (101)	679 (785)	40 (65)
Sugar Cane	24	48.7	68 (183)	1983 (2291)	57 (86)
Vegetables	211	4.17	54 (81)	502 (584)	48 (73)

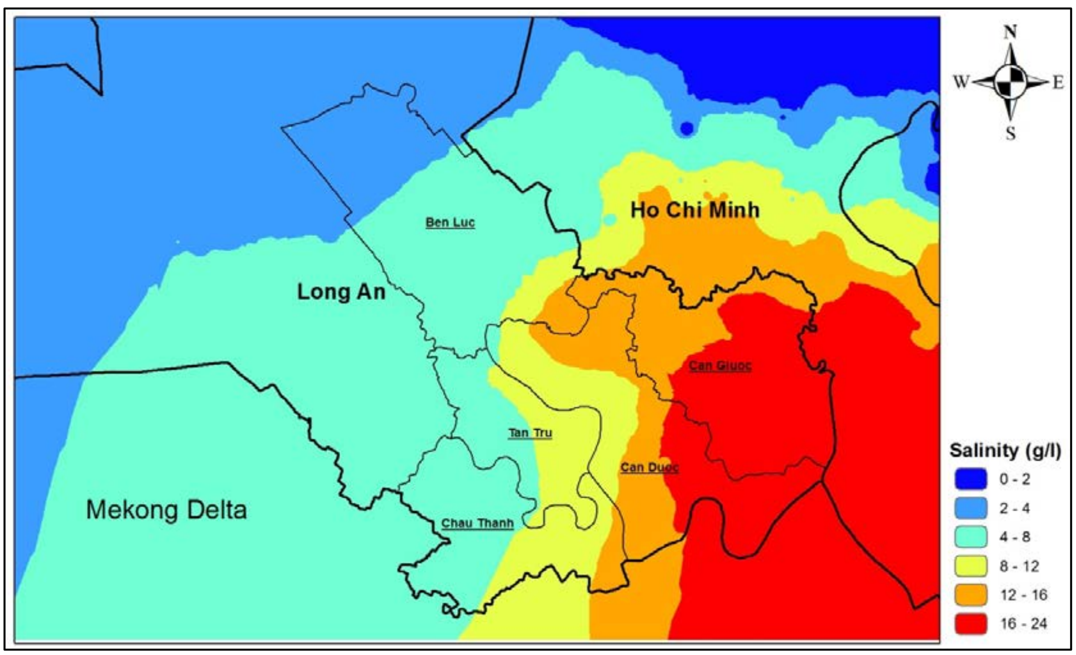
Reference: various data sources, Sub-NIAPP, Ringler, SIWRP, and agricultural census. Exchange rate is assumed to be 1USD ~19,000 VND. Numbers in parenthesis correspond to districts located closer to the sea.

2.3.- Climate change projections

Climate change scenarios of future salinity concentration levels have been produced for the Dong Nai Delta following from earlier work conducted by SIWRP and the World Bank. Projections of changes in temperature and precipitation were introduced into a rainfall-runoff model (NAM) to produce upstream flow projections. The combination of flow projections with different scenarios of sea level rise (MONRE, 2009) was used in a hydro-dynamic model (MIKE 11) to produce salinity maps in the delta. Climate projections were selected from an ensemble of climate models that simulate the A2 emissions scenario of the IPCC FAR(2007). The main goal of climate change projections was to examine the upper and lower boundaries in the range of possible climate scenarios. Two climate model projections were selected according to a moisture index that ranked model outputs according to precipitation and temperature. A wet scenario was associated to the Goddard Institute for Space Studies (GISS –ER) climate model and a dry scenario was associated to the Institut Pierre Simon Laplace (ISPL-CM4) climate model.

Overall, climate change scenarios suggest a decrease in runoff in the dry period which, combined with sea level rise leads to increases in salinity concentration over time. Areas closer to the sea tend to have greater increases in salinity levels. These salinity projections assume that there are no new water infrastructures in place. Figure 9 provides a good overview of the spatial distribution of salinity levels in 2050.

Figure 9: Projected average salinity for 2050 (dry scenario)



Source: SIWRP (2010)

3.- Economic Model of Agriculture Production

An economic model of agricultural land use is constructed using data available from crop cost and return studies and land use observations for the area. The model aims at maximizing the net annual benefit from agricultural production in each of the delta's districts taking into account biophysical and economic constraints. This model is used to estimate the effect of increased salinity on crop production in the area. The direct economic impacts of salinity accumulation are reflected in net agricultural profit loss. Changes in cropping patterns (intensive and extensive margin) due to salinity accumulation are also estimated within the model. It is also assumed that the region is a price-taker in agricultural markets; hence prices are assumed to be exogenous in the model. Rainfed agriculture is not considered in the model given that irrigated crop production is the dominant agricultural industry in the districts of study.

Estimation takes place within the context of positive mathematical programming (Howitt 1995), as a self-calibrating three-step procedure. First step, a linear program for profit maximization is solved. In addition to the traditional resource and non-negativity constraints a set of calibration constraints is added to restrict land use to observed values. The second step is parameterization of a quadratic cost function and the production function itself from the first order conditions. LaGrange multipliers from the binding calibration constraints in the first step are used to estimate slope and intersect of the average cost function. A third and last step incorporates the parameterized cost functions into a non-linear profit maximization program, with constraints on resources only. Salinity effects are incorporated by calculating the impact of reduction in crop yields due to salinity.

The economic effects of salinity changes are estimated by iterating the optimization algorithm for different salinity levels and measuring the costs of changes in cropping combinations, crop yields, and areas with respect to the base case.

3.1.- The Objective Function

The economic model proposed here is based on a class of models called Positive Mathematical Programming or PMP (Howitt, 1995), widely used in applied research and policy analysis. It is assumed that farmers in each district within the Dong Nai delta seek to maximize net revenue derived from their farming activities in a given year. Therefore, the backbone of the analytical model is an objective function that explicitly sets out to maximize profits. That is:

$$\max_{X\geq 0} \sum_{g} \left(\sum_{i} p_i * f_{gi} - \sum_{h} \omega_h * X_{gih} - \sum_{i} (\widehat{\alpha_{gi}} * X_{gih} + \frac{1}{2} * \widehat{\gamma_{ig}} * X_{giland}^2 \right) \quad \text{Eq. 1}$$

The first term on equation 1 represents gross revenue, where p_i is the output price of the perennial or annual crop *i*, each of which is produced according to a production function f_{gi}. X_{gih}, described in more detail in the next section, is the matrix of *i* perennial and annual crops, and *h* agricultural inputs, and sets the input requirements for producing all crop products. Inputs include: land, labor and water. The subscript g refers to the regions of study.

The cost to produce a unit of crop *i* is defined by two remaining terms: the first term is the market price of the inputs, ω_h, multiplied by the quantity of inputs used X_{ih}; and the second term, in parenthesis, is the implicit cost associated with land allocation. It has a quadratic specification with parameters α_i and γ_i and captures the increasing marginal cost associated with allocating larger amounts of land to a given crop. As a given farmer allocates increasing amounts of land to a specific crop, the new land may be of inferior quality or not as suitable to grow that particular crop. More generally, this term captures non-linear effects that may enter into the decision-maker's problem and that are not directly observable or measurable causing costs to rise non-linearly with area.

The original objective function is then adjusted to better capture seasonality in the farming system. Equation 1 will be used to represent the objective function for each crop rotation (winter-spring and summer autumn). Additional constraints will reflect the availability of resources for each season as well as the rotational constraints on perennial crops.

3.2- The Production Function

The production function $f_{gi}(X_{gih})$, provides an estimate of output produced in district g by an existing set of inputs h for each cropping activity i. The functional form used for f is a constant elasticity of substitution (*CES*) and the parameters are calibrated as in Howitt (2006). Elasticity of substitution is assumed to vary by crop but not by region. The specification of the generalized CES production function is:

$$f_{gi} = A_{gi}\left[\sum_{h} \beta_{gih} X_{gih}^{\rho_{gi}}\right]^{\frac{\epsilon_i}{\rho_{gi}}} \quad \text{Eq. 2}$$

where A_i represents the area share parameter, and β_{ih} are the production function parameters; $\gamma = \frac{\sigma - 1}{\sigma}$, σ is the elasticity of substitution among inputs; and ε_i is the returns-to-scale parameter.

3.3 Model Calibration and Parameterization

The first step in PMP is devoted to obtaining marginal values for the calibration constraints to parameterize a quadratic cost function in the second step. The linear program with calibration constraints has as its explicit objective the maximization of net revenue using land in each of the two crop rotations as the decision variable and is as follows:

$$\max_{x^1_{gi}\geq 0,\, x^2_{gi}\geq 0} \sum_g \left(\sum_i p^1_{gi} * \hat{y}^1_{gi} * X^1_{gi} - \sum_i \omega^1_{ih} * a^1_{gih} * X^1_{gih} \right) + \sum_g \left(\sum_i p^2_{gi} * \hat{y}^2_{gi} * X^2_{gi} - \sum_i \omega^2_{ih} * a^2_{gih} * X^2_{gih} \right) \quad \text{Eq. 3}$$

subject to seasonal and district-level resource constraints:

$$\begin{cases} \sum_g \sum_i X^1_{gi} = B_{land} \\ \sum_g \sum_i X^2_{gi} = \sum_g \sum_i X^1_{gi} \\ X^1_{g,sugar} = X^2_{g,sugar} \end{cases} \quad \text{Eq. 4}$$

$$\sum_g \sum_i a^r_{gi,lab} * X^r_{gi,lab} = B^r_{lab} \quad \forall\, r \in (1,2) \quad \text{Eq. 5}$$

$$\sum_g \sum_i a^r_{gi,wat} * X^r_{gi,wat} = B^r_{wat} \quad \forall\, r \in (1,2) \quad \text{Eq. 6}$$

$$X^r_{iland} \leq \hat{X}^r_{iland} \quad \text{Eq. 7}$$

where in Eq. 3 p_i is defined as before, $\hat{y}$ is the yield per hectare of land dedicated to crop i, ω_{ih} is the unit cost of input h used in the production of crop i, and a_{ih} are inputs per hectare $\left(X_{ih} / X_{iland} \right)$. B_{land}, B_{lab} and B_{wat} reflect the total availability of land, labor and water, respectively. The superscript r indicates whether it is the first rotation (1) or the second rotation (2) which correspond to the winter-spring season or the summer autumn season. Eq. 4 contains the seasonal constraints. X^1_{gi} is the amount of land dedicated to region i in region g under the winter spring season (rotation 1). The total amount of land dedicated to crops per season must be equal to B_{land}, in our case, the total amount of crop land in season 2 is less than cropland in season 1 due to increased salinity, therefore there is also fallow land during season 2 (summer autumn). The last restriction of equation 4 ensures that perennial crops (sugarcane) are properly taken into account.

In Eq. 7, $\hat{X}^{r}_{iland}$ is the total amount of land allocated to crop *i* in season *r* that is *observed* by researchers; this constraint prevents specialization and preserves observed crop allocation patterns while estimating shadow values of limited or non-marketed inputs. Notice that although the shadow values associated with the fixed inputs such as land, labor, and water may change from farmer to farmer, they are not crop specific. However, the Lagrange multiplier associated with Eq. 7 is both region- and crop-specific.

2.4 Estimation of Production Function Parameters

Estimation of the full set of parameters for the production function with 4 inputs in Eq. 2 requires each crop *i* to be parameterized in terms of 4 parameters β_{ih}, one for the return-to-scale parameter ε_i and the crop specific parameter A_i in Eq. 2.

In this paper we follow an analytical rather than an econometric method in which the parameters are calculated using the economic optimality conditions for the use of each input and some prior values for some key parameters such as the elasticity of substitution. These conditions seek maximization by setting the value of the marginal product of each input equal to its unitary cost. In which the former is defined by its output price multiplied by the derivative of the production function (Eq. 2) with respect to each input. For the unconstrained inputs, the unitary cost is simply their market price; for the constrained inputs, each unitary cost is the sum of their purchase prices and their respective shadow values, λ_{land}, λ_{Labor}, $\lambda_{SurfaceWater}$. Regarding the value of land, however, in addition to the market and shadow prices, the calibration constraint represented by Eq. 7 further increases the value of this fixed input. In other words, the true marginal cost associated with land allocation to the i^{th} crop is the sum of: 1) the market price of land; 2) the shadow value of land, λ_{Land}; and 3) $\lambda_{i\,\overline{land}}$.

By algebraically manipulating the optimality equations we reach expressions for each of the parameters β_{ih}, and A_i , α_i and γ_i in Eq. 1 as a function of values on input prices, output prices, and input quantities. For this exercise we assume constant returns to scale for all crops ($\varepsilon_i = \varepsilon = 1$) and a priori value of 0.4 for the elasticities of substitution (σ_i). We perform exact calibration of the elasticities using the method proposed by Merel and Bucaram (2010). An appendix containing the derivation and calculation of elasticities and parameters β_{ih}, and A_i, as well as α_i and γ_i of Eq. 1 may be requested to the author .

2.5 Economic Simulation Model

Equation 8 uses the parameterized CES production function $\hat{f}^r_{gi}$ to find the optimal set of inputs that maximizes net revenue:

$$\max_{x^1_{gi}\geq 0,\, x^2_{gi}\geq 0} \sum_g \Bigg(\sum_i p^1_{gi} * \hat{f}^1_{gi} * X^1_{gi} - \sum_i \sum_h (\omega^1_{ih} * X^1_{gih} + \hat{c}^1_{giland} * X^1_{giland} + \frac{1}{2} * \hat{\gamma}_{gi} * \left(X^1_{giland}\right)^2) \Bigg) + \sum_g \Bigg(\sum_i p^2_{gi} * \hat{f}^2_{gi} * X^2_{gi} - \sum_i \sum_h (\omega^2_{ih} * X^2_{gih} + \hat{c}^2_{gi} * X^2_{giland} - \frac{1}{2} * \hat{\gamma}_{gi} * \left(X^2_{giland}\right)^2 \Bigg) \quad \text{Eq. 8}$$

subject to technological constraints as well as resource availability constraints both at regional and seasonal level:

$$\hat{f}_{gi}^{r} = yred_{gi}\, A_{gi}\left[\sum_{j=1}^{3}\beta_{gij}x_{gij}^{\rho_{gi}}\right]^{\frac{\epsilon_{gi}}{\rho_{gi}}}$$

$$\begin{cases} \sum_{g}\sum_{i}X_{gi}^{1} = B_{land} \\ \sum_{g}\sum_{i}X_{gi}^{2} = \sum_{g}\sum_{i}X_{gi}^{1} \\ X_{g,sugar}^{1} = X_{g,sugar}^{2} \end{cases}$$

$$\sum_{g}\sum_{i}a_{gi,lab}^{r} * X_{gi,lab}^{r} = B_{lab}^{r} \quad \forall\, r \in (1,2)$$

$$\sum_{g}\sum_{i}a_{gi,wat}^{r} * X_{gi,wat}^{r} = B_{wat}^{r} \quad \forall\, r \in (1,2)$$

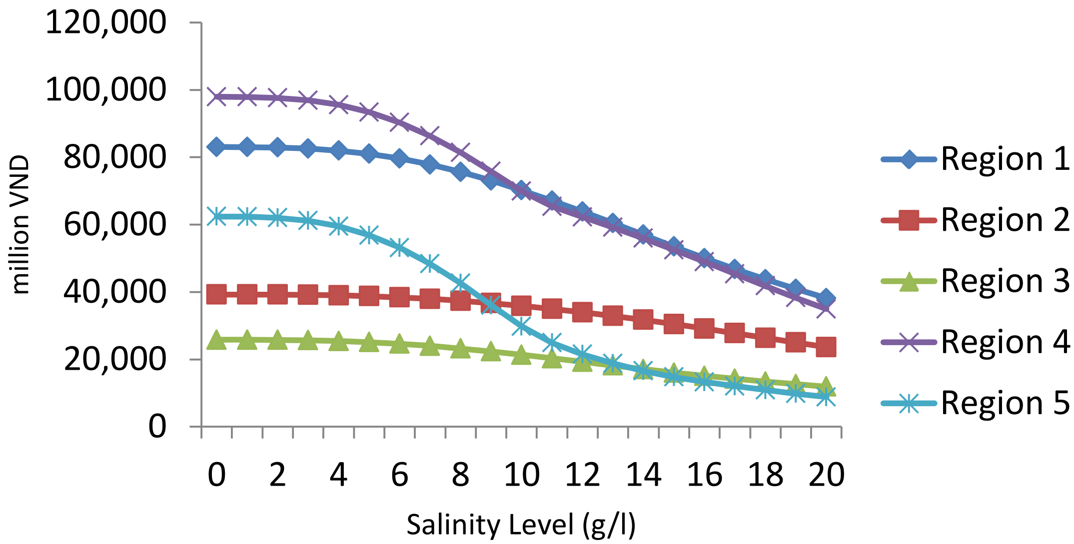
In equation 8, $\hat{f}_{gi}^{r}$ is characterized by the production function defined by the parameters obtained in the previous subsection. The second term in the equation has now the PMP calibrated cost function. The production function includes now the term $yred_{gi}$ which represents the yield reductions from van Genuchten and Hoffman (1984) and is detailed in equation 9 below. Y_{maxgi} is the maximum average yield of crop i in region g; c_{gi} is the salinity in the region; $c50_{gi}$ is the salinity at which the yield is reduced by 50% and is obtained from field experiments; τ is an empirical constant.

$$yred_{gi} = \frac{Y_{maxgi}}{1 + \left(\frac{c_{gi}}{c_{50gi}}\right)^{\tau}} \quad \text{Eq. 9}$$

2.6.- Simulation Results

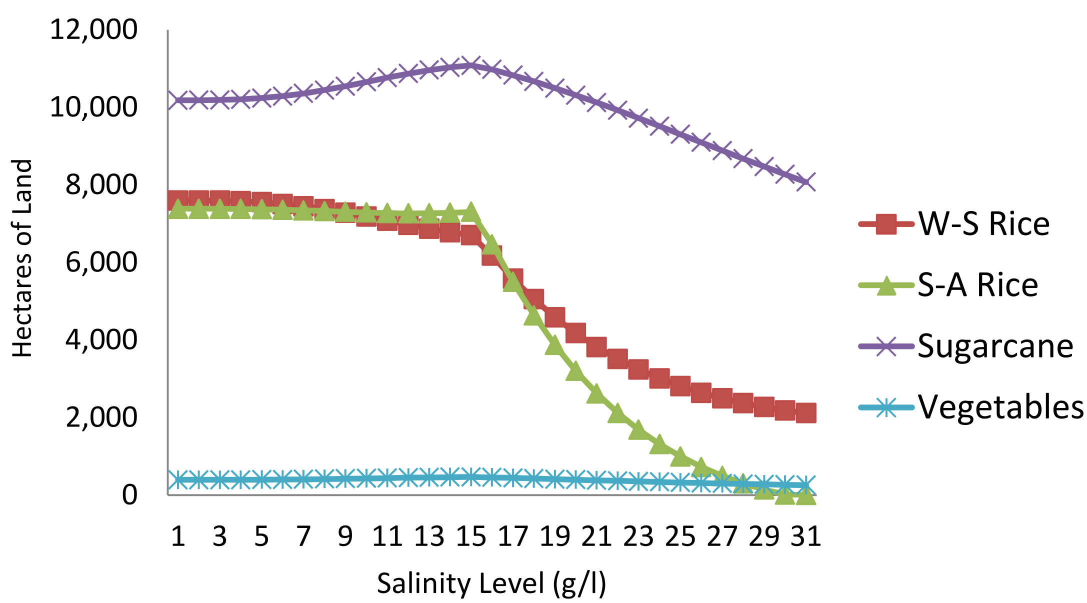
We simulate increases in salinity using the calibrated model and are able to parameterize a salinity damage function to agriculture. Preliminary results suggest that annual agricultural production losses due to increased salinity follow a non-linear pattern. The different districts present different responses to salinity increases see figure 10.

Figure 10: Annual production value as a function of salinity



From an economic point of view, agricultural production can adapt to increased salinity by switching from low value-low salt tolerant crops such as rice to high value-high tolerant crops such as sugarcane or vegetables for a certain range of salinity levels (see figure 11).

Figure 11: Crop mix as a function of salinity



4.- Water Infrastructure Investment Model.

A water infrastructure investment model is used to study the optimal timing and location of sluice gates construction in the delta. The implicit objective of the model is to minimize land value loss due to salinity by choosing when and where to construct sluice gates in the districts. The economic value of agriculture land is derived using our agriculture land use model, which relates annual net benefits from agricultural production to salinity concentration levels. We approximate the net benefit from land in a given year t as a function that is quadratic in salinity (equation 9). S_t is the state variable representing the level of salinity at time t. The value of agricultural land will also depend on whether the sluice gate is built. X_t is a binary control variable representing the decision to build, a value of 1 means that we build a sluice gate in the district.

$$f(S_t, X_t) = a - b * S_t - c * S_t^2 \quad \begin{cases} f(S_t, 0) = a - b * S_t - c * S_t^2 \\ f(S_t, 1) = a - b * \delta - c * \delta^2 - d \end{cases} \qquad \text{Eq. 9}$$

The parameter a represents agricultural land production under current salinity levels and the parameters b and c are coefficients used to construct a quadratic salinity loss function. When a sluice gate is built, the districts incurs in a onetime fixed cost, d.

The transition of salinity levels from year to year is as follows (equation 10). Salinity increases by μ percent each year if no sluice gate is constructed and can be stabilized at a level δ which follows from previous studies in the area such as Nguyen (2009). The transition equation is as follows:

$$g(S_t, X_t) \begin{cases} g(S_t, 0) = (1 + \mu) * S_t \\ g(S_t, 1) = \delta \end{cases} \qquad \text{Eq. 10}$$

We start with a deterministic, discrete space and discrete control program, assuming a planning period of 40 years. The model maximizes the expected net present value of agricultural land, i.e. the discounted streams of annual agricultural production profits. The problem is formulated as a dynamic program with one state and one control variable using the Bellman equation as follows:

$$V(s) = \max_{X_t=0,1}\{f(s) + \beta * V(s+1), f(f) - d + \beta * V(f)\} \quad \text{Eq. 11}$$

This model will be used to study several aspects of sluice gate construction in the delta. First we study the effects of uncertainty on the decision to build sluice gates by examining the optimal timing profile of construction under two climate scenarios that reflect the range of possible future climate outcomes. Second, we study the economic tradeoffs between protecting upstream areas versus areas closer to the sea by building a multi-region investment model that incorporates district-specific crop productivity and infrastructure cost.

4.1.- One region model simulation results

We numerically solve for the optimal policy rule, i.e., the timing profile of sluice gate construction and simulate the optimal state path using matlab version 7.10.

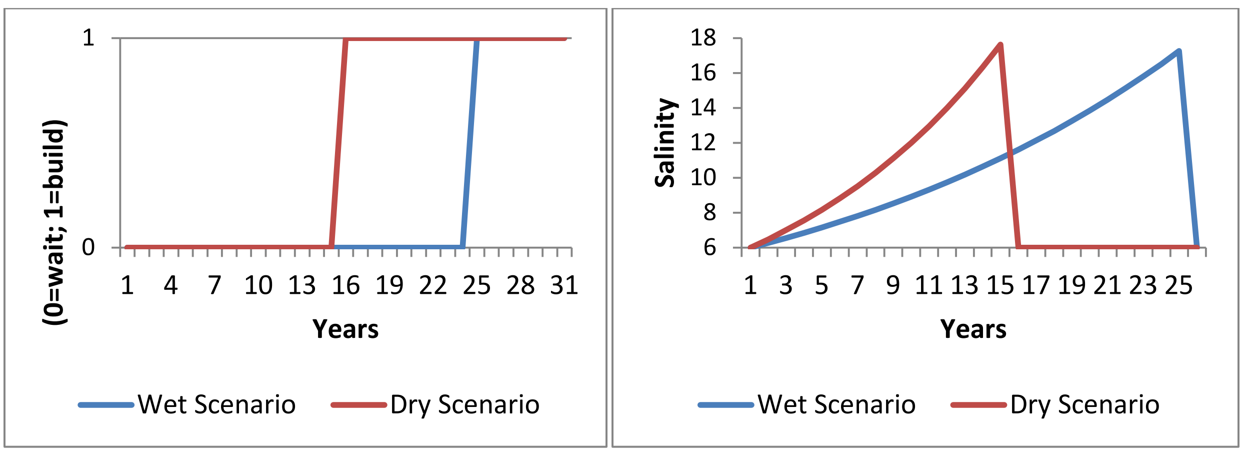
Table 3: Parameter Values (Base Case)

Parameter	Value
discount rate ()	0.95
a (net benefit from land)	150
b (linear salinity damage coefficient)	0.5
c (quadratic salinity damage coefficient)	0.04
d (fixed cost of infrastructure investment)	100
μ (salinity drift rate)	0.05
f (constant salinity value after infrastructure is built)	6

T (number of periods)	50

Our first experiment is to examine the implications of uncertain climate change scenarios in the decision to construct sluice gates. In order to do this we construct two extreme scenarios, a "wet" scenario where salinity does not build up as fast (base case) and a "dry" scenario where salinity increases faster (8 percent). We then compare the optimal timing of investment under these scenarios assuming that the decision maker is risk-neutral. Simulation results suggest that from an economic point of view it is optimal to build sluice gates earlier under a dry scenario (see figure 12).

Figure 12: Model simulations comparison of wet and dry scenario

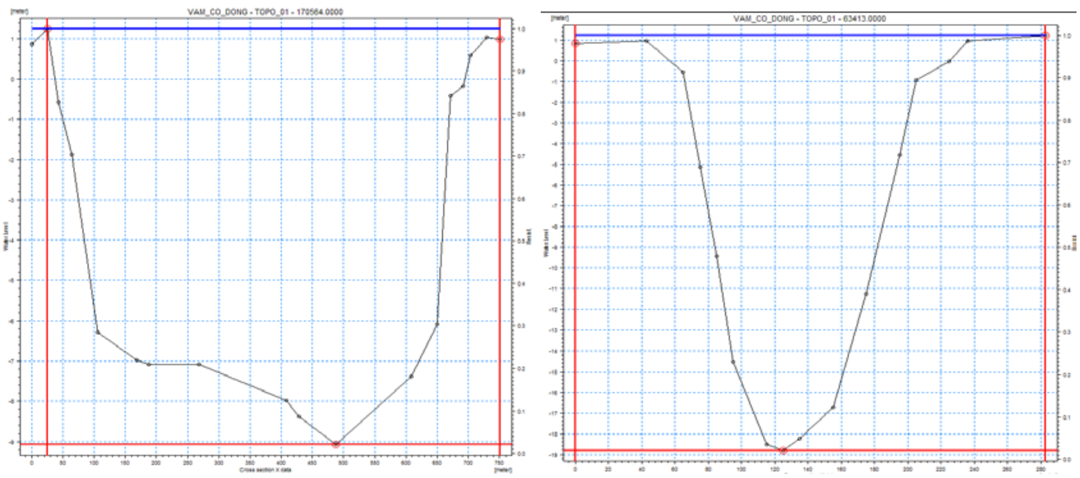


(a) Optimal Timing Sluice Gate Investment **(b)** Optimal Salinity Path

4.2.- Multi-region model simulation results

The one region model is extended to a three region model to study the economics of sluice gate location along an interlinked hydrologic system. A tradeoff arises between protecting additional areas closer to the sea and the additional cost of sluice gate construction. Building a sluice gate closer to the sea implies a higher cost given the fact the river section to be covered is greater, see figure 13, at the same time the amount of agricultural land that is protected is also greater. However, the additional benefit from protecting downstream decreases as we move closer to the sea due to the fact that agricultural productivity is already facing greater salinity impacts.

Figure 13: Cross Section of East Vam Co River (downstream-upstream)



Source: SIWRP (2009)

The model structure is similar to that of the one region model. Region specific land value functions are developed for the three regions, see equation 12. The value of land to be considered now includes three regions as opposed to only one region (equation 13); an additional constraint ensures that productivity from land cannot be negative (equation 14). It is worth pointing out that our state space is now composed of salinity in region i (S_{it}) and our control space includes i+1, i.e., sluice gate location and the possibility of no protection at all.

$$f_i(S_{it}, X_{it}) = a_i - b_i * S_{it} - c_i * S_{it}^2 \quad \text{Eq.12}$$

$$F(S_{it}, X_{it}) = \sum_{i=1}^{3} f_i(S_{it}, X_{it}) \quad \text{Eq. 13}$$

$$f_i(S_{it}, X_{it}) = \max\{f_i(s_{it}, x_{it}), 0\} \quad \text{Eq. 14}$$

Our global land value function is as a function of regional salinity and sluice gate location as follows:

$$F(S_{it}, X_{it}) = \begin{cases} F(S_{it};\ X_{1t} = 0, X_{2t} = 0, X_{3t} = 0) = f_1(S_{1t}) +\ f_2(S_{2t}) +\ f_3(S_{3t}) \\ F(S_{it};\ X_{1t} = 1, X_{2t} = 0, X_{3t} = 0) = f_1(\delta) +\ f_2(\delta) +\ f_3(\delta) -\ d_1 \\ F(S_{it};\ X_{1t} = 0, X_{2t} = 1, X_{3t} = 0) = f_1(S_{1t}) +\ f_2(\delta) +\ f_3(\delta) -\ d_2 \\ F(S_{it};\ X_{1t} = 0, X_{2t} = 0, X_{3t} = 1) = f_1(S_{1t}) +\ f_2(S_{2t}) +\ f_3(\delta) -\ d_3 \end{cases}$$

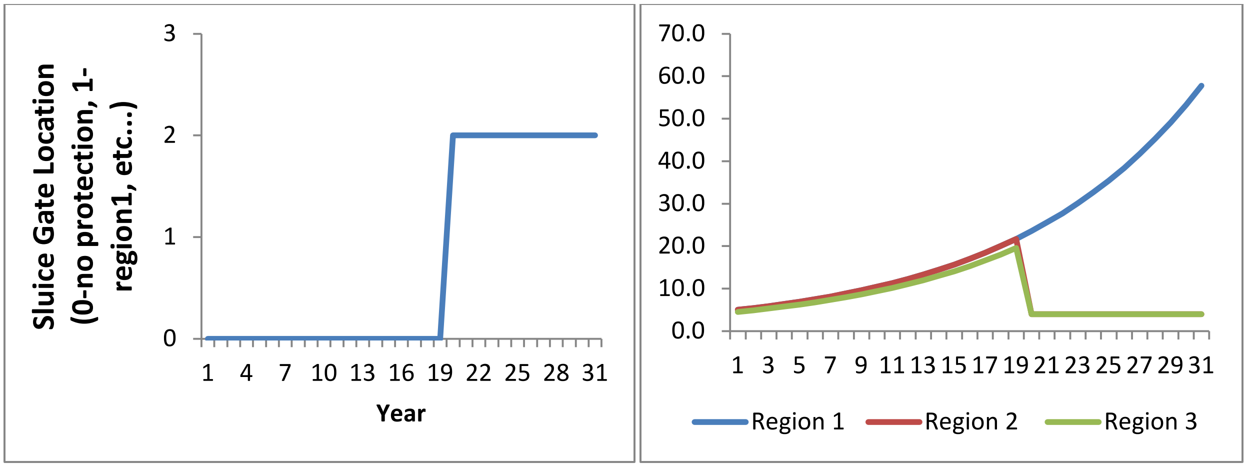
The state transition is as follows:

$$g(S_{it}, X_{it}) = \begin{cases} g(S_{it};\ X_{1t} = 0, X_{2t} = 0, X_{3t} = 0) => \ S_{it} = (r_i * S_t) * (1 + \mu) \\ g(S_{it};\ X_{1t} = 1, X_{2t} = 0, X_{3t} = 0) => S_{it} = \delta \\ g(S_{it};\ X_{1t} = 0, X_{2t} = 1, X_{3t} = 0) => S_{1t} = (r_1 * S_t) * (1 + \mu);\ S_{it} = \delta\ \forall i = 2,3 \\ g(S_{it};\ X_{1t} = 0, X_{2t} = 0, X_{3t} = 1) => S_{it} = (r_i * S_t) * (1 + \mu)\ \forall i = 1,2;\ S_{3t} = \delta \end{cases}$$

The spatial characteristics of salinity and protection costs are reflected in the previous equations. A region-specific rescaling factor r_i is included to reflect spatial salinity dynamics (see figure 6 and 9). Sluice gate costs differ depending on the location as follows $d_1 > d_2 > d_3$, i.e., it is more expensive to build a sluice closer to the sea (see figure 13).

The model simulations suggest that it is not economically viable to protect areas that are very close to the sea. In other words, it is optimal to protect region 2 and 3 and to “abandon” region 1 (see figure 14, a). There are several reasons for this. First, downstream areas are already constrained by salinity and will face greater salinity in the future when compared to upstream regions. Second, the sluice construction costs are much higher. In addition to that, if we were to account for the possibility of permanent land inundation due to sea-level rise the optimal location for construction will be further away from the sea. The optimal region-specific salinity path also shows salinity increases over time in region 1, i.e. agricultural land is not protected (figure 14, b). Salinity in regions 2 and 3 is controlled and reaches the level δ at the same time given the spatial hydrological connection between regions.

Figure 14: Model simulations multi-region model



(a) Optimal Location & Timing Sluice Gate **(b)** Optimal Regional Salinity Path

5.- Conclusion

The climate change effects on hydrologic extremes will be particularly felt in the Dong Nai river delta due to its hydrologic and economic characteristics. Salinity levels are likely to increase which will put additional pressure on agricultural production areas that are currently constrained by soil salinity buildup in the dry season. Adapting to increased salinity will involve adjusting cropping patterns, changing land uses and constructing new water infrastructure. Finding the right balance between the different adaptation options will be a challenge for development planning in the Dong Nai Delta. We integrate these agronomic and hydrologic aspects of climate change in the delta into a framework that examines the tradeoffs between choosing different options and suggests economically optimal combinations of adaptation strategies.

An economic model of agricultural land use and production is used to evaluate the economic feasibility of adjusting to increased salinity through both changes in the intensive and the extensive margin. The results of the agriculture model simulations suggest that salinity damages to agriculture are not as pronounced when adjustments in the farming system are allowed for a certain range of salinity levels. The possibility of switching towards more salinity tolerant crops such as changing from rice to sugarcane can reduce the overall economic impact of increased salinity in the region.

A water infrastructure investment model is used to evaluate the optimal timing and location sluice gate construction in the delta. Simulation results suggest that there is economic value for building protective infrastructure in certain districts within the delta. Earlier investment in infrastructure is preferred in situations where salinity increases faster. We also find that there is also a tradeoff between protecting districts located closer to the sea and upstream districts due to their different cost of protection and degree of exposure to salinity damages. In some cases, it is not economically viable to protect areas that are too close to the sea.

This study highlighted the desirability of using an integrated framework to analyze the economic implications of climate change when it comes to planning for agricultural production and infrastructure investments. Finally, this methodology has the potential to be applied to other areas where both land use and water infrastructure investment plans need to be re-examined in light of future changes in the climate. Future extensions of the work may include studying the implications of introducing new crop varieties that are more resistant to salinity or the option value associated with uncertainty and irreversibility of infrastructure investments.

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