The Economics of Water Infrastructure Investment Timing and Location under Climate Change

David Corderi Novoa[1], Jay R. Lund[2], and Jeffrey Williams[3]

Abstract*

The Dong Nai Delta in Vietnam has been projected to face long-term changes in physical conditions stemming from climate change. Sea level rise combined with changes in the hydrologic cycle will result in increased salinity conditions, causing significant damage to the current style of agricultural production. Adapting to these changes in salinity will require not only adjusting the cropping patterns, but also new water infrastructure investments. Two important questions arise for planners and practitioners. First, a balance needs to be found with regards to the appropriate timing of the investment. An important amount of investment is needed for new water infrastructure while salinity will increase gradually over time. Second, considerable trade-offs exist with respect to the location of the investment arising from the morphological characteristics of the delta. Constructing water infrastructure closer to the sea implies a higher investment cost. However, the additional benefits will be reduced since regions closer to the sea already have lower agricultural productivity due to greater salinity. This paper develops an economic model to analyse the optimal timing and location of water infrastructure investments in the Dong Nai Delta of Vietnam.

Keywords: climate change, water infrastructure, investment, salinity control, dynamic optimization

JEL codes: C61, Q54, Q25, O21

---

[1] Department of Infrastructure and Environment, Inter-American Development Bank, 1300 New York Avenue NW, Washington, DC 20577, USA; *dcorderi@iadb.org*.

[2] Department of Civil and Environmental Engineering, University of California at Davis, One Shields Avenue, Davis, CA 95616, United States.

[3] Department of Agricultural and Resource Economics, University of California at Davis, One Shields Avenue, Davis, CA 95616, United States.

∗ This paper is part of David Corderi's PhD dissertation. The authors want to thank Jim Wilen, Steve Boucher and Richard Howitt for useful comments. Special thanks to members of the Southern Institute of Water Resources Planning (SIWRP) in Ho Chi Minh city for sharing information on the hydrology of the Dong Nai Delta, Claudia Ringler at IFPRI for sharing the agricultural data in the region and specialists of the World Bank for sharing policy insights.

1.- Introduction

The Dong Nai River Delta concludes the Dong Nai River Basin, the largest river basin of Vietnam. The Delta's lowland areas serve as a hub for major economic activities in southern Vietnam, channeling water to thousands of hectares of agricultural land, millions of households, and hundreds of urban and industrial activities. Yet, the Delta is subject to physical forces, which affect economic activity in the area. During the six-month dry period that occurs in the Delta, limited freshwater flows in the rivers combined with seawater intrusion result in a considerable accumulation of salinity in the soils. Agricultural production has adjusted historically to salinity conditions by altering cropping patterns, water use and even through the construction of water infrastructure such as irrigation canals and sluice gates.

Long-term changes in the physical conditions of the Delta triggered by climate change are expected to increase salinity in the soils, causing significant damage to the current style of agricultural production (World Bank, 2007). Water infrastructure investments have been proposed as a long-term strategy for accommodating both expected physical changes and regional development in the Delta. This paper evaluates the economic desirability of water infrastructure investments to control salinity levels in the rivers. Infrastructure, such as sluice gates, has already been used in other agricultural areas suffering from seawater intrusion such as the Mekong delta (Käkönen, 2008). These structures have been able to protect freshwater systems and even transform brackish areas into freshwater areas for the cultivation of crops such as rice.

This paper starts by analyzing the appropriate timing to build water infrastructure, a sluice gate, in a region of the delta in a context of gradual salinity increases. If no sluice gate is built, salinity will slowly increase and damage agricultural production. Given the fixed investment cost of a sluice gate, constructing a gate to stabilize salinity will only be economically viable after salinity has increased over the years to some level. An economic model is built in this paper to assess how different parameter values and assumptions with respect to available agricultural technology will affect the optimal timing for investment.

The second question addressed in this paper is the investment tradeoff given the morphological characteristics of the delta. Constructing sluice gates closer to the sea implies a higher investment cost. However, the additional benefits will be reduced since regions closer to the sea already have lower agricultural productivity due to greater salinity.We extend the economic model to analyze the appropriate location for sluice gate investments. This extension expands the one region model into a three inter-connected regions located along the river.

2.-Previous Literature.

Numerous studies have performed economic analysis of salinity control programs all over the world. Most of the analysis focuses on static aspects of adjustments to increases in salinity such as adjusting crop acreage, irrigation technology, crop water application, and reallocating water among water users (see for example Gardner and Young (1985)). Lee and Howitt (1996) consider the possibility of implementing salinity control investments to improve water management in on-farm and off-farm uses. The authors analyze the economic return of these salinity control investments as well as the interplay with other salinity adjustment measures such as changes in the crop mix and water inputs in the Colorado River basin. Comparative statics is used by Lee and Howitt (1996) to obtain the optimal mix of both agricultural adjustments and investments to reduce the amount of salinity in the basin. The analysis assumes that salinity levels will not change over time due to climate change; it is therefore a static investment analysis on how to improve the existing salinity situation.

Characklis et al. (2005) study long-term regional costs and benefits of salinity control projects and other adaptation measures. The authors calculate the net present value with and without a specific project to control salinity in the Colorado River basin. Agriculture and municipal water users are considered the main beneficiaries of salinity reduction. The analysis by Characklis et al. (2005) considers a planning period over which salinity increases at a specific rate. The possibilities of changing crops, water allocation, irrigation technology and even desalination are then evaluated within this framework. The authors compare the returns of salinity control project which already pre-determined. In this paper, we use a similar assumption on the incremental pattern in salinity and explore the optimal design of a salinity control investment plan. As in Characklis et al. (2005) and Lee and Howitt (1996) we use mathematical programming model to estimate the benefits of salinity control in agriculture. In the study area, however, salinity dynamics are different from the ones previously studied. The increase in salinity in the Lower Dong Nai delta is mainly a consequence of hydrologic river flow and changes in the tidal regime due to sea level rise. Given this specific characteristics, we assume that changes in on-farm water uses have a negligible effect in reducing salinity.

This research also contributes to the literature on investment in water infrastructure[4] to adapt to new hydrological conditions due to climate change. Previous approaches to studying water infrastructure investments in the context of climate change adaptation have mainly focused on dams for water storage. Callaway et al. (2007) explicitly model the expansion of a water

[4] Previous literature on investments in capacity expansion is also related to these types of problems; see for example Manne (1967).

infrastructure system to adapt to climate change. Their empirical model considers the construction of a dam as an adaptation measure to decreased water availability in the dry season. The authors study the optimal capacity of a reservoir for different projections of water availability, considering the interplay between the infrastructure investment and other non-structural measures such as water transfers through markets. 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. The authors assess the economic performance of a given infrastructure investment plan along the Nile river under scenarios of changes in precipitation and river runoff. Our paper expands on the previous studies by examining the optimal size and location of the water infrastructure investment given a gradual increase in salinity levels.

The dynamic nature of our infrastructure investment analysis has also been considered from a theoretical point of view. Wright and Erickson (2003) review the literature on investment timing, uncertainty and irreversibility, started by Dixit and Pyndick (1994), and consider its application to climate change adaptation. The authors develop an optimal stopping model to study the optimal timing for investments in adaptation. Their modeling study is not based on empirically estimated parameters or a specific sector problem; rather, their work illustrates how different parameter values alter the optimal timing for investment. The insights provided by the authors' analysis are similar to the ones we attempt to gain using the sluice gate investment model developed in this paper.

3.- An Economic Model of Sluice Gate Investment Timing

In this section, we present a model, one that focuses on the issue of timing and the value of investing in a sluice gate in the delta. If no sluice gate is built, salinity will increase and damage agriculture. There exists the option of constructing a sluice gate which can potentially stabilize salinity at a particular level. A significant cost is also associated to building a sluice gate so the question becomes when a sluice gate should be built. This is an optimal stopping problem. By casting this problem within this framework, we can identify not only the optimal timing but also the threshold salinity level that triggers the construction of a sluice gate.

3.1.- Sluice Gate Description, Cost and Benefits.

A sluice gate is a hydraulic infrastructure built across a canal or a river to control the flow of water passing through. One or more gates may be built within the same structure to allow for more flexible control of water flows. A bridge connecting both sides of the river or canal is normally constructed above the gate area, which permits the traffic of people and vehicles. In the context of a river delta, sluice gates are built to regulate the mixing of freshwater coming from rivers located upstream with saltwater coming from the sea located downstream in the delta. See figure 1 for an illustration.

Figure 1: Photo of a Sluice Gate in the Mekong Delta

Source: World Bank (2007)

These gates operate such that when the water level from the river side is higher than the water level from the sea side, the sluice gate is opened and freshwater flows freely into the sea. Conversely, when the water level from the sea side is higher than the water level in the river side, the gate will be operated such that it opens partly or even closes completely so that the salinity on the river side can be controlled. During the rainy season, sluice gates are opened to drain upstream areas and avoid flooding. In the dry season, upstream freshwater flows are typically lower than seawater. Sluice gates can then be used to control the salinity concentration in the river. They may be open or closed from hours to days. Table 1 shows an example of the operational procedure developed by the Southern Institute of Water Resources Planning (2007) for a sluice gate in the Mekong Delta. In areas where freshwater flows are highly affected by hydrologic conditions of the sea, the sluice gate will close when the water level from the sea reaches a specified height.

Table 1 Example of Typical Sluice Gate Operation Procedures in the Dry Season

December	January	February	March	April
Take and drain (in out)	Close if water level > 2.2m	Close to store; Drain	Close if water level >1.8m; limit in; drain contaminated water	Close to Store;

Nguyen (2009) studies optimal sluice gate operation to control salinity during the dry season in a district of the Mekong Delta. The author analyzes both the hydrologic and the economic aspects of controlling the amount of sea water flow into the river system when the water level on the sea side is higher than on the river side. Nguyen (2009) constructs a water flow model to characterize responses of the physical system to different gate opening rates. An average salt balance is calculated as a function of the freshwater flow from upstream and the salt flux from sea water.

Nguyen (2009) then considers the economic tradeoffs from having the gate closed or opened using an optimal control model. When the gate is closed there are costs from blocking boats transporting goods along the river or preventing the migration of fish into the river. When the gate is opened, farmers lose revenue since crops either have lower yield or cannot be grown due to salinity.

Nguyen (2009) integrates the economic costs of sluice gate operation and the hydrologic constraints representing water flows and salinity in the river into an optimization problem. Optimal sluice gate operation, i.e., the rate of opening and closing the gate across the river, is obtained such that salinity is stabilized at a specific level and the net present value of economic cost associated with it is minimized. The author finds that an economically viable sluice gate operation regime can contain salinity at values between 2 and 4 g/l. We will use his conclusion in the specification of the sluice gate investment models in the following subsection.

Sluice Gate Cost

The cost of a sluice gate is mainly determined by its size, which is a function of the section of the river where it is located. Gate size is normally measured in width and height from the bottom of the river. Sluice gates currently operating in the delta range from 30 meters of width by 4.5 meters of height to 5 meters of width by 3 meters of height. Construction, operation and maintenance costs range from 400 billion Vietnamese dong (VND) to 750 billion VND according to the Southern Institute of Water Resources Planning. Unlike dams, sluice gate costs rise approximately in a linear fashion with respect to size of construction.

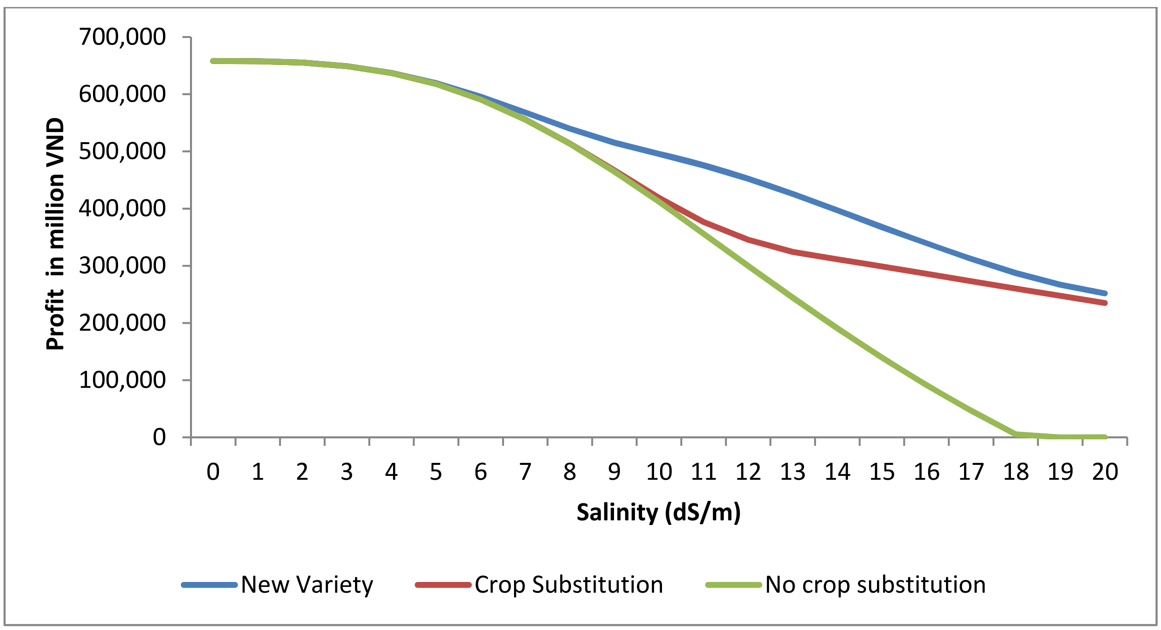
Benefit Estimation

The benefits of constructing a sluice gate stem from the possibility of controlling salinity in the rivers of the delta. We will only consider the positive effects for agricultural production, even though urban, industrial or environmental water uses may also benefit from controlling salinity. The benefit of sluice gates will therefore be estimated according to the number of hectares of agricultural land within a river or irrigation canal where salinity is regulated. For this purpose, we use an economic model of agricultural production in the delta developed in Corderi (2011) to estimate the value of production with respect to different levels of salinity. This mathematical programming model provides estimates of agriculture production disaggregated to the district level.

We will use the agricultural production model to derive investment benefits under two different specifications. For simplicity, we estimate a quadratic relationship between profits and the level of salinity using the simulated profit response from the agricultural model. Sluice gates' benefits are implicitly measured in terms of avoided agricultural loss by comparing the cases with and without a sluice gate.

The first model specification will be used for the investment timing model for the whole delta area. In this case we will study the optimal timing given three alternatives: no crop substitution, changing the existing crop mix, and introducing new crop varieties. Figure 3 shows the estimated agricultural profits for a range of salinity concentrations given different crop adjustment alternatives.

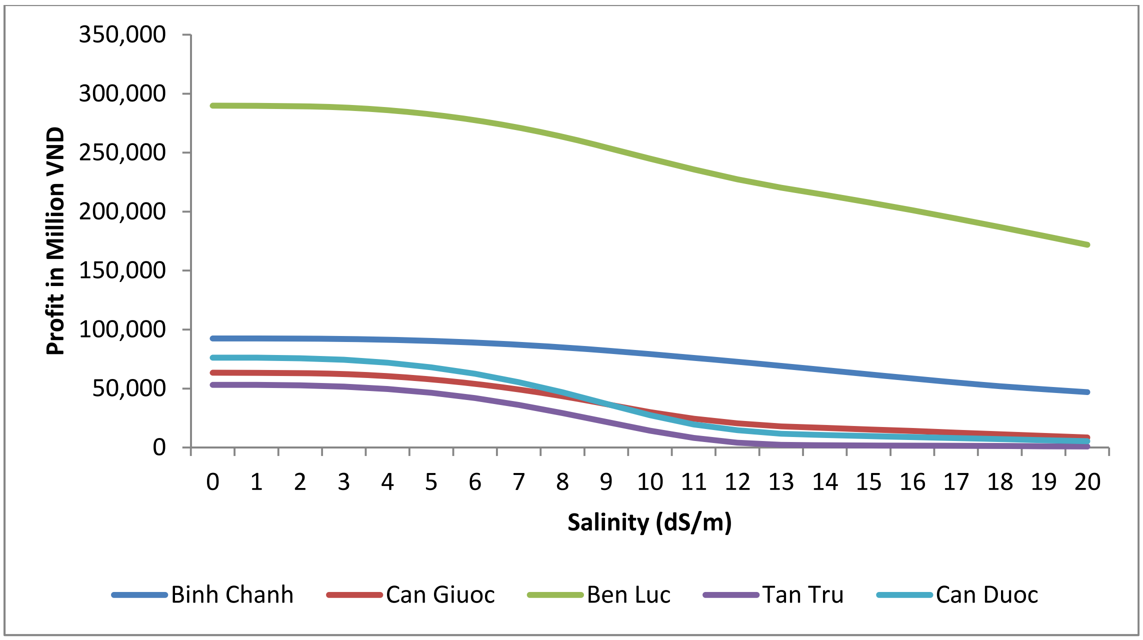
Figure 2 Estimated Salinity-Profit Functions with alternative specifications



The second specification of the agricultural production model will be the investment problem at the regional level. Figure 3 shows the parameterized agricultural profit functions based on a simulation for different salinity levels. Each district has a different response to salinity in economic terms, resulting from diverse endowments of land, technology and crops being grown. For the regional investment model, we emphasize an area along the Dong Nai

River. The selected area comprises approximately 30 percent of Binh Chanh district and 80 percent of Can Giuoc district. The agricultural profit function of the study area is a composite of the agricultural profit functions of both districts, each weighted by its proportion of land. The total production in the area is roughly 780 billion VND, from almost 14,000 hectares of agricultural land.

Figure 3 Estimated Salinity-Profit Functions at the District Level



3.2.- Model Formulation and Results

The sluice gate investment model assumes that salinity increases over a planning horizon of 40 years and finds the optimal timing (year) for building a sluice gate such that the value of agricultural production profits is maximized.[5] The problem is formulated as a dynamic programming problem with one state variable and one control variable. We use a deterministic, discrete space and discrete control specification where time *t* is measured in years. The state

[5] We do not consider an infinite horizon model specification because the average lifetime of a sluice gate is limited to decades.

variable (S_t) represents salinity level at year t. The control variable (X_t) is binary and represents the decision at year t on whether or not to build a sluice gate; a value of 1 means that a sluice gate is constructed whereas a value of 0 means that the decision is to wait with respect to the construction of this infrastructure. Given the nature of changes in salinity, i.e. incremental changes over time, casting the problem as a deterministic instead of a stochastic one does not alter the optimal solution. We perform a sensitivity analysis to explore the implications of alternative trends in salinity changes stemming from uncertainty over the speed of change in salinity levels in the delta.

In this dynamic optimization problem, the transition of salinity levels from year to year is the crucial equation of motion. If no sluice gate is constructed salinity increases exponentially by μ percent each year.[6] When a sluice gate is constructed, and operated according to Nguyen (2009), salinity is stabilized at δ dS/m.

$$g(S_t, X_t) = \begin{cases} g(S_t, 0) = (1+\mu)^t * S_{t-1} \\ g(S_t, 1) = \delta \end{cases} \quad (9)$$

Equation 10 represents the payoff associated with waiting to build and building a sluice gate. When no sluice gate investment is in place, there is no cost incurred and agricultural profits are earned in that year. Agricultural profits will depend on the salinity level of a given year. We use a quadratic function to represent the relationship between agricultural profits and salinity levels, as explained in the previous section. The parameter a represents agricultural profits when no salinity is present. The parameters b and c are the linear and quadratic salinity loss estimates

[6] Salinity increases are a result of lower upstream freshwater flows and sea level rise (30cm), which have been simulated in a hydrodynamic model (MIKE11). I calculate the difference between salinity conditions in 2050 and in 2010 to obtain the parameter μ.

respectively. When a sluice gate is built, a one-time fixed cost d is incurred and the value of agricultural profits follows from substituting salinity level δ in the estimated quadratic function.

$$f(S_t, X_t) = \begin{cases} f(S_t, 0) = a - b * S_t - c * S_t^2 \\ f(S_t, 1) = a - b * \delta - c * \delta^2 - d \end{cases} \tag{10}$$

We use the Bellman equation to solve this problem. The equation can be written as follows:

$$V(S_t) = \max_{X_t = 0,1} \{ f(S_t, X_t = 0) + \beta * V_{t+1}(S_{t+1}), \tag{11}$$

$$f(S_t, X_t = 1) + \beta * V_{t+1}(\delta) \}$$

Equation 11 implicitly describes the value of agricultural production with respect to salinity. The investment decision is captured in each of the two arguments of the *max* operator. The first expression corresponds to the payoff from the decision to wait, i.e., earning agricultural profits given salinity in year *t* plus the value of agricultural land when salinity is allowed to increase over the next years. The second argument represents the decision to build, i.e., paying the construction cost in year *t* and earning agricultural profits associated with a stabilized salinity level δ.

One approach to solve this optimal stopping problem is to first calculate the salinity level that will make the value of building the sluice gate exceed the value of waiting to invest. Given the initial salinity level S_0, the state transition function and the calculated salinity threshold, it is possible to calculate the year at which the investment is made since each stage of the program represents a year, which has a given salinity level.

We numerically solve the model represented by equations 9 through 11 in Matlab version 7.0 using the computational economics toolbox developed by Miranda and Fackler (2002). We use the algorithm *ddpsolve* to solve for the optimal policy rule, i.e., the timing profile of sluice gate construction. Both value function iteration and backwards recursion yield the same results, as they should.[7] Table 2 contains the parameter values used for the base case simulation. Once the optimal policy rule is determined, we simulate the optimal state path using $S_0 = 4$ as initial condition.

Table 2: Parameter Values[8] (Base Case)

Parameter	Description	Value
β	discount factor[9]	0.95
a	intercept of agricultural profit function (billion VND)	892.8
b	linear term of agricultural profit function	-0.1
c	quadratic term of agricultural profit function	36.79
d	fixed cost of sluice gate construction (billion VND)[10]	650
μ	salinity drift rate (percent)[11]	4.5%
δ	constant salinity after sluice gate is built (dS/m)	4
T	number of years	40

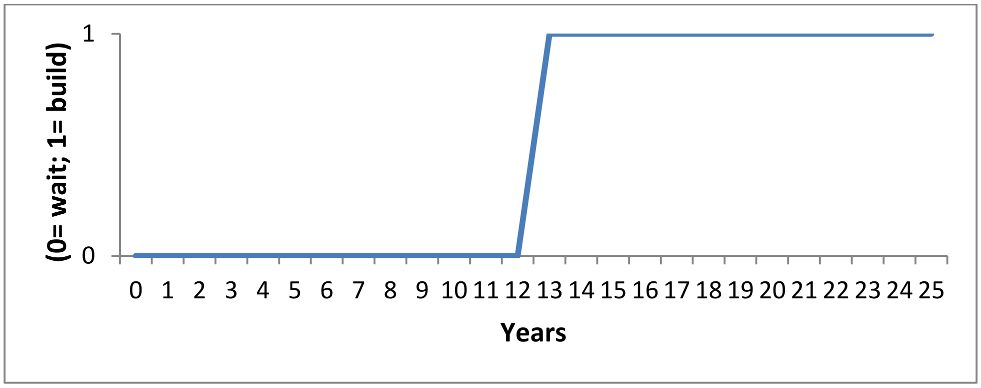
Figure 4 shows the optimal timing for sluice gate construction, the simulated optimal salinity path, and the evaluation of the value function at the optimal solution. Results from the base-case simulation suggest that the optimal time to construct a sluice gate is at year 12. The salinity threshold level at which the investment is made is approximately 7 dS/m and is reached at year 13 after the sluice gate is constructed and operated (see figure 4b). Finally, the value of land as a function of the year of investment is shown in figure 4c. The value decreases before

[7] I assume a terminal value of 0 in the backwards recursion approach.
[8] Parameters *a*, *b* and *c* are obtained by running a regression of agricultural profits on salinity and squared salinity with an intercept. The R^2 of the regression is 0.97.
[9] The value of the discount factor corresponds to a discount rate of 5 percent.
[10] The value is an approximation of the cost to build a relatively large sluice gate.
[11] The growth rate is calculated by comparing salinity values projected for 2050 with values of 2007.

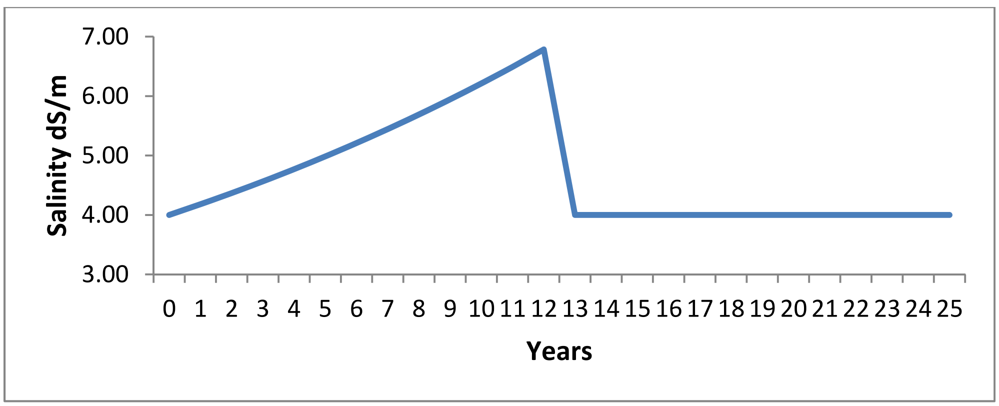
year 12 which represents the fact that salinity is increasing since the sluice has not been built. After year 12 the value of land is constant because salinity is stabilized at a constant level.

Figure 4: Optimal Timing Model Base Case Results[12]

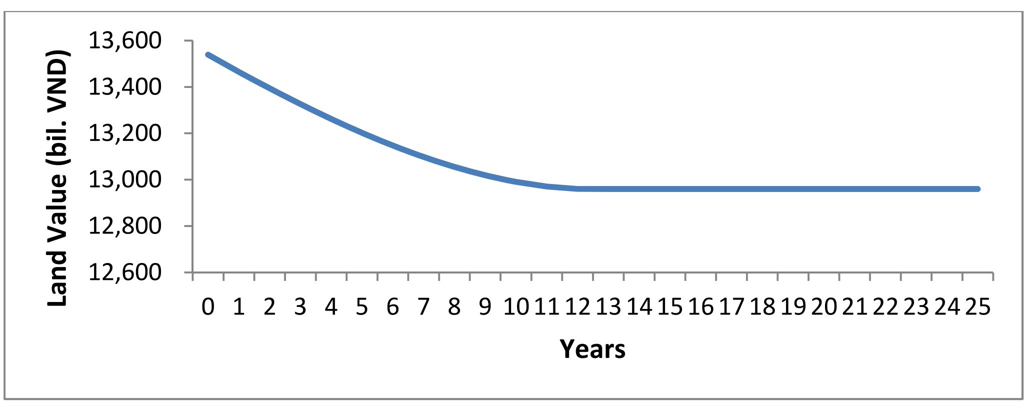
(a) Optimal Timing of Sluice Gate Investment



(b) Optimal Salinity Path



(c) Production Value in Optimal Solution



[12] The graphs representing the policy rule and the optimal state path should present completely vertical lines at the optimal time for investments. The moderate slope is only an artifact of the graphing software used. This is true for all figures presenting optimization results.

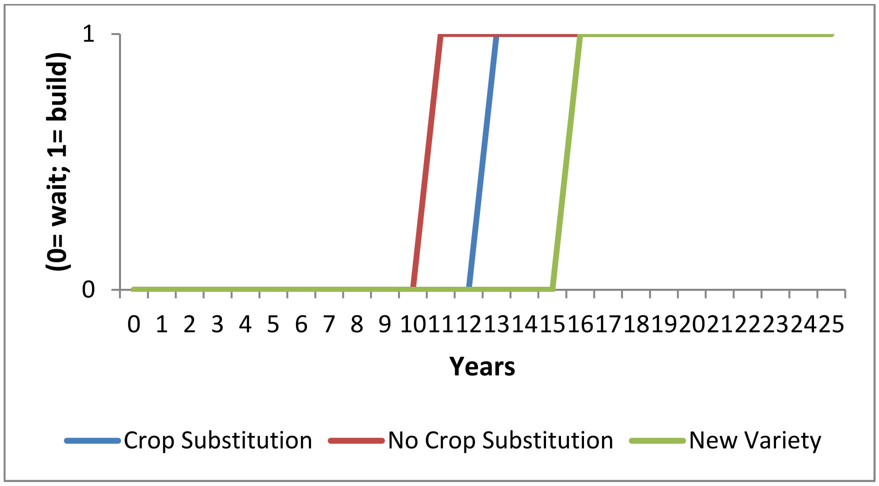
3.3.- Sensitivity Analysis

Sensitivity analysis is conducted with respect to the specification of the agricultural profit function, the salinity trend, the value of sluice gate construction, and the choice of discount rate. The agricultural profit function determines the response of profits with respect to different salinity levels. This function represents the potential benefits of sluice gate construction and determines the salinity threshold at which the investment is made. The profit function can differ considerably depending on the mix of agricultural adaptation options considered in the context of increased salinity. Based on previous work by Corderi et al. (2011) we can estimate the presumed agricultural profit function under three different assumptions. The profit function where crop substitution is used as a response to salinity constitutes the base case of this analysis. The other two cases are the profit function under the assumption that no crop substitution is available, and the possibility of introducing salinity resistant crop varieties in addition to substituting among existing crops. As in the base case, we approximate the previously derived profit functions using a polynomial of order 2 with respect to salinity. The two additional profit functions differ from the base case in the linear and quadratic terms (b and c).

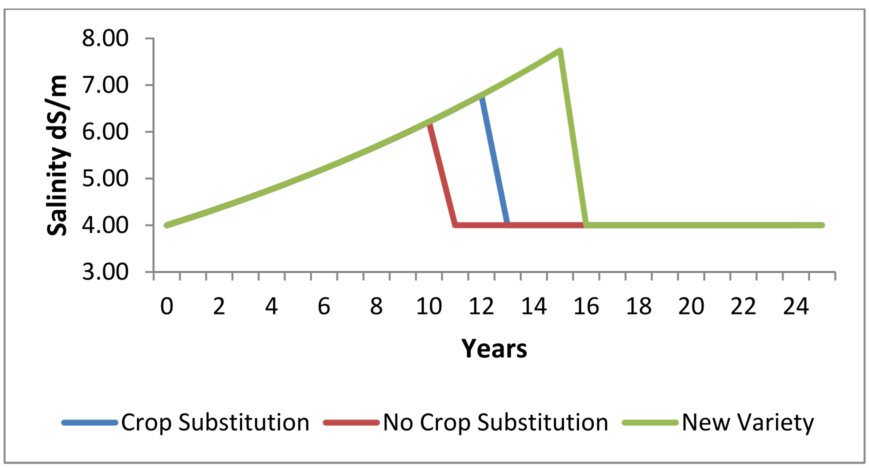
The simulation results are shown in figure 5. Sluice gate construction occurs earlier than the base case when no crop substitution is possible (figure 5a). Conversely, construction happens later than the base case when salinity resistant varieties are available. The results are as expected, the availability or lack of options to mitigate salinity damages in agriculture delays or accelerates the investment in sluice gates. The salinity threshold is approximately 6, 7 and 8 dS/m for the case of no crop substitution, crop substitution and new rice varieties respectively (see figure 5b). Modeling agricultural production under a pessimistic (no crop substitution) and an optimistic (varietal improvement) assumption yields a difference of 5 years in terms of optimal timing for investment. This difference is significant given that the cycle for medium-term agricultural land use plans is normally 5 years in Vietnam.

Figure 5: Sensitivity Analysis of Agricultural Profit Function Specification

(a) Optimal Timing Sluice Gate Investment



(b) Optimal Salinity Path



The rate at which salinity increases between the present and year 2050 is also an important factor to consider. In the base case scenario, we considered an exponential growth rate, i.e., salinity increases more slowly at the beginning of the planning period but the growth rate accelerates towards the end of the planning period. We simulate the base case problem using an alternative specification for salinity growth. A linear trend with the same initial and terminal salinity level as in the exponential case is constructed. This trend specification implies that salinity increases faster at the beginning of the planning period and therefore investment is made earlier. The salinity threshold for construction is unchanged, as expected (see table 3).

We also simulate the possibility of having a cost of sluice gate construction that is 20 percent higher than the base case. Sluice gate construction is delayed and the salinity threshold is greater (see table 3). Agricultural losses must now be greater to justify the expenditure in a more expensive infrastructure. The final simulation pertains to the choice of discount factor. We obtain the optimal policy rule associated with a lower discount factor, i.e., a higher discount rate. As expected, the salinity threshold is greater and sluice gate construction is delayed.

Table 3 Salinity Threshold and Optimal Timing for Alternative Scenarios

	Base Case	No Crop Substitution	New Rice Variety	Linear Trend	Higher Sluice Cost (+20%)	Lower Discount Factor (β=0.86, r=15%)
Salinity Threshold (dS/m)	7.09	6.21	8.08	7.09	7.74	7.40
Investment timing (year)	12	10	15	8	15	14

4.- An Economic Model of Sluice Gate Investment Location

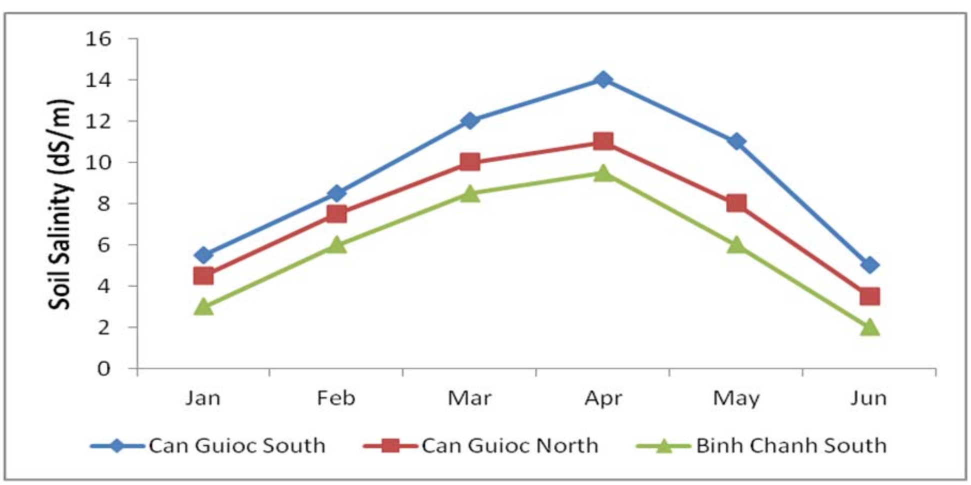
The previous section focused on the analysis of sluice gate construction timing in the river delta. The model used to evaluate the investment assumes that the location where the sluice gate is built is itself not a choice. In this section we relax this restriction and examine the economic implications of choice on location of sluice gate investment, especially the timing. Two characteristics of the delta make this problem interesting. On one hand, rivers and canals are wider the closer they are to the sea. The cost of building a sluice gate is therefore higher or lower depending on its distance to the sea. On another hand, agricultural areas located closer to the sea experience greater salinity and hence have lower productivity. A tradeoff arises between protecting upstream areas versus areas located closer to the sea. In other words, building a sluice gate closer to the sea will protect more agricultural land of lower productivity at a higher cost. An economic model is developed to study the tradeoffs associated with sluice gate location. We divide the homogenous region considered in the previous section into three smaller interconnected regions that have differentiated sluice gate cost and agricultural productivity.

4.1.- The Spatial Characteristics of the Delta

The Spatial Distribution of Salinity

The spatial distribution of salinity concentration in the agricultural land follows from the delta's morphologic characteristics. Downstream areas that are closer to the sea are subject to higher salinity concentrations throughout the dry season. The same pattern is observed in the three regions selected for study. The southern part of the Can Giuoc district is subject to higher salinity than the southern part of the Binh Chanh district (see figure 3.5).

Figure 3.5: Spatial Salinity Dynamics



The Spatial Variation of Sluice Gate Dimensions

The size of the section of rivers in the delta can vary significantly as they are closer to the sea. The cross sections of the Dong Nai River have similar heights of 17 meters but differ greatly in their width. The upstream Dong Nai river is approximately 200 meters whereas downstream it is about 1700 meters.

The greater the size of the river section, the greater the area a sluice gate must cover, hence the greater the cost of construction. Table 3.4 shows an example of the size of different sluice gates located in the south Mang Thit irrigation system in the Mekong delta. The variation in size is up to ten times in this particular area.

Table 3.4: Example of Sluice Gate Dimensions

Sluice Name	Gate Width	Bottom Altitude (depth)	Area
Can Long	30	-4.5	150
Na Tho	5	-3	15

4.2.- Model Formulation and Results.

The model formulation is similar to the one-region model. The region considered in section 3.3 is now divided into three regions interconnected along the river. Again, the problem is formulated as a dynamic programming problem with one state variable and one control variable, except that the control variable represents both time and space. We use a deterministic, discrete space and discrete control specification where time t is measured in years. The state variable (S_t) represents salinity level at time *t* which is then adjusted through a rescaling variable (r_i) for each of the *i* regions, which helped to solve the problem numerically.

The control variable (X_t) is a discrete variable that can take the value from 0 to 3. It represents the decision at year t on where to build a sluice gate. A value of 0 means that no sluice gate is constructed, a value of 1 means that a sluice gate is constructed in region 1 (Can Giuoc South), which is closer to the sea, a value of 2 means that construction takes place in region 2 (Can Giuoc North) which is upstream from region 1, a value of 3 means that gate is located in region 3 (Binh Chanh South), the furthest from the sea.

The transition of salinity states from year to year is as follows (see equation 12). If no sluice gate is constructed salinity increases exponentially by μ percent each year in each region. If a sluice gate is built in region 1 ($X_t = 1$), then all regions are protected and salinity is stabilized at δ, adjusted by the region specific salinity scaling factor r_i . If a sluice gate is built in region 2 ($X_t = 2$), then salinity in region 1 continues to increase exponentially whereas salinity in regions 2 and 3 is stabilized. The logic is the same for an investment in region 3.

$$g(S_{it}, X_{it}) = \begin{cases} g(S_{it};\ X_t = 0) => \ S_{it} = (r_i * S_t) * (1 + \mu)^t \\ g(S_{it};\ X_t = 1) => S_{it} = r_i * \delta \\ g(S_{it};\ \ X_t = 2) => S_{1t} = (r_1 * S_t) * (1 + \mu)^t;\ S_{it} = r_i * \delta\ \forall i = 2{,}3 \\ g(S_{it};\ X_t = 3) => S_{it} = (r_i * S_t) * (1 + \mu)^t\ \forall i = 1{,}2;\ S_{3t} = r_3 * \delta \end{cases} \tag{12}$$

The net benefit function of sluice gate investment depends now on where the gate is constructed (see equation 13). When no sluice gate is built, agricultural profits depend on the salinity of a given year for each region. A quadratic function is used to represent the relationship between agricultural profits and salinity in each region. The parameters a_i b_i and c_i are estimated by region. An additional constraint prevents land productivity from becoming negative.

When a sluice gate is built in region 1 a one-time fixed cost d_1 is incurred and the value of agricultural profits in all regions follows from substituting salinity level δ in the estimated quadratic function. When the location of the gate is in region 2, only regions 2 and 3 benefit from it and the cost incurred is d_2. Finally, when the gate is built in region 3, only that region benefits from it and the subsequent cost of the investment is d_3.

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

where (13)

$$f_i(S_{it}) = a_i - b_i * r_i * S_{it} - c_i * (r_i * S_{it})^2$$

$$f_i(\delta) = a_i - b_i * r_i * \delta - c_i * (r_i * \delta)^2$$

$$f_i(S_{it}) = \max\{f_i(S_{it}), 0\}$$

We use the Bellman equation to solve this problem. The equation can be written as follows:

$$V(S_{it}) = \max_{X_t=0,1,2,3} \left\{ \begin{matrix} F(S_{it}, X_t = 0) + \beta * V_{t+1}(S_{i,t+1}), F(S_{it}, X_t = 1) + \\ \beta * V_{t+1}(S_{i,t+1}), F(S_{it}, X_t = 2) + \beta * V_{t+1}(S_{i,t+1}), \\ F(S_{it}, X_t = 3) + \beta * V_{t+1}(S_{i,t+1}) \end{matrix} \right\} \quad (14)$$

We numerically solve[13] the model represented by equations 12 through 14 to derive the optimal policy rule, i.e., the location and timing profile of sluice gate construction. Table 5 contains the parameter values used for the simulation. Once the optimal policy rule is determined we simulate the optimal regional state path using $S_0 = 4$ as initial condition.

[13] The code is written in Matlab version 7.0. I use the algorithm *ddpsolve* from the computational economics toolbox developed by Miranda and Fackler (2002).

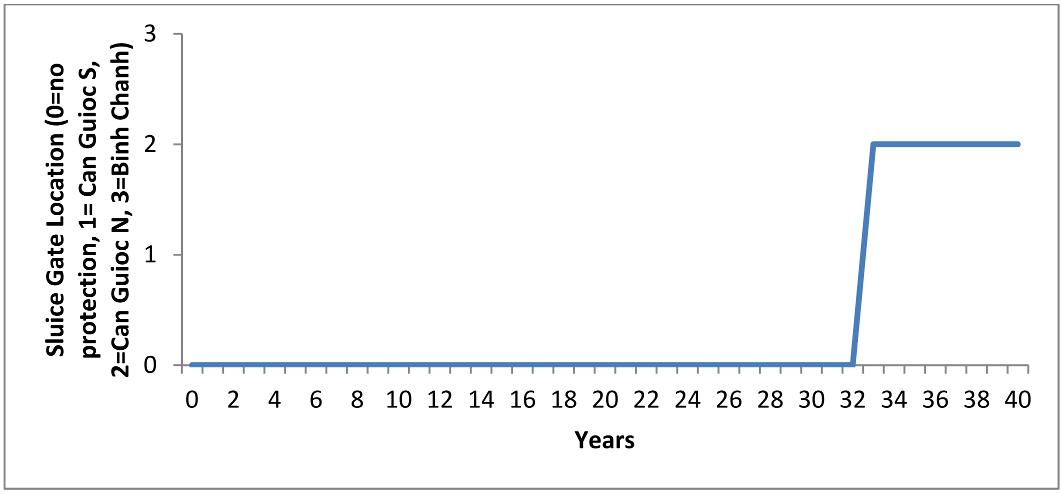
Table 5: Parameter Values Regional Model (Base Case)

Parameter	Description				Value
β	discount factor				0.95
μ	salinity drift rate (percent)				5%
δ	constant salinity after sluice gate is built (dS/m)				4
T	number of years				40
Region-Specific Parameters					
	a	b	c	d	r
Reg. 1: Can Giuoc South	148.45	-7.58	0.02	650	1.3
Reg. 2: Can Giuoc North	520	-26.5	0.07	520	1
Reg. 3: Binh Chanh North	391.7	-5.48	-0.18	430	0.9

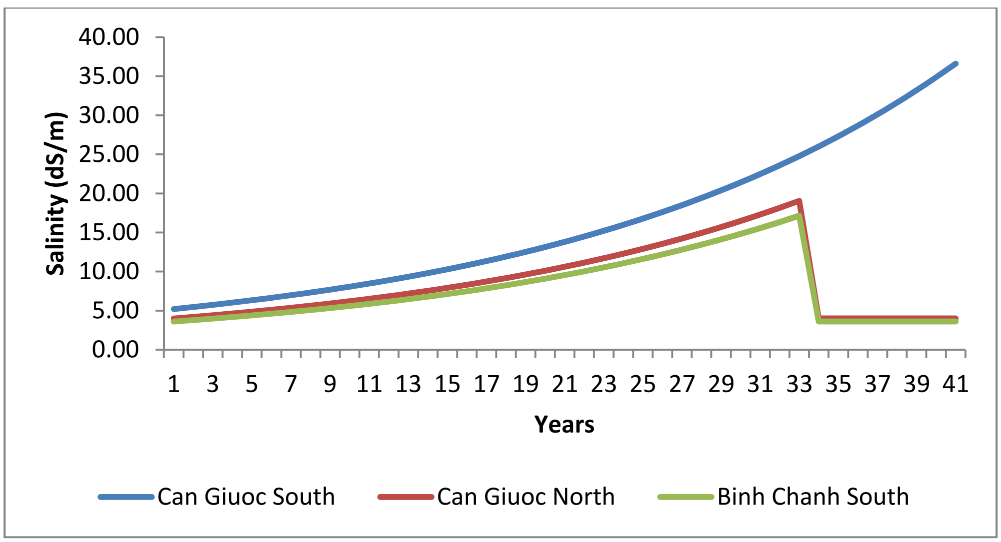
The model simulations suggest that it is not economically viable to protect the region is closest to the sea. In other words, it is optimal to protect regions 2 and 3 and to “abandon” region 1 (see figure 7a). The optimal region-specific salinity path also shows how salinity in regions 2 and 3 is stabilized (figure 7b) at the same time given the spatial hydrological connection between them. Salinity increases over time in region 1 since agricultural land is not protected. Can Giuoc South is the closest region to the sea. The additional agricultural profits that would be obtained by protecting this region do not cover a 25 percent increase in costs (from 520 to 650 bil VND).

Figure 7: Model simulations multi-region model

(a) Optimal Location & Timing of the Sluice Gate



(b) Optimal Regional Salinity Path



The optimal location of the sluice gate is quite sensitive to the difference in the cost of protection. Smaller differences between the cost of protecting region 1 and 2 imply that there are greater chances that protecting region 1 will be viable. In general the choice of protection will be done if the difference in cost is smaller than the right-hand-side of equation 15. This second term is the difference between the value of agricultural profits when the region is protected and when it is not, for any time period in the planning horizon.

$$d_1 - d_2 < -b_1\big((r_1 * \delta) - (1+\mu)^t * S_0\big) + c_1\big((r_1 * \delta) - (1+\mu)^t * S_0\big)^2, \quad (15)$$

$$t \in [0, T]$$

A two-region model and a four-region model have also been developed to contrast with this three-region model version. Results from these models provide some insights about the optimal sluice gate location. In the two-region model, regions 1 and 2 are merged into one sole region. Under these conditions it is optimal to protect the downstream region. In the four-region model, region 2 has been further divided into two smaller regions. Simulation results present an optimal investment that is exactly the same as in the four region model, i.e., regions 2, 3 and 4 are protected whereas region 1 is abandoned.

The results from the alternative model specifications suggest that efficiency gains can be realized by abandoning low productivity areas given that these are closer to the sea and have higher protection costs. The size and associated agricultural profit of an area to be protected as well as the variation in the sluice gate construction costs along the river are the major determinants of optimal sluice gate location. At the same time, a minimum scale of protection, i.e. a minimum number of regions, is needed to cover the investment cost in a sluice gate.

5.- Conclusions

Water infrastructure investments can be an option to control increased salinity in the Lower Dong Nai delta. These structures alleviate the losses in agricultural production associated with higher salinity. Sluice gates have already been used in other agricultural areas suffering from seawater intrusion such as the Mekong delta. Once a gate is built, it can stabilize salinity at a particular level providing that it is operated under certain rules. This paper has presented a methodological framework to analyze the economics of sluice gate investment timing and location.

Sluice gate operation involves tradeoffs for different river users. Farmers benefit from closing the gates to decrease salinity whereas sectors such as boat transportation and aquaculture benefit from opening the gates more often during the dry season. Nguyen (2009) finds that operating sluice gates to stabilize salinity below 4 dS/m is a feasible option that minimizes economic losses to all river users. This information is used in the modeling framework analyzing sluice gate investment.

The first question addressed in the modeling framework is the appropriate timing to build a sluice gate. Since salinity is only increasing gradually over time and the cost of building a sluice gate is significant, early construction may not be economical. Simulation results suggest that the optimal timing for investment differs considerably depending on whether the possibility of adjusting cropping patterns is considered. The possibility of adapting the agricultural system by introducing new salt resistant varieties delays the optimal timing for investment when compared to a situation of no crop substitution. Other parameters such as a higher sluice gate cost or a higher rate of salinity growth shift the economic viability of construction to later or earlier periods respectively.

The second question addressed in this paper is the tradeoffs associated with the spatial characteristics of the delta. Regions located closer to the sea have lower productivity and a higher cost of protection than upstream regions. An economic model of sluice gate investment location is developed to address this issue. Simulation results suggest that abandoning regions closer to the sea and concentrating salinity control in upstream regions improves the value of the investment. These results critically depend on the resolution of the model in terms of region size and cost variability in sluice gate construction. Further research work can expand the resolution of the regional model to assess the implications for optimal investment. Another important aspect to be explored is the option value of waiting to invest in the context of uncertain timing of changes in salinity. A real options analysis can be used to quantify the value of waiting.

6.- References.

Block, P. 2006. Integrated management of the Blue Nile Basin in Ethiopia: Precipitation forecast, hydropower, and irrigation modeling. PhD Dissertation, University of Colorado – Boulder. Boulder, Colorado.

Callaway, J.M., D. B. Louw, J. C. Nkomo, M. E. Hellmuth, and D. A. Sparks, (2007). “The Berg River Dynamic Spatial Equilibrium Model: A New Tool for Assessing the Benefits and Costs of Alternatives for Coping with Water Demand Growth, Climate Variability, and Climate Change in the Western Cape.” AIACC Working Paper No. 31.

Characklis, G.W., R. C. Griffin and P.B. Bedient, (2005). Measuring the Long-Term Regional Benefits of Salinity Reduction. Journal of Agricultural and Resource Economics, 30 (1) : 69-93.

Dung Do Duc, (2010). Southern Institute of Water Resources Planning [SIWRP], Vietnam, personal communication.

Gardner, R.L., and R.A. Young, (1985). An Economic Evaluation of the Colorado River Basin Salinity Control Program. Western Journal of Agricultural and Resource Economics, 10, 1:1-12.

Lee, D.J., and R.E.Howitt, (1996). Modeling Regional Agricultural Production and Salinity Control Alternatives for Water Quality Policy Analysis. American Journal of Agricultural Economics. 78:41-53.

Käkönen, M., (2008). Mekong Delta at the Crossroads: More Control or Adaptation? Ambio, Vol. 37, No.3, pp. 205-212.

Manne, A. (1967). Investments for Capacity Expansion: Size, Location, and Time-Phasing. MIT Press, Cambridge, MA (USA).

Miranda, Mario J. and Paul L. Fackler. *Applied Computational Economics and Finance*. Cambridge MA: MIT Press, 2002.

MONRE (2009) Climate change: Sea level rise scenarios for Vietnam, Hanoi, Ministry of Natural Resources and Environment of Viet Nam.

Nguyen, T. H. 2009. Hydrological Modeling and Sluice Gate Control in the Mekong River Delta. PhD Dissertation, University of Washington. Washington.

SIWRP (2007) Operational Procedure of Quan Lo – Phung Hiep Hydraulic Works System, HCMC, Vietnam.

World Bank (2007), Rural Development in Vietnam: Policy Brief. Hanoi. Vietnam

Wright, E.L. and J.D. Erickson, (2009). Climate Variability, Economic Adaptation and Investment Timing. International Journal of Global Environmental Issues. Vol. 3, No 4, pp.357-368.

Appendix

Figure A. Map of Administrative Boundaries for Selected Districts of Study

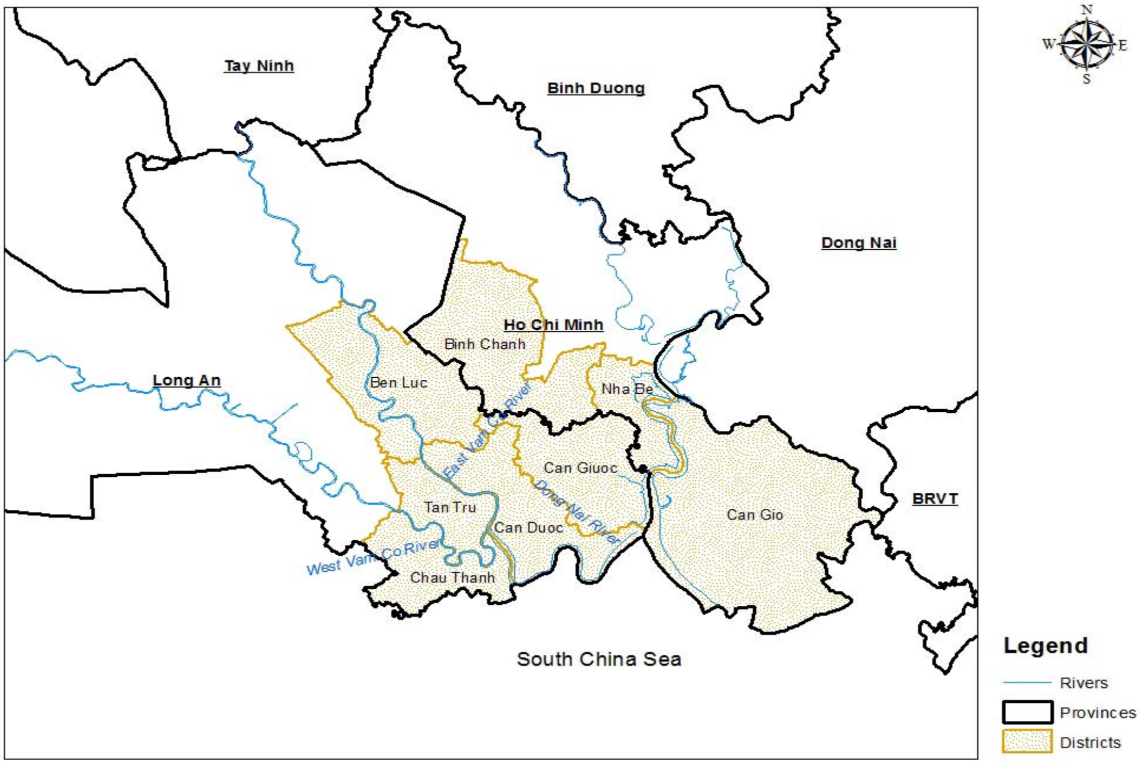
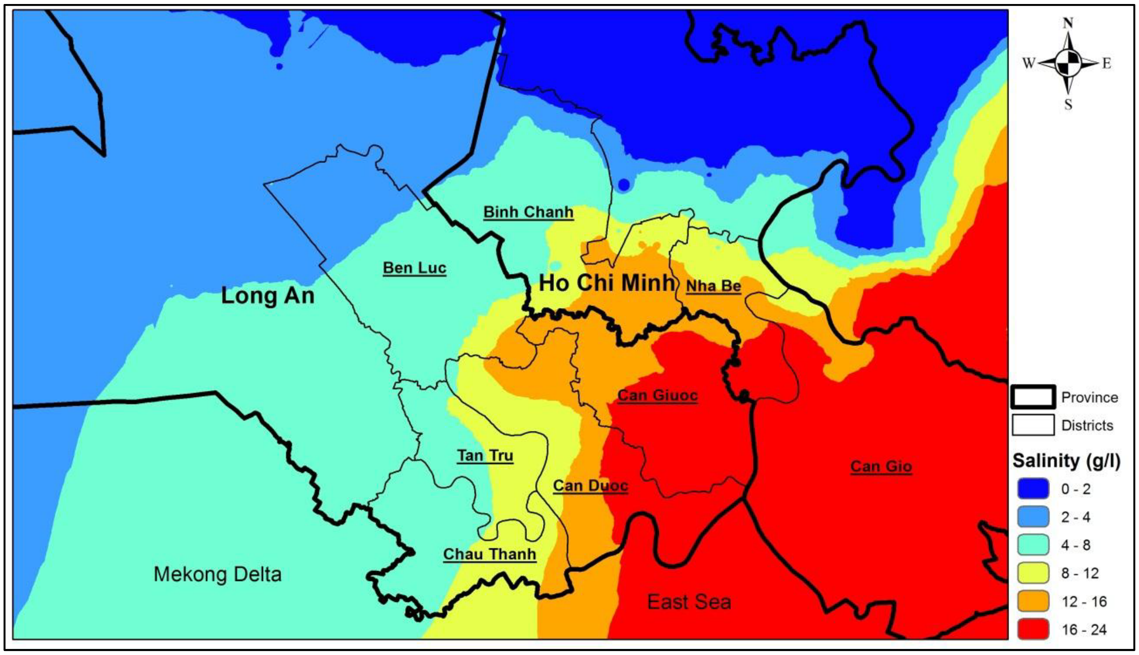


Figure B. Projected average salinity for 2050 (based on simulations using the MIKE 11 hydrodynamic model)



Source: SIWRP (2010)