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Abstract: Tidal effects and salinity intrusion are two defining characteristics of coastal zones. The first causes complex variations of water level and unsteady flows in the river and canal network. The second is a constraint to agriculture and freshwater fishery, but provides suitable conditions for brackish water aquaculture. These phenomena bring about conflicts in the development of agriculture, fishery and aquaculture due to different requirements of water quality. Hydraulic and salinity modeling have been developed and applied to simulate tidal propagation and salinity intrusion, and to analyze the effects of water management on hydrological and salinity conditions that control land use in the coastal zones. This paper presents experiences in developing and applying a hydraulic and salinity model, the Vietnam River Systems and Plains (VRSAP), for water resources development in Ca Mau Peninsula, Mekong Delta, Vietnam. During the planning and feasibility study phase in 1989-1991 that focused on rice production, this model was used to analyze the impacts of protection from salinity intrusion for different water management units. During the implementation and operation phase from 1992 to the present, it has been used to find out suitable sluice operation schedules for improving agricultural production in the region. Recently, because conflicts in the requirement of fresh water for agriculture and brackish water for shrimp culture occurred, the model is being refined and applied to upscale the effects of intaking saline water and supplying fresh water from the field to canal system level, and also to analyze the effect of sluice operation on the hydrological conditions that would accommodate both agriculture and aquaculture in different parts of the region.

Keywords: Land use conflicts; Land use planning; Water management; Water quality; Tidal effects.

1. INTRODUCTION

Daily tidal fluctuation and seasonal salinity intrusion are two defining characteristics of estuarine and deltaic coastal zones. The tidal effect causes complex variations of water level and unsteady flows in the river and canal network, while saltwater intrusion determines water suitability for irrigation, fishery and aquaculture. Hence, coastal zone management has focused strongly on the resolution of conflicting demands arising from the multiple uses of resources (Klein, 2002). Particular problems follow from the introduction of brackish water shrimp aquaculture, which has led to adverse social and environmental impacts (WRI, 1996). This paper presents experiences in applying the hydraulic and salinity modeling approach for analyzing the likely impacts of water management on land uses and water quality in a coastal zone, Ca Mau Peninsula of the Mekong Delta, Vietnam.

2. HYRAULIC AND SALINITY MODELING

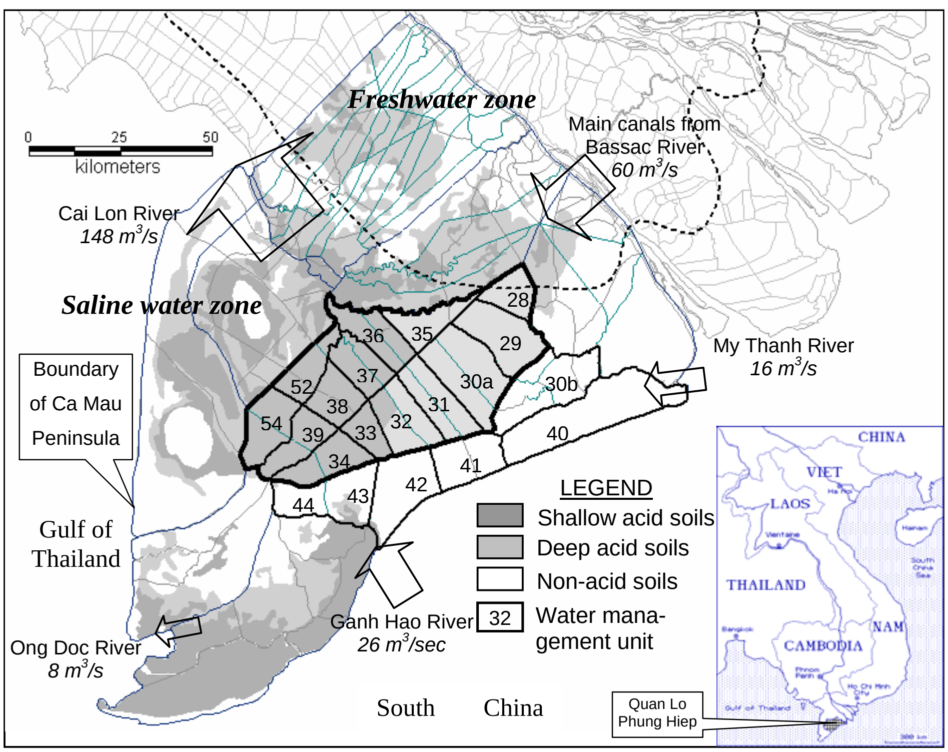
Hydraulic and salinity models have been developed and applied previously to simulate tidal propagation and salinity intrusion, and to analyze the effects of water management on hydrological conditions that control land use in coastal zones. One-dimensional hydraulic models rely on transect-based sampling of depths and velocities, and solve standard equations (Manning's equation, mass and energy balance) to simulate water surface levels and mean streamwise velocity at each transect over a range of discharges (IPCC, 2002). In many development studies in Europe, the USA and Asia (Mekong, Chao Phraya, Brahmaputra), the results obtained from one-dimensional models have been satisfactory (van der Tuin, 1991).

In this study, the Vietnam River Systems and Plains (VRSAP) model (KHUE, 1986, NEDECO, 1991) has been used to analyze the hydraulic and salinity dynamics of the study region. Water interchange between any canal segment and the adjoining land area is simulated by indicating the nature of flow between them as either uncontrolled or controlled by structures. VRSAP aggregates water interchanges in a scheme of 372 nodes, 455 segments and 190 fields to compute water level and salinity for each node and each field, and discharge for each segment. A segment can also be a hydraulic structure, such as a sluice, operated in various ways: completely closed, open for one direction flow, or open for two direction flows. More details about the algorithms of the model and its performance are given by Dong (2000), Halcrow (2001), and Hoanh et al. (2003).

3. CA MAU PENINSULA, MEKONG DELTA

The Quan Lo Phung Hiep region (hereafter called the QLPH region) in Ca Mau Peninsula, with a total area of approximately 450,000 hectares, is a target area for expansion of rice production into the saline water zone (Fig. 1). The QLPH region is a low-lying, flat delta with elevation less than 1.5 m. The two most important soil groups are the acid sulphate soils (ASS, 52% of the total area) mainly located in water management units (WMUs) 33, 34, 36, 37, 38, 39, 52 and 54 in the west (Fig. 1), and the saline soils (47%). Sandy and peaty soils cover only about 1% of the total area. The region has two distinct seasons: the rainy (or wet) season from May to November and the dry season from mid-November to April. Roughly 90% of the annual rainfall (1,800 mm) is concentrated in the rainy season. Hence, freshwater availability for irrigation is a major constraint of agriculture in the dry season.

Figure 1: Location of Quan Lo Phung Hiep region, net flow and direction during one tidal cycle of 14.5 days in February 1990 in the main river and canal system.



4. PREDICTING IMPACTS OF WATER CONTROL

Saltwater intrusion from the sea, mainly through the My Thanh and Ganh Hao rivers (Fig. 1), makes water quality in most parts of the QLPH region unsuitable for irrigation from January to June. Hence, protection against saltwater intrusion was identified as the key intervention for agricultural development. The development of a water control system for this purpose can be separated into 3 phases: the planning and feasibility study phase (1989-1991), the implementation phase (1992-2000) and the operation and adjustment phase (from 2001 to the present).

4.1 The planning and feasibility study phase

Three main questions in this planning phase were:

Q1: How to provide fresh water and protect from saltwater intrusion to increase rice production?

Q2: Where is the boundary of the agricultural intensification area?

Q3: What are the effects of saltwater protection and irrigation on the hydrological conditions in the QLPH region and surrounding area?

Using VRSAP, Sonntag and McNamee (1989) investigated three water management options against saltwater intrusion during the planning phase:

(A) Protection for each small unit bordered by lateral canals and irrigation of some units near the main streams.

(B) Protection and irrigation of the central part of 250,000 ha by construction of 11 large sluices along the southern boundary of water management units 28, 29, 30a, 31, 32, 33, 34 and 39 (Fig. 1).

(C) Protection and irrigation of the whole QLPH region by construction of a dike along the seashore and very large sluices at the My Thanh and Ganh Hao river mouths.

The answers to planning questions derived from the model results are summarized in Table 1.

Table 1: Answers to planning questions for three water control options

Option	Planning questions		
	Question 1	**Question 2**	**Question 3**
A	• Build many small sluices in secondary canals. • Enlarge canals connecting WMUs 28 and 29 (Fig. 1) to the Bassac River.	Irrigation in dry season is possible only for WMU 28 and a part of WMU 29.	Fresh water will be supplied only in protected secondary canals. Changes in hydrological conditions are not significant.
B	• Build 11 large sluices to protect the central part. • Enlarge canals connecting WMUs 28, 29 and 35 to the Bassac River. • Dredge and enlarge primary and secondary canals in the central part.	Irrigation is possible in the central part except in WMUs 30b and 40 to 44 (see Fig. 1).	Brackish water environment will change to freshwater environment in the central part of QLPH.
C	• Build 5 large sluices in the main rivers to protect the whole QLPH region. • Enlarge canals connecting WMUs 28, 29 and 35 to the Bassac River. • Dredge and enlarge primary and secondary canals in the whole QLPH region.	Irrigation for the whole project area is possible, but requires high investment costs.	Brackish water environment will change to freshwater environment over the whole QLPH region. Salt water intrudes farther into the Bassac River and the Cai Lon River in the dry season.

The model predicted that the water level in options B and C would be significantly lower during the dry season (0.25 cm lower in the central main canal) compared with the natural condition. The major effect would be the change from saline to freshwater environment. The effect on salinity intrusion length in the Bassac River would be insignificant, since the amount of fresh water diverted into the protected area would be only 6% of the dry season flow of this river.

As a follow-up action, option B was analyzed in detail in a feasibility study to find out a suitable investment strategy for water management in the QLPH region (ESSA et al., 1992). Twenty-eight development scenarios were formulated by combining 7 construction schedules with 4 land use strategies. The schedules were either simultaneously started in the whole region or sequentially from east to west, in a short duration of 5 years with external (international) funding sources or in a long duration of 7 years based on government budget, or by a phase of 3 years each with an interruption of 5 years in between to learn the environmental and social impacts. The land use strategies were maximizing rice production, maximizing income, diversifying cropping systems or minimizing the effects of acid water in the

QLPH region by only cultivating acid-tolerant crops on deep and slight ASS, and slow land use changes on shallow and severe ASS.

The scenario analysis (ESSA et al., 1992) showed that the difference in construction schedules has an insignificant effect on economic returns of the investment if investments in land use changes by farmers are not at pace with those for major water control structures by the government. However, a strategy of minimizing acid water combined with a long duration schedule showed significantly higher economic returns than other scenarios because the latter need investment to enhance acid water drainage in the western part of the region.

4.2 The implementation phase

The construction schedule based on a government budget started in 1992. In response to the concern about effects of acid water in the western part, the project was split into three phases (Haskoning, 1998): phases I and II cover the areas of non-acid and slightly acid soils in the east and the southwest; phase III covers the area with severe acid soils in the northwest (WMUs 39, 52 and 54; Fig. 1).

The progressive increase in salinity protection afforded by the phased construction of sluices from east to west resulted in a corresponding east-west expansion of intensified rice cultivation area. In 1996, the double rice area increased to 82,000 ha (28% of target protected area). During this period, under the "reform" policy, rice production shifted from a subsistence economy to a market economy, and farmers' income from rice cultivation gradually increased. In 1997, when 7 sluices were built, social assessment and environmental impacts were reviewed (SIWRP, 1997 and Haskoning, 1998), and implementation of phase III was decided. Results from the VRSAP model showed that water level and salinity had been controlled for the purpose of agricultural development. Hence, in 2000, when 11 sluices had been built and the secondary canals in the acid sulphate soil area had been excavated, the total area of double and triple rice and upland crops increased to 101,000 ha (35% of target protected area).

4.3 Operation and adjustment phase

In the 1980s, farmers practiced extensive shrimp culture (with *Metapenaeus* spp. fry naturally recruited from incoming sea water) in areas with acid sulphate soils. From the mid-1990s onward, shrimp farmers, attracted by the high profits (two to ten times those of rice cultivation) of producing tiger shrimp (*Penaeus monodon*) for export, switched to stocking tiger shrimp post-larvae, and pond shrimp culture became popular (Brennan et al., 2000). The area of shrimp culture in the region increased from about 10,000 ha in 1990 to over 30,000 ha in 1996 (SIWRP, 2003).

As the sluices in the western part became operational after 1998, thereby advancing the salinity-protected area westward, the supply of brackish water required for shrimp production was cut off. Many farmers were forced to abandon aquaculture and to convert to less profitable rice farming. Some shrimp farmers resisted and attempted to maintain favorable conditions by blocking secondary canals and pumping brackish water into their fields, but this created conflict with rice farmers, who depended on fresh water to irrigate their fields. Such conflict was serious in Bac Lieu Province, where the interface between fresh and saline water exists, and prompted the government to re-examine the original policy emphasizing rice production and to 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 (Hoanh et al., 2003). Land use zoning was carried out by consulting with local and provincial authorities, and national planners. A boundary between the intensive agricultural zone (rice based) and mixed agri-aquacultural zone (shrimp-rice based) was outlined and three benchmark sites with specific salinity requirements were identified along the arterial Phung Hiep canal in the central part of the QLPH region. An urgent question raised by the authorities of Bac Lieu Province was how to operate the sluice system to simultaneously maintain both brackish water and freshwater conditions in different areas that are suitable for intensive rice, shrimp-rice and shrimp cropping patterns.

The VRSAP model was applied with an updated scheme of 1,638 segments, 1,032 nodes and 648 fields to find out a suitable sluice operation schedule. Examples of model outputs for different sluice operation options are given in Figure 2. If all sluices were closed, the 10 dS/m isohaline (border of gray zone on the maps) would be west of the QLPH region and salinity would not be high enough for shrimp in the central part. If the Lang Tram sluice were opened, the 10 dS/m isohaline would move progressively eastward and intrude into the intensive agricultural zones. However, at the same time as the Lang Tram sluice were opened, opening the Ho Phong sluice at ebb tide to drain water out would curtail the eastward advance of the salinity boundary caused by opening the Lang Tram sluice.

Using the knowledge gathered from such modeling exercises, several scenarios comprising different combinations of sluice operation were formulated: (a) opening all the sluices to the west of Ho Phong to allow salinity intrusion, (b) opening the Ho Phong sluice at ebb tide to curtail excessive salinity intrusion to the intensive agricultural zone, and (c) adjusting the opening duration of each sluice to control the movement of the salinity boundary. These scenarios were provided to the water management authorities in Bac Lieu Province to guide actual sluice operations from 2001 onward and salinity has been managed as predicted by the model. The new water management policy has had a profound effect on land use, in particular aquaculture, with a significant expansion of shrimp cultivation area to 51,000 ha in 2001 and 64,000 ha in 2002 (SIWRP, 2003).

Figure 2: An example from analysis of the effects of main sluice operation on salinity intrusion in the protected area (bordered by dark line in Figure 1).

5. DISCUSSION AND CONCLUSIONS

This case study illustrates the value of hydraulic and salinity modeling for water resource development in the coastal zone where tidal flow and saltwater intrusion are important phenomena. In the planning and feasibility study phase, the model helps answer basic questions on engineering interventions and likely impacts. Alternative empirical methods (van der Tuin, 1991) reflect only the statistical relationships between model inputs and outputs without physical meaning; therefore, they cannot be used to predict the future effects of the anticipated interventions that we have not yet experienced. Simple hydraulic scale modeling (van der Tuin, 1991) cannot be applied for a dense network of a few thousand segments under tidal effects as in Ca Mau Peninsula. The mathematical model is the only solution for this complex situation.

In the feasibility study, a main question is how to achieve the highest economic returns from an investment in salinity control and irrigation system. Since the economic returns are dictated by land uses, which in turn depend greatly on hydrological conditions, the ability to predict future changes in these conditions is the key factor in the investment decision. The model results helped identify the best construction schedule that would bring the highest return on the investment. Such analysis is not possible without the model because no statistical methods can provide the effects of sluice operation on water level and salinity in each year in the whole region.

In the implementation phase and operation and adjustment phase, the model was a useful tool to determine suitable sluice operation schedules to solve the conflict between the need for fresh water for rice cultivation in the eastern part and the need for brackish water for shrimp raising in the western part of the region. The model outputs also helped identify the need and effect of new interventions such as adjusting cropping systems, building seasonal temporary dams and improving the canal system.

Coastal planners and managers will always face a certain degree of uncertainty not only because the future is by definition uncertain but also because knowledge and data on natural and socio-economic coastal processes are and always will remain incomplete (IPCC, 2002). Therefore, the new direction in development of coastal zones is to try the "non-new infrastructure" alternatives (as in the operation and adjustment phase of this study) rather than building new infrastructure that cannot be adjusted flexibly when any conflict in resource use occurs.

A remaining question in this case study relates to the propagation of water acidity in the QLPH region. The issue of acidic pollution from ASS leachates from the fields and the newly dredged canals is more important to shrimp culture because shrimp is more sensitive to changes in water quality than rice. A module for water acidity is being developed to predict the effects of land use and water management on water acidity in the QLPH region.

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