INTEGRATED ANALYSIS OF CHANGES IN RICE CROPPING SYSTEMS IN THE MEKONG RIVER DELTA, VIETNAM, BY USING REMOTE SENSING, GIS AND HYDRAULIC MODELING

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ABSTRACT

Rice is cultivated in the Mekong River Delta of Vietnam under various cropping systems and cultivation techniques, influenced largely by environmental conditions. This paper describes a study on the dynamic changes in rice cropping systems in response to changes in agro-hydrological conditions resulting from infrastructure interventions to prevent salinity intrusion. Multi-date cloud-penetrating radar imagery were used to map the spatial distribution of different rice-based cropping systems. Changes in cropping systems were determined using secondary data and field surveys. Changes in hydrological and salinity conditions following the phased construction of sluices to control saline water intrusion were quantified by secondary data and validated hydraulic and salinity simulation. GIS was used for integrating data from various sources into a spatially coherent database, and for analyzing and understanding the influence of changing bio-physical conditions on the evolution of cropping systems. The results show that the phased construction of sluices effectively pushed the salinity intrusion boundary toward the southwest, and that farmers tend to be risk averse in adjusting their cropping systems to changing environmental conditions. We found a strong relationship between the dry season rice crop areas and areas that are free of salinity in February. The knowledge base and the analytical results of such a study provide the relevant authorities with a rational basis for water resources planning and management, which greatly influences agricultural production and farmer livelihood in the delta. Implications on further studies to predict changes that will result from future expansion of areas protected from salinity intrusion are discussed.

1. INTRODUCTION

Rice, the most important crop in the Mekong Delta, Vietnam, is cultivated under various cropping patterns and cultivation techniques, depending on the hydrology, rainfall pattern and availability of irrigation at specific locations (Tuong, et al., 1991). Farmers adjust the rice-based cropping systems in response to changes in the environment. In general the trend is towards increasing rice cropping intensity and crop diversification as bio-physical constraints of the environment are ameliorated. In recent years, water control structures such as embankments and sluices have been constructed in the Ca Mau Peninsula of the Delta to progressively prevent salinity intrusion. Understanding the dynamic of land uses in responses to changes in the environment (water quality in this case) will help in anticipating future scenarios and identifying future constraints when the area protected from salinity is expanded. This will also contribute to the understanding of farmers' resource utilization in other coastal areas.

This study was carried out in the Ca Mau Peninsula of Mekong River Delta of Vietnam with the following objectives:
1. To understand, document and model the changes in environmental conditions brought about by infrastructure development to control saline water intrusion.
2. To understand the dynamics of land use and cropping pattern, reflecting farmers' strategies in response to changes in environmental conditions.
3. To predict possible changes in land use in various scenarios of hydraulic intervention to prevent further salinity intrusion

This paper illustrates that to achieve the above objectives, there is a need for integration of various kinds of information and data for a more holistic understanding of the biophysical conditions and socio-economic circumstances that drive changes, using tools that facilitate such integration.

2. DESCRIPTION OF THE STUDY SITE

2.1 Location of the study site

The study is carried out in the Quan Lo - Phung Hiep Water Control Project (QLPH_WCP) area of 279,000 ha, where major irrigation and water control infrastructure development is being carried out to improve water supply and water quality conditions to increase agricultural production, particularly rice (Fig. 1). The study area has a tropical monsoon climate with distinct dry (mid-November to April) and rainy (May to mid-November) seasons. It is predominantly a flood plain and is generally flat, with micro-topographical differences occurring between river and canal levees and pockets of inland swamps, coastal ridges and inter-ridge depressions. The soils are generally young and of alluvial origin, and heavy textured except on sandy ridges (Hoanh, 1996).

Under natural conditions, the area is subjected to saline water intrusion during the dry season. High salinity level in the canal networks induced soil salinity in most of the study area in the dry season. Because of the effect of saline water intrusion, about 96% of the soils in the study area were mapped as having “salic phase”, i.e. being saline during part of the year (Ve, et al., 1988). Soil salinity is reduced during the rainy season, due to the leaching effect of rainfall. In recent years, salinity of the (top) soil in areas protected from salinity has reduced markedly. About 36% of the soils in the study area were mapped as acid sulfate soils; 35% of which were severely acid, having the sulfuric layer within 50-cm depth. Crop performance can be adversely affected where the acidity layer in the soil is shallow, particularly in the early part of the rainy season.

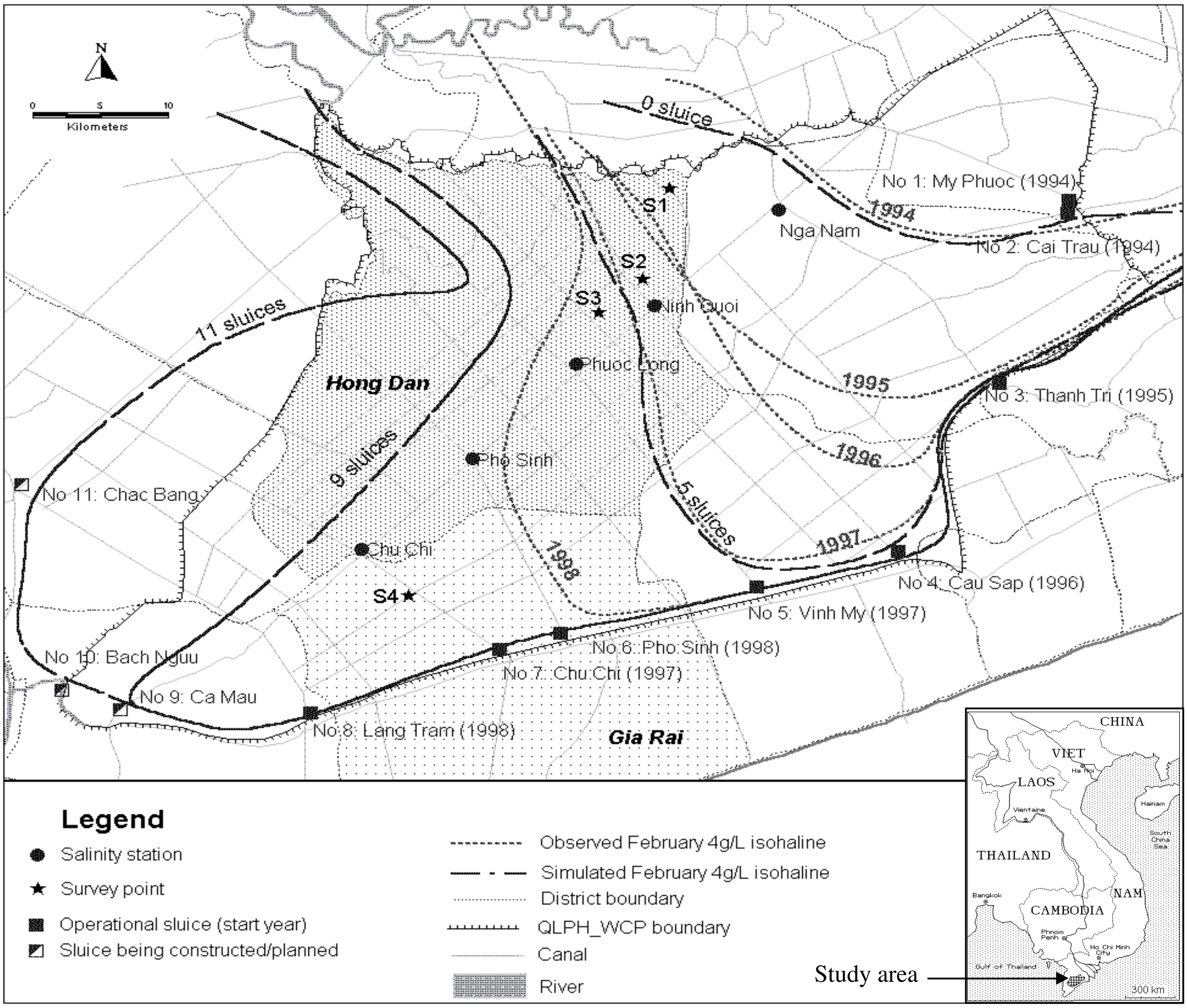

Figure 1. The Quan Lo - Hung Hiep Water Control Project area with district boundaries, showing locations of the salinity protection sluices, salinity monitoring stations & field survey points, and the 4 g L^{-1} isohalines for February (observed, 1994 – 1998; and simulated for 0, 5, 9 & 11 sluices). For clarity of the figure, we have not included isohalines of other months/scenarios.

2.2 General land use/cropping patterns in the area

Traditionally one rice crop, called "Mua" in the local language, is grown, using traditional variety with long maturation period, during the rainy season (Jul/Aug to Dec/Jan) after the rains have flushed out the salinity from the root zone of the soil. Over the past decade these traditional rice varieties have been gradually replaced by modern, short-statured, high-yielding varieties of shorter maturation period in areas that are have more favorable water conditions, i.e. shallow flood depth (Tuong, et al., 1991). More recently in these areas, two crops of rice (summer-autumn, or He Thu: May/Jun-Aug; followed by autumn-winter, or Thu Dong: Sep-Nov/Dec) are grown within the rainy season, particularly where salinity is not high and can be leached out by early rainfall. In areas with acid sulphate soils and are medium- to deep-flooded, farmers practice shrimp culture (fry recruited from incoming sea water) or shrimp-rice system where shrimp is raised during the dry season followed by rice in the rainy season after flushing out of salinity from the field.

2.3 Interventions to prevent salinity intrusion

Since the main constraint for rice production in the area was high salinity in the dry season, one of the strategies for increasing rice production is to prolong the salinity-free period and to increase the supply of fresh water to the area. This would enable farmers to grow a winter-spring, or Dong Xuan, rice crop (Nov/Jan to March/May) during part of the dry season. Since 1994, the government has been constructing a series of embankments and sluices along the periphery of the project area that is directly exposed to the ingression of saline water from the coastal rivers, progressing from the northeast to the southwest. Figure 1 shows the position and the year of effective operation of each of the existing sluices, as well as those being constructed or planned for construction. In parallel with the salinity prevention measures, the canal network within the project area was also improved to enhance the transport of fresh water from the Mekong River to the project area.

3. METHODOLOGY

3.1 Characterizing dynamics of land use and cropping systems

We used a combination of remote sensing, secondary statistical data and field interviews to characterize the dynamics of land use and cropping systems in the study area. Taking advantage of the distinct radar backscatter response of paddy rice cultivation and having ground information on rice cropping systems and crop calendars, we used multi-date SAR data from the ERS-2 satellite to map the 1996 rice cropping systems (Liew, et al., 1998), and related the results with the expansion of area protected from salinity intrusion (Kam, et al., 1998).

We also collected secondary data on planted area for the different rice crops for two districts (Hong Dan and Gia Rai, Fig. 1) within the study area for the period 1993–1998, and determined changes in cropping intensity (ratio of planted area to physical area). The two districts were selected to represent contrasting ends of the chronological spectrum and geographical gradient in terms of protection from salinity intrusion in Bac Lieu province. Hong Dan started experiencing the effects of salinity protection in 1995 (in the northern part of the district) while in Gia Rai, which is closer to the coast, the effects of salinity protection were evident only in 1998.

Interviews with farmers and key informants were carried out in September 1999 to document changes in cropping systems and crop calendars in response to changes in the salinity situation. Four survey points (Fig. 1) were selected to represent areas that have experienced changes in salinity intrusion for different periods of time.

3.2 Characterizing changes in salinity level

3.2.1 Use of secondary data. We compiled salinity data collected by the Sub-Institute of Water Resource Planning (14 stations) and the Meteorological and Hydrological Service of the South (12 stations) for the period 1994 – 1999. We plotted daily maximum salinity on the 15th day of each month at five selected stations (Nga Nam, Ninh Quoi, Phuoc Long, Pho Sinh and Chu Chi) along Quan Lo Phung Hiep canal (locations indicated Fig. 1) to examine the time series salinity profile, corresponding to different phases of sluice construction. These stations are near by the cropping system survey points. With the exception of Nga Nam, which was slightly upstream of the survey point S1, each of the four remaining stations was selected to be downstream from a survey point. For example the salinity profiling point at Ninh Quoi was downstream of survey point S2. Changes in the cropping system and crop calendar over the years at the survey points could then be interpreted in relationship with changes in water salinity conditions of the nearby stations (S1 to Nga Nam, S2 to Ninh Quoi, S3 to Phuoc Long and S4 to Chu Chi).

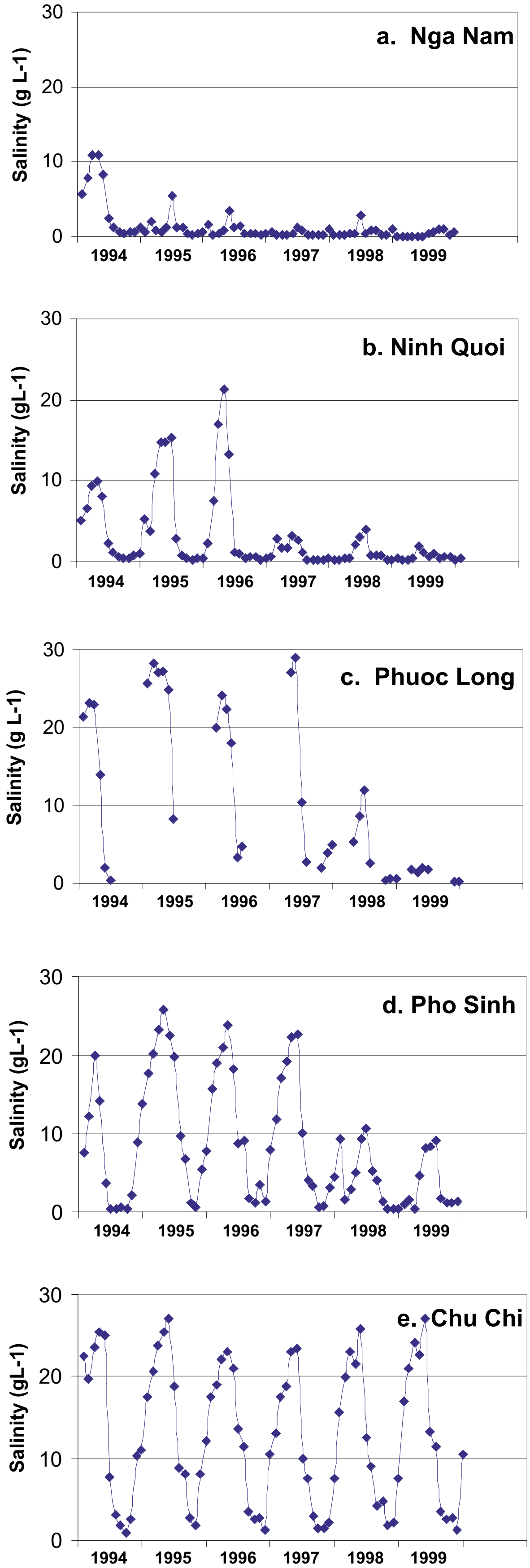

Figure 2. Salinity (maximum value on the 15th day of each month) at five stations along the Quan Lo - Phung Hiep Canal, 1994-99 (locations indicated in Fig. 1)

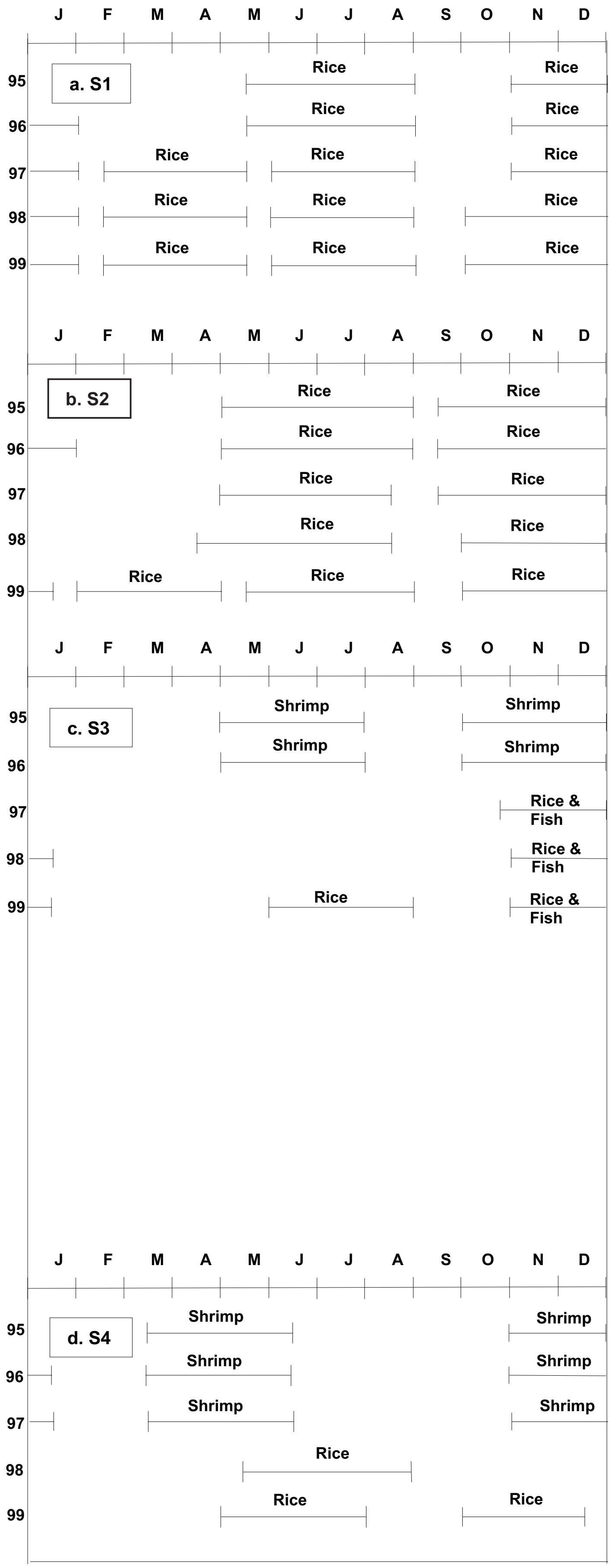

Figure 3. Land use and cropping calendars at four survey points S1 to S4, 1995-99. Locations of the survey points are indicated in Fig. 1

Using the point-based salinity data of 26 stations, we constructed monthly 4 g L^{-1} isohalines for January to June, for the period 1994 to 1998, which were digitized into the GIS. District-wise estimates were made of the area unaffected by salinity in February (to determine if Dong Xuan crop is feasible) by overlaying the isohalines for the years 1994 to 1998 with the district boundary map in the GIS. Within these saline-free areas, we also computed the extents of acidic soil. Particular attention was placed on Hong Dan district, which experienced yearly changes in area protection from salinity intrusion within the study period.

3.2.2 Simulation model. The Vietnam River Systems and Plains (VRSAP) hydraulic and salinity model (Khue, 1986; NEDECO, 1991) was used to simulate and analyze the effects of of new sluice, and canal construction and improvement of existing canals on the hydrological conditions of the study area. The model makes use of implicit finite difference scheme to solve one-dimensional Saint-Venant equations and advection-dispersion equation for simulating the flow of water and dissolved substances in open channel network of the study site. The model assumes a quasi two-dimensional scheme to take into account the storage effects and the overland flow of the plains (e.g. rice fields) in between the canals.

Inputs to the models include topographic data of the waterway network and plains, hydrological data at monitoring stations (including boundary and initial conditions) and climatic data (rainfall and evapotranspiration). The topographic data comprise geometric information (e.g. length, width, depth, bottom elevation) and hydraulic parameters (e.g. Manning roughness coefficient) for each segment of the river/canal, each sluice and each parcel of the plain. The hydrological data input includes water level, discharge and salinity at boundary nodes and segments. Output data include water level and salinity at selected nodes (i.e. at each end of the river/canal segment), and discharge at selected segments. The point-based output data are brought into the GIS to be interpolated to generate isohalines, and to be combined with other geographical data for spatial analysis.

Using the 1994 – 1998 hydrological boundary conditions and topographic data, the model was first validated for February of each year with the observed water level and salinity data at the hydrological stations. The model was then used to predict future hydrological conditions corresponding to planned construction of additional sluices, new canals and improvement of existing canals by the Vietnamese government . Two scenarios were investigated, (a) when the 9^{th} sluice is constructed at Ca Mau and (b) when the additional 10^{th} and 11^{th} sluices are constructed at Bach Nguu and Chac Bang respectively (Fig. 1). The 4 g L^{-1} isohalines in February for the two scenarios were constructed by GIS interpolation of the salinity outputs at the nodes of the canal system.

3.3 Relating the dynamics of cropping systems changes with agro-hydrological changes and soil conditions, and predicting future scenarios

Regression analyses were carried out to explore relationships between district-wise area under the Dong Xuan crop and area with salinity <4 g L^{-1} in February, and areas with salinity <4 g L^{-1} that have acid and non-acid soil conditions. The regression relationship was used to determine the possible increase in the Dong Xuan crop area corresponding to two scenarios (a) and (b) described in 3.2.2.

4. RESULTS AND DISCUSSION

4.1 Dynamics of land use and cropping pattern in relation to changes in agro-hydrology: point-based analysis

4.1.1 Salinity profiles at monitored stations. Figure 2 depicts the changes in monthly salinity at five stations along the Quan Lo – Phung Hiep canal during the 1994–1998 period. At all the stations, water salinity reached the maximum at the end of the dry season (Apr–May) and was lowest in the wet season (Aug–Oct). As the construction of the sluices proceeded westward along the southern periphery of the study area (Fig. 1), there was a corresponding chronological progression of salinity reduction during the dry season at the five stations. The dry season salinity at Nga Nam, the most eastward of the five stations, reduced from 1995 (Figure 2a), upon completion of the first three sluices, i.e. My Phuoc, Cai Trau, and Thanh Tri. Salinity at Ninh Quoi, the next station to the west, decreased in 1997 upon completion of the Cau Sap sluice, while at Phuoc Long it decreased in 1998 upon completion of the Vinh My sluice. At these stations, salinity protection sluices remarkably reduced the dry season salinity from 22 – 28 g L^{-1} to a range from less than 4 g L^{-1} (Figures 2a, b, c).

Further to the southwest, the Pho Sinh station did not show the effect of salinity control until 1998 (Fig. 2d), after the completion of the Pho Sinh, Chu Chi, and Lang Tram sluices. The dry season salinity at this station however remained rather high (about 10 g L^{-1}). The station Chu Chi showed no sign of reduction in salinity even in 1999 (Fig. 2e). Salinity still entered the study area from the west, via Ca Mau.

4.1.2 Dynamics of land uses and cropping pattern at surveyed locations. Figure 3 shows the changes in land use and cropping calendars at four surveyed locations. Traditionally, farmers at location S1 cultivated the He Thu (May-Aug) and early Dong Xuan crop (Nov-Jan). Farmers intensified rice cultivation to triple cropping only in 1997 (Fig. 3a), although the salinity profile at the nearby station Nga Nam shows that the area was already completely protected from saline water intrusion in 1995 (Fig. 2a). Similarly, farmers at location S2 changed their cropping pattern from double to triple cropping in 1999 (Fig. 3b) even though the surrounding area was already free of salinity in 1997 (station Ninh Quoi, Fig. 2b). The data show that farmers increased their cropping intensity, taking advantage of the extended salinity free period from February to April, but this change lagged about two years after salinity protection became effective. There can be two reasons for this lag. One is that it may take one or two years for farmers to adjust to the new condition and to be assured make sure that salinity has reduced to a level low enough for dry season rice cropping. Another reason might be that the soil may still be saline for one or two years after water is already free of salinity.

Farmers at location S3 changed from two seasons of brackish water shrimp to one rice + fish in 1997; and to one rice and one rice + fish in 1999 (Fig. 3c). Farmers thus stopped raising brackish water shrimp one year before the area was protected from salinity intrusion, as indicated by station Phuoc Long (Fig. 2c). Farmers at location S4 (Fig. 3d) changed from brackish water shrimp to single rice crop in 1998 and to double cropping of rice in 1999, although salinity at the nearby station (Chu Chi) had not yet declined in 1999 (Fig. 2e). Farmers who raise shrimp rely on saline water intrusion. Construction of sluices for preventing salinity intrusion halted the recruitment of shrimp larvae and also changed the nature of the environment for shrimp survival. Shrimp farmers anticipated the changes in water quality and changed to rice before the actual change in water quality took place.

4.2 Dynamics of land use and cropping pattern in relation to changes in agro-hydrology: District and regional analysis

4.2.1 Monthly isohalines as affected by salinity prevention sluices. Figure 1 shows the shift in the 4 g L^{-1} isohalines in February from 1994 to 1998. The sluices prevented salinity from the East Sea (South China Sea) entering the area. As the sluices were gradually constructed from the northeast to southwest, the salinity retreated gradually to the southwest. The isohalines for January and for March to June also show similar patterns of retreat (data not shown). Of the two districts we focused on, Hong Dan district experiences a broader spectrum of annual retreat of salinity intrusion within the study period.

There was a high concurrence between the observed isohalines and those constructed from outputs of the VRSAP model for the period 1994 – 1998, indicating that the model simulated well the effects of hydraulic structures on the hydrology of the area. Figure 1 shows, as an example, the simulated February 4 g L^{-1} isohalines prior to sluice construction and upon completion of 5 sluices, which correspond with the observed isohalines for 1994 and 1997 respectively. The simulation shows that when the sluice No 9 (Ca Mau) is constructed (i.e. future scenario (a), section 3.2.2), the 4 g L^{-1} isohaline retreats much further to the southwest, but a major portion of the northern part of Hong Dan will still have salinity >4 g L^{-1} in February. The area with February salinity < 4 g L^{-1} will increase to 63,000 (compared to 32,300 ha in 1998). When all the 11 sluices are constructed (i.e. scenario (b)), most of Hong Dan (91,300 ha or 94%) will have salinity less than 4 g L^{-} in February.

4.2.2 Changes in rice cropping pattern and area in Hong Dan and Gia Rai Districts. Figure 4 shows the changes in area of the different rice crops and cropping intensity for Hong Dan and Gia Rai districts. Hong Dan district saw the appearance of the irrigated Dong Xuan crop in 1995, made possible by protection from salinity intrusion in the dry season, as evidenced by the retreat of the 4 g L^{-1} isohaline in 1995 to within the northeastern corner of the district. However, a sharp increase in the Dong Xuan crop occurred only in 1997. This conforms to our field observation of a two-year lag between improvement in water quality and farmers' decision to grow dry season rice crop.

At Gia Rai, the major shift from traditional rice to modern variety with shorter season in the rainy season started in 1996, but the Dong Xuan crop did not start until 1998. There is a corresponding increase in cropping intensity but not at the scale encountered in Hong Dan. This corresponds with the retreat of the isohalines (Figure 1), whereby Gia Rai district became free of salinity in February later than Hong Dan.

The statistical data for 1996 conforms very well with estimates from SAR remote sensing data. For example, estimates of double rice and triple rice area (including the irrigated Dong Xuan crop) in Hong Dan district in 1996 (19,240 ha and 500 ha respectively) correspond well with the reported area under these rice cropping systems (19,600 ha and 700 ha respectively). The reported area is higher because it is gross area, including the surrounding bunds, ditches etc.

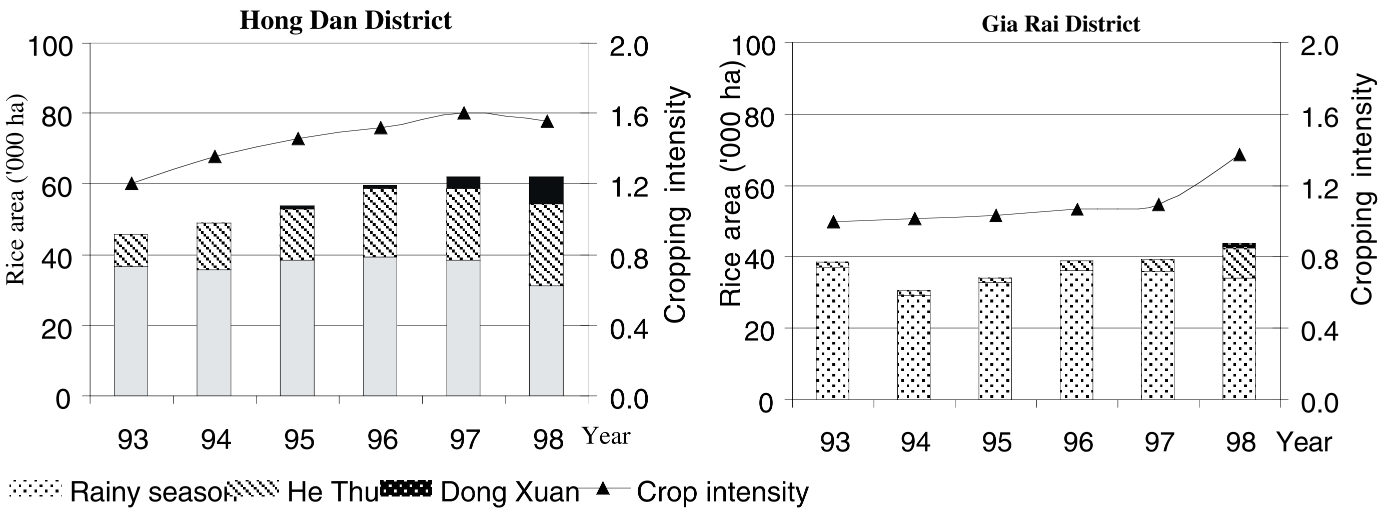

Figure 4: Area planted with different rice crops and cropping intensity in Hong Dan and Gia Rai districts.
Data source: Office of Statistics of Bac Lieu Province

4.3 Relation among cropping intensification, area protected from salinity intrusion and soil quality, and predicting future scenarios

Figure 5 shows the relation between Dong Xuan crop area and the area with February salinity < 4 g L^{-1} during 1994 – 1998 in Hong Dan district. The saline-free areas are further divided into acid and non-acid soils. Simple linear regression of Dong Xuan area on total saline-free area in February gave a very high statistical significance to the model (Fig. 5). Multiple linear regression of Dong Xuan area on non-acid and acid saline-free area gave high statistical significance to the model (P-value <=0.0007), but moderate significance to the non-acid component (P-value <=0.05), and low significance to the acid component (P-value <=0.15). The result indicates that farmers' decision to grow the Dong Xuan crop is largely influenced by water salinity condition in February, but not on soil acidity condition. A possible reason for this is that the Dong Xuan crop starts at the end of the rainy season when the soil would have undergone submergence for sufficient time during the rainy season to curtail the oxidation of sulfudic materials. Furthermore, a major portion of soil acidity may have been leached or flushed out of the fields by rainfall and overland flows.

Using the regression relationship of Dong Xuan area with total area unaffected by salinity in February, it is estimated that cultivation of Dong Xuan crop in Hong Dan district will further increase to 15,640 ha and 22,620 ha following the completion of 9 (scenario a, section 3.2.2) and 11 sluices (scenario b) respectively.

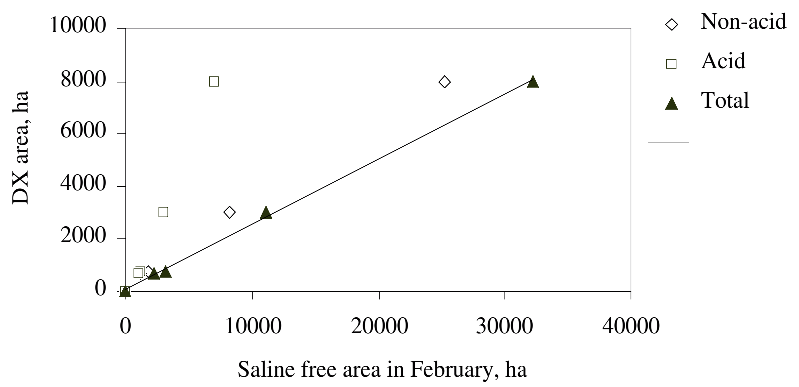

Figure 5: Dong Xuan area versus saline-free area in February, Hong Dan district of Bac Lieu province

5. CONCLUSIONS

In this study we have been able to relate the dynamics of changes brought about by infrastructure development with the corresponding changes in farm household production strategies. Farmers in this region are risk averse. This is reflected in their strategies of adjusting their production system in anticipation of changes on the one hand (e.g. shifting from shrimp farming to rice and rice-fish systems), while taking a time lag before making advantage of improved conditions for intensifying rice cultivation on the other.

In carrying out the study we depended on data from a variety of sources, both primary and secondary and primary. We adopted a GIS-modeling approach. The GIS has been useful for integrating data sets from disparate sources, e.g. land use maps created from remote sensing, conventional maps such as district boundary and soil maps. It also enables the integration of biophysical and socio-economic data sets to facilitate analysis. Linkage of GIS to the hydraulic and salinity modeling enabled us to combine the results of modeling with other GIS map layers to facilitate spatial analysis and prediction.

We intend to extend the study to simulate the hydraulic and salinity model for other months, i.e. from January to June, as well as increase the survey points and sampling locations. This would enable us to use the spatial relationships between cropping intensity and salinity-free periods to simulate and predict the rate and spread of rice cropping intensification, taking into account possible soil-related constraints. Furthermore, the study focused on rice cropping systems, while farmers' livelihood depends on may other activities besides rice farming. To fully assess the impact of the hydraulic structure intervention on the rural livelihood, we also need to investigate the effect of changing environments on other farming activities such as fisheries, as well as marketing opportunities for alternative agricultural products.

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