Using GIS-Linked Hydraulic Model to Manage Conflicting Demands on Water Quality for Shrimp and Rice Production in the Mekong River Delta, Vietnam

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Abstract: Different land uses may have conflicting demands on water quality. In the 1990's, a system of sluices and embankments was built to gradually protect an area of more than 250,000 ha in Ca Mau peninsula, Mekong River Delta, Vietnam from salinity intrusion. This allowed rapid intensification of rice cropping in the protected area. Salinity protection, however, conflicted with the interests of shrimp farmers in the western part of our study area in Bac Lieu province. It was shown that the use of the Vietnam River System and Plains (VRSAP) hydraulic and salinity model, coupled with GIS, helped the local government address conflicting water quality requirements for rice and shrimp production. VRSAP utilizes implicit finite difference scheme to solve one-dimensional Saint-Venant equations and advection-dispersion equations to simulate the water level, discharge and salinity in a network of rivers, canals, and hydraulic structures. The 1996 hydrological and meteorological data was used to calibrate and evaluate the model. The model was then used to analyse the hydrological conditions in the area corresponding to different scenarios of sluice operations in the 2001 dry season. The results were displayed in a GIS for spatial analysis of the movement of the brackish water boundary. The model was able to simulate the effect of sluice operation that would allow sufficient salinity at the western part for shrimp production and to determine the timing of sluice closure to ensure that the brackish water would not reach the major rice-growing areas in the eastern part. The model can potentially be used as a real-time decision support tool for water resources management.

Keywords: Hydraulic and salinity model; Water management; Land use; Rice and shrimp cultivation

1. INTRODUCTION

Agricultural production in coastal lowlands is often hindered by salinity intrusion due to tidal fluctuation. One strategy for overcoming this constraint is to build sluices and embankments to block tidal inflow of seawater. However, water salinity is fundamental to many key fishery and aquaculture activities, such as shrimp raising. To accommodate conflicting needs for agriculture and fisheries, water resource managers face the challenge of operating the sluices so that the salinity in different parts of a coastal area can be controlled according to their water quality requirement of the prevailing land uses. Modelling tools can play an important role in supporting their decision-making.

Previous investigators have used numerical models and Geographical Information System (GIS) to investigate seawater intrusion into estuaries for environmental management and land use planning [NEDECO, 1991; Weiss et al., 1994; French et al., 1999; Ward, 2000].

This paper reports the use of a hydraulic model, coupled with GIS, to analyze the effect of operation of sluices on the temporal variability and spatial distribution of salinity and to help the local government resolve the conflict in water quality requirements for rice and shrimp production in the Mekong River Delta, Vietnam.

2. STUDY SITE

The study site comprises an area of 160,000 ha of Bac Lieu province, located in Ca Mau peninsula, Mekong River Delta (Figure 1). Eighty-five percent of the population is engaged in agricultural and fisheries activities, with rice growingthe most important agricultural activity.

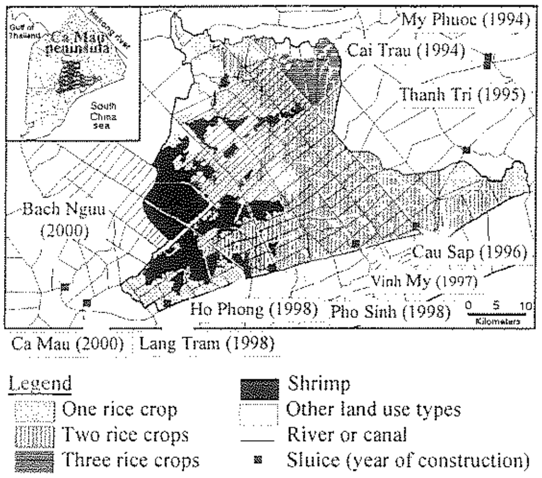


Figure 1: Location of study area, 1998 land use, sluices and years of construction.

Inadequate rainfall and salinity intrusion from the sea prevent rice cultivation during the dry season (December to May). Traditionally, only one rice crop could be grown during the rainy season, from June to November. In areas that are not suitable for rice, some farmers practice shrimp culture using seed stock through natural recruitment of *Metapaneaeus spp.*

In the early 1990's, in response to high demand of rice in the country, the government decided to (i) build a series of sluices that could be closed at high tide to protect rice lands from saline intrusion for over 250,000 ha and (ii) improve the canal networks to increase the supply of fresh water from the Mekong River. From 1993 onward, 10 large sluices and many small ones were built in stages from the eastern to the western part of the study area. As the saline-protected area expanded, thousands of farmers are able to grow two or even three rice crops per year, especially in the eastern part (Figure 1).

However, by the end of the 1990's, over production of rice in Bac Lieu and elsewhere in the delta caused a sharp decline in rice price in the local markets. Meanwhile aquaculture innovations boosted profits from shrimp farming considerably [Brennan et al., 2000]. By 1998, tiger shrimp culture became widespread in the low-lying acid sulphate soils in the western part of the study area (Figure 1).

From 1998 onward, as the sluices in the western fringe of the study area became operational, the supply of brackish water needed for the shrimp ponds was cut off. Many farmers were forced to abandon shrimp raising, resulting in a drastic loss of income. This prompted the government to re-examine the original development objective, which focussed on increasing rice production, and explore alternative land use plans that would accommodate shrimp cultivation in the western part while maintaining the areas of intensive rice production in the eastern part. The ability to achieve this balance hinges upon judicious management of the sluice gate operation to meet the shrimp farmers' need for brackish water in the dry season and the rice farmers' need for freshwater to produce multiple rice/upland crops per year. This management can be guided through the use of hydraulic modelling.

3. HYDRAULIC AND SALINITY MODEL FOR THE STUDY SITE

3. 1 Model Selection

Seawater intrusion is a complex phenomenon due to the presence of tidal currents [Speirs and Gurney, 2001]. Despite some limitations of one-dimensional models in simulating the hydrodynamics of a partially mixed estuary [Hsu et al., 1999], the application of these simpler models, simple balance approaches and semi-empirical methods is more feasible than the two- or three-dimensional models [van der Tuin, 1991]. To simulate water and salinity movement in the dry season under low freshwater flow and well-mixed conditions, we adopted the one-dimensional Vietnam River System and Plains (VRSAP) model, which has been extensively applied to the Mekong River Delta [Khue, 1986, NEDECO, 1991; ESSA et al., 1992].

3.2 Model Description

VRSAP is a numerical model using Saint-Venant equations for solving complex flow and mass transport problems in a complex network of interconnecting open channels. The continuity and the momentum equations for each segment of the channel network are as follows:

$$\frac{\partial Q}{\partial x} + B_c \frac{\partial z}{\partial t} = q \qquad (1)$$

$$\frac{\partial z}{\partial x}+\frac{\alpha_0}{g}\frac{\partial(Q/A)}{\partial t}+\frac{\alpha}{g}\frac{Q}{A}\frac{\partial(Q/A)}{\partial x}=\frac{-|Q|Q}{K^2} \quad (2)$$

in which:

$$K = AC\sqrt{R} \qquad C=\frac{1}{n}R^{1/6}$$

where Q is the discharge (L^3T^{-1}), x is the distance along the segment, B_C is the canal width, including storage area, averaged over the segment (L), z is the water level (L), t is time (T), q is the lateral flow per unit length ($L^3T^{-1}L^{-1}$) into the segment, α_o and α are adjustment coefficients, varying from 1.0 to 1.1, g is the gravity acceleration (LT^{-2}), A is the cross-section area (L^2), C is the Chezy coefficient for bottom roughness ($L^{-2}T^{-1}$), R is the hydraulic radius (L), n is the Manning's coefficient.

The model applies the concept of advection and dispersion [Harleman, 1971] to simulate salinity intrusion:

$$\frac{\partial(A_cS)}{\partial t}+\frac{\partial(QS)}{\partial x}-\frac{\partial}{\partial x}(D_xA\frac{\partial S}{\partial x})=qS_v \quad (3)$$

where A_C is the cross section, including storage area evenly spread along the segment (L^2), S is the salt concentration (ML^{-3}), D_X is the longitudinal dispersion coefficient (L^2T^{-1}), S_V is the salt concentration of lateral flow (ML^{-3}).

A segment can be a reach of a river or canal, or a hydraulic structure such as a sluice. Water interchange between segments and the land area is simulated within VRSAP by defining parcels of land (fields) bounded by specified channel segments, and by indicating the nature of flow (uncontrolled or controlled by structures) between them. The model assumes that when there is no standing water in the field, evapotranspiration continues, thus causing soil drying, until a "sub-surface" storage is depleted. Conversely, at the onset of the rainy season, the sub-surface storage has to be filled before water accumulates above the soil surface.

Using the implicit finite difference scheme [Delft Hydraulics, 1989], VRSAP computes water level and salinity for each node and each field, and discharge for each segment. Two types of input data are required for the model: (i) the configuration and dimensions of the river and canal network, including sluices and operation schedule; and (ii) hydrological data (water level, discharge and salinity) at boundaries and initial conditions of segments, nodes and fields.

3.3 GIS-database for Schematization and Output Presentation

For spatial data management, visualization and analysis, the topographical and hydrological input database, as well as the model outputs, are brought into a GIS. The river and canal network are represented as inter-connected line segments, while the observed and simulated hydrological variables, such as water level and salinity, are assigned to nodes (waterway junctions) and polygons (fields), and discharge to line segments (canals and rivers). The spatial interpolation tools of the GIS are used to generate isohalines from the point-based model results. The isohalines delineate salinity regimes depicting the spatial effect of water control interventions. The mapped form of the model results lends itself readily to spatial analysis of the impacts on land use.

3.4 Calibration and Evaluation of VRSAP Model

The VRSAP model was used to simulate the hydrology of the entire Ca Mau peninsula (see inset of Figure 1) to take into account the influence of the surroundings on the water regime in the study area. The 1996 data on observed water level at 5 stations and salinity at 16 stations were used for calibration and evaluation. The geometry of the canal network is based on 1996 conditions, representing a complex hydraulic scheme comprising 1,607 canal segments; 1,017 nodes and 632 fields. We used as boundary conditions the 1996 hourly values of water level and salinity at 7 stations along the coast and the Mekong River bounding the peninsula. The model runs on a time step of 15 minutes, using Manning and dispersion coefficients as previously determined by Khue [1986] and NEDECO [1991] for the Mekong River Delta. Data collected in February-March 1996 were used to estimate those model parameters to which the model outputs are particularly sensitive, but are not available for a large region. The parameters include: (i) the type of flow exchange and size of the exchange structure between fields and canals; and (ii) the sub-surface storage of the fields. The calibration results indicate that the width of most creeks/weirs connecting fields and canals varied from 0.5 to 1m per 100-ha field area. The sub-surface storage was 150 mm. This value was adjusted downward to 50 mm for fields with two/three rice crops per year.

Using the calibrated parameters, the model was evaluated against the measured values for April - June 1996. Figure 2 shows that the model satisfactorily simulates salinity at the Ca Mau sluice.

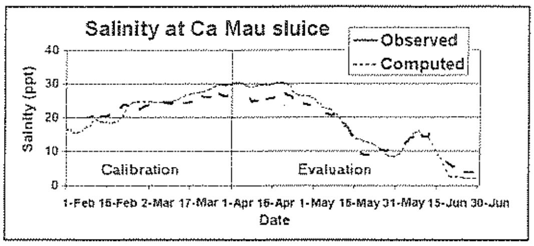


Figure 2. Observed and computed salinity at the Ca Mau sluice.

4. THE VRSAP MODEL AS A GUIDE FOR OPERATING WATER CONTROL SYSTEMS FOR RICE AND SHRIMP

We used the evaluated GIS-linked VRSAP model to determine whether it would be possible to operate the existing sluices to allow intensive rice cultivation in the eastern part and shrimp culture in the western part of the study area. This entails matching the salinity requirement of different land uses at different locations with the salinity distribution as simulated for different sluice operation scenarios. The main steps in this matching process are depicted in Figure 3 and described in the following sections.

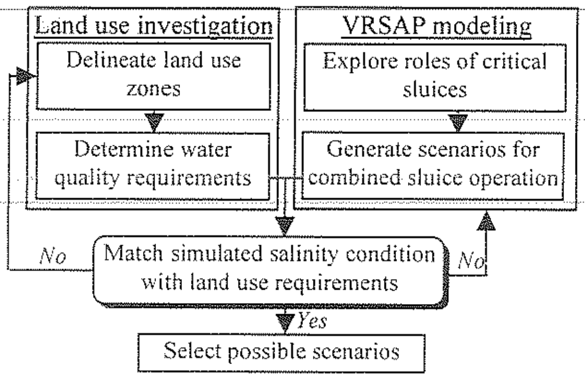


Figure 3: Scheme for selecting possible sluice operation scenarios.

4.1 Delineating Land-use Zones.

To reflect the land use policy change, land use zoning was carried out by consulting with the provincial authorities, their local representatives and the national scientists. Six zones were delineated (Figure 4), and their corresponding land uses and cropping calendars determined (Figure 5), taking into account farmers' preferences, soil characteristics and the "expected" water quality.

The proposed land uses vary from 2 shrimp crops in the western part to three rice/upland crops in the eastern part (Figure 4). In between are transitional zones with 2 rice crops, or 1 shrimp crop in the dry season followed by 1 rice crop in the rainy season.

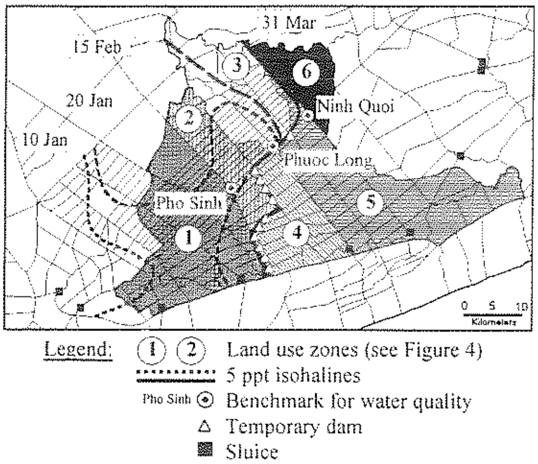
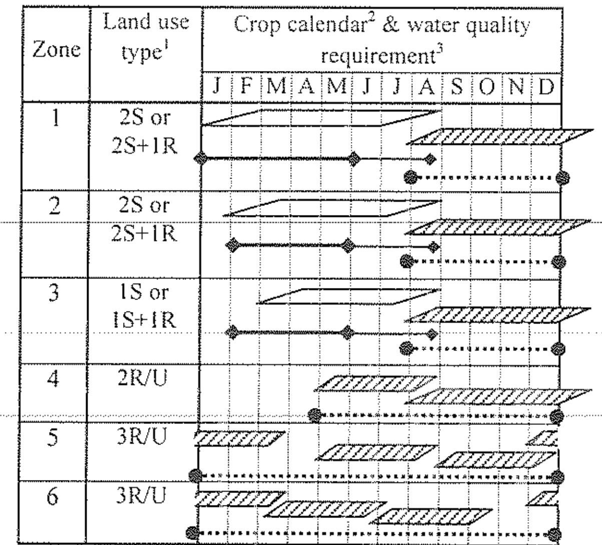


Figure 4. Land use zones, benchmarks and isohalines for scenario C (see Table 1).



[1] S: shrimp; R/U: rice or upland crop;

[2] : shrimp : rice/upland crop

[3] : salinity > 5 ppt : salinity < 4 ppt

: brackish water stored in shrimp fields even though canal salinity < 5 ppt

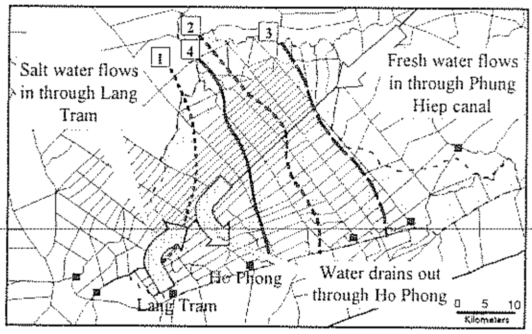
Figure 5. Land use, cropping calendar and salinity requirement in different zones.

4.2 Determining Water Quality Requirement.

Shrimp farming requires water salinity exceeding 5 ppt, while the upper salinity limit for rice is 4 ppt. As a simplification, we used 5ppt as the required threshold for both shrimp and rice. The monthly salinity requirements for different zones are shown in Figure 5. Three benchmarks were identified along the arterial Phung Hiep canal (Figure 4). At Pho Sinh, water salinity before mid-Jan should be < 5 ppt for rice growing in zone 2 and > 5 ppt thereafter until the end of the dry season, to allow for 2 crops of shrimp in zones 1 and 2. At Phuoc Long, water salinity should be > 5 ppt from mid-Feb until the end of dry season for at least 1 shrimp crop in zone 3, but should fall below 5 ppt from July to January for wet season rice in zones 3 and 4. At Ninh Quoi, water salinity should be < 5 ppt throughout the year to allow up to 3 rice/upland crops per year in zones 5 and 6.

4.3 Exploring Roles of Critical Sluices.

The model was used to analyse the effects of sluice operation on salinity conditions, using the canal network data and boundary conditions of 2000. We mapped the movement of the simulated 5 ppt isohaline to understand the role of different sluices on salinity distribution. Some examples are shown in Figure 6.



Line 1: All sluices closed
Line 2: Lang Tram opened in Jan
Line 3: Lang Tram opened in Jan-Feb
Line 4: Lang Tram opened in Jan-Feb and Ho Phong opened at ebb tide

Figure 6: Flow directions and 5 ppt isohalines on 31 March under several sluice operations.

If all sluices were closed, the 5 ppt boundary would be west of the study area (line 1, Figure 6). If the Lang Tram sluice was opened, the 5 ppt boundary would move progressively eastward the longer the sluice is kept open (lines 2 and 3, Figure 6). However, opening Ho Phong sluice at ebb tide (to drain water out of the study area) would curtail the eastward advance of the salinity boundary caused by opening the Lang Tram sluice (line 3 vs line 4, Figure 6). This is because drainage at Ho Phong would induce more freshwater to flow from the Mekong River into the study area through the Phung Hiep canal.

4.4 Generating Scenarios for Combined Sluice Operation.

Using the knowledge gathered from steps described above, we formulated a number of scenarios comprising different combinations of sluice operation: (a) opening sluices west of Ho Phong (to allow salinity intrusion); (b) opening Ho Phong sluice at ebb tide (to curtail excessive salinity intrusion to zones 4, 5 and 6); and (c) the timing and duration of each sluice operation. Table 1 shows examples of three such scenarios, and the simulated results for certain critical dates at the three benchmark points.

Table 1: Three simulated scenarios of sluice operation and water salinity at benchmarks.

Sluice[1]	Operation mode[2] at each month						Salinity[3] (ppt) at benchmarks on critical dates			
	J	F	M	A	M	J	Date	Pho Sinh	Phuoc Long	Ninh Quoi
Scenario A										
LT	O_2	O_2	C	C	O_o	O_o	10-Jan	**6 [<5]**	5 [<5]	0 [<5]
HP	O_o	C	C	C	O_o	O_o	20-Jan	7 [> 5]	6 [> 5]	4 [<5]
							15-Feb	14 [>5]	14 [>5]	**12 [<5]**
							31-Mar	17 [>5]	14 [>5]	**12 [<5]**
Scenario B										
LT	O_2	C	C	C	O_o	O_o	10-Jan	3 [<5]	1 [<5]	0 [<5]
HP	O_o	C	C	C	O_o	O_o	20-Jan	**3 [> 5]**	**1 [> 5]**	0 [<5]
							15-Feb	14 [>5]	11 [>5]	4 [<5]
							31-Mar	19 [>5]	13 [>5]	4 [<5]
Scenario C										
LT	O_i	C	C	C	O_o	O_o	10-Jan	3 [<5]	1 [<5]	0 [<5]
HP	O_o	O_o	C	C	O_o	O_o	20 -Jan	6 [> 5]	5 [> 5]	0 [<5]
							15-Feb	11 [>5]	10 [>5]	5 [<5]
							31-Mar	21 [>5]	16 [>5]	5 [<5]

[1] LT: Lang Tram; HP: Ho Phong

[2] O_2 : Opened for two-way flow C : Closed

O_o: Opened at low tide for drainage

O_i : Opened at high tide for saline water intake

[3] simulated salinity compared with [required threshold]. Salinity on 31 March represents maximum salinity in the year. Simulated values that do not satisfy the thresholds are printed in bold in cells marked gray.

4.5 Matching Simulated Salinity with Land Use Requirements.

The sluice operation scenarios explored were assessed if the resulting salinity distributions satisfy the water quality requirements. This was firstly done by comparing the simulated salinity values at the three benchmarks with the required thresholds at critical dates. Table 1 shows that Scenario A would not meet the water quality requirement in January, February and March. Scenario B would also not be acceptable in January, while Scenario C would satisfy the requirements at all three benchmarks.

Secondly, the results of the promising scenario were transferred to the GIS to generate isohalines to see if the spatial distribution of salinity would correspond with the land use zones. The analysis helps to reveal situations where the salinity requirements at benchmarks are met, but the spatial distribution of salinity would still be unsatisfactory. For example, with Scenario C, there is still the possibility that brackish water could flow from zones 1, 2 and 3 into zones 4 and 5 via the small canals. This could be rectified by building a series of small temporary dams in the dry season along the border between these zones (Figure 4). The figure also shows that the salinity distribution, as delineated by the 5 ppt isohalines on 15 February and 31 March, would comply with the requirements of zones 4 and 5 if these dams were in place. Without these dams, the 5 ppt isohaline on 31 March would traverse zones 4 and 5 similarly to line 3 in Figure 6.

The model outputs were provided to the local authorities to guide the actual sluice operations in 2001, which achieved the objective of accommodating the needs of the shrimp and rice farmers.

5. CONCLUSIONS

The VRSAP model is able to simulate the temporal and spatial distribution of water salinity in the study area. Using the model, we identified possible sluice operation scenarios that would allow seawater to enter the study area for dry season shrimp culture at the western part, but not far enough to affect the intensive rice cropping areas at the eastern part.

The VRSAP model can potentially be used as a real-time decision support tool, but this requires timely acquisition of boundary conditions and meteorological data for inputs into the model. Although hydraulic modelling is useful for exploring sluice operation scenarios, it does not preclude the need for regular monitoring of the hydrological conditions in the study area.

6. ACKNOWLEDGEMENTS

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