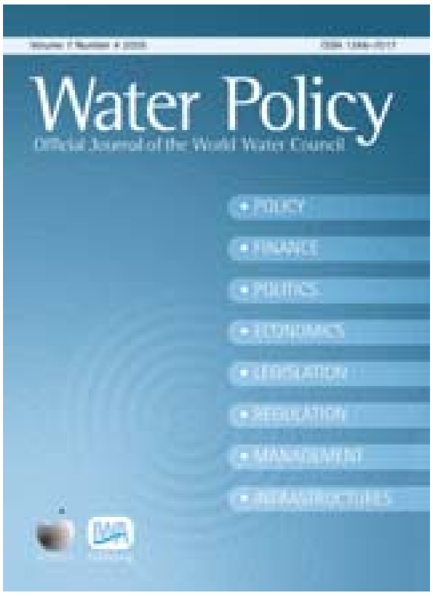
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Hydraulic and water quality modeling: a tool for managing land use conflicts in inland coastal zones

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Abstract

Tidal effect and salinity intrusion are two defining characteristics of inland coastal zones, causing, respectively, complex variations in water levels and flows in river and canal networks, and serious problems for agriculture and freshwater fishery, but bringing significant benefits for brackish water aquaculture. To evaluate these conflicts and synergies in the development of agriculture, fishery and aquaculture, this paper adopts a hydraulic and salinity modeling approach that simulates the tidal propagation and salinity intrusion, and evaluates the effects of water and land use management on these hydrology- and salinity-related phenomena in coastal zones. The paper presents the empirical results from the application of a hydraulic and salinity model specifically developed for the context of the Ca Mau peninsula, Mekong Delta, Vietnam, and also demonstrates how such a modeling approach can provide valuable policy-relevant information at different phases for water resource planning, development, operation, and management in hydrologically and environmentally sensitive coastal regions.

Keywords: Coastal zones; Hydraulic and salinity modeling; Land use conflicts; Water management

1. Introduction

Tidal effect and salinity intrusion are two defining characteristics of inland coastal zones. The first causes complex variations of water level and unsteady flows in the river and canal network, while the second is a constraint to agriculture and freshwater fishery but provides suitable conditions for brackish water aquaculture. Salt water intrusion is one of the most important effects in coastal zones. These

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phenomena bring about conflicts in development of agriculture, fishery and aquaculture due to different requirements of both water quantity and quality. Hence, coastal zone management has focused strongly on conflicts stemming from the multiple uses of resources provided by user and production functions (Klein, 2002).

In many places, coastal aquaculture has led to drops in agricultural productivity and farm incomes, reduced water supplies, loss of income from fishing and forestry, and increasing hazard of coastal flooding (WRI, 1996). Hydrological research during the last few decades has focused attention mainly on modeling the dynamic response of the channel network (Preliminary Foresight Committee on Hydrological Science, 2003; Cuthbertson, *et al.*, 2006; Faeh, 2007). Hydraulic and salinity models have been developed and applied to simulate tidal propagation and salinity intrusion, and to analyze the effects of water management on hydrological conditions that control land use in the coastal zones (OTA, 1982; van der Tuin, 1991; Savenije, 1993; Prandle, 2004). This paper presents experiences in applying a hydraulic and salinity model, the Vietnam River System and Plains (VRSAP), for water resources development in a coastal zone, the Ca Mau peninsula of the Mekong Delta, Vietnam.

2. The study area and the model

2.1. The study area

The Quan Lo Phung Hiep region (hereafter called the Region) in the Ca Mau peninsula, Mekong Delta, Vietnam, with a total area of approximately 450,000 hectares, is a target area for rice land expansion. The 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 (52% of the total area), mainly located in water management units (WMUs) 33, 34, 36, 37, 38, 39, 52 and 54 in the west (Figure 1), and the saline soils (47%). Sandy and peaty soils cover only about 1% of the total area. Two seasons are distinguished in the Region: the rainy (or wet) season from May to mid-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. During the dry season, fresh water availability for irrigation is a major constraint to rice production. On the other hand, solar energy for photosynthesis is more abundant than in the rainy season, and rice crops in the dry season usually yield more.

The hydrological regime in the Region is governed by the flow of the Mekong river and the tide from the seas. The Mekong river flow, with an average of approximately 14,000 $m^3\ s^{-1}$, is run-off from the monsoon rainfall over a large catchment area (approximately 795,000 km^2) with a seasonal distribution pattern: flood season from June to December with a peak in September, and a low flow season from January to May with lowest discharge in April (2,340 $m^3\ s^{-1}$). During the past century, canals have been constructed to provide transport routes. These canals intersect and connect with the natural rivers (Figure 1), thus providing multiple routes for both fresh water supply and drainage, and salt water intrusion into the entire Region. From January to June, water in most canals is too saline for irrigation. The East (the South China Sea) and West (the Gulf of Thailand) seas are hydrologically different in terms of tidal amplitude (3.0 m vs 0.7 m), highest tide level (+1.6 m vs +1.0 m) (Figure 1), and salinity (50 dS/m vs 39 dS/m) at main river mouths. During the dry season, the difference in tidal regimes drives flows from the East sea to the West sea across the Region (Figure 1). Special attention is given to the problem of acid water in the western part of the Region. During the early part of the rainy season, the

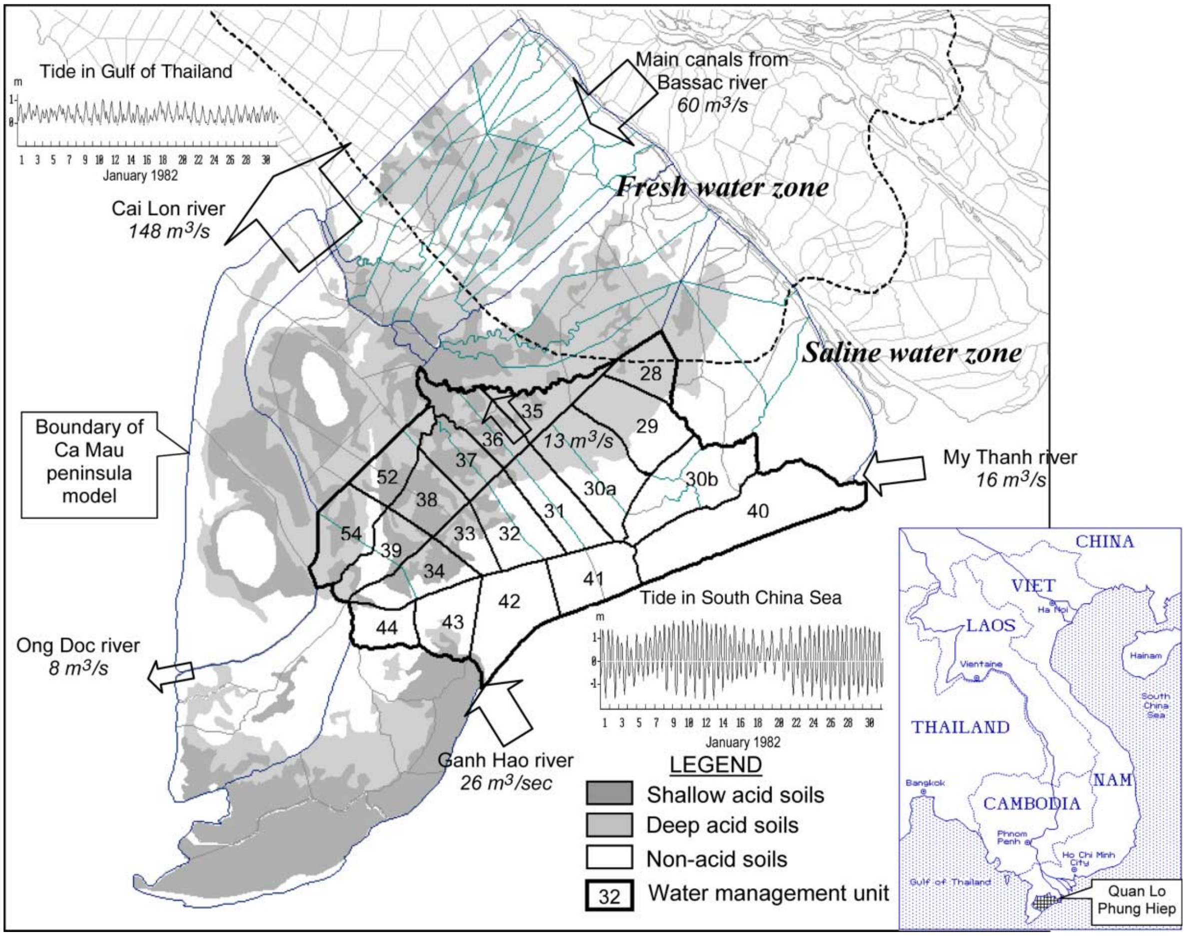

Fig. 1. Location of Quan Lo Phung Hiep region, net flow and direction during one tidal cycle of 14.5 days in February, 1990.

water pH in the canals drops from normal values (6–7) to below 4, under the influence of acid water flushed from the acid sulphate soils.

While soil type is a main factor in selecting the agricultural production system, water conditions (water availability represented by water level in the canals, water salinity and pH) are major factors in selecting cropping calendars. Production of rice, the most important product in the Region, totalled over 0.8 million tonnes in 1990, and was increased to 1.3 million tonnes in 2000. Aquaculture and fisheries constitute another major category of economic activity. Three main types, i.e. brackish water shrimp (the most important economic product), fresh water prawns and fish are reared. A mixed agriculture-aquaculture production system is the shrimp-rice rotation in which farmers dig ditches around the rice field and strengthen the field bunds following the rice harvest to rear shrimps.

Salt water intrusion from the seas via four main rivers, the My Thanh, Ganh Hao, Cai Lon and Ong Doc (Figure 1) makes water quality in most parts of the region unsuitable for irrigation from January to June. Therefore protection against salt water, especially from the East seas through the My Thanh and Ganh Hao rivers, was identified as the key intervention for agricultural development of the

Region (Sonntag & McNamee, 1989). The development of a water control system can be separated into three phases: the planning phase (1989–1991), the feasibility study phase (1991–1992), and the implementation phase (1993 to present).

2.2. The model

Because analysis of observed hydrological data is not sufficient to answer questions related to changes and impacts of water conditions in the Region and surrounding areas under the interventions of water management, the VRSAP model, with a scheme of the whole Ca Mau Peninsula, was applied. This model was developed at the Sub-Institute for Water Resources Planning (SIWRP, former name of the Southern Institute for Water Resources Planning), Vietnam, to simulate the hydrological conditions in the Mekong Delta under different water management scenarios (Khue, 1986), as a part of salinity intrusion studies funded by the Australian Government through the Interim Mekong River Committee. The model was evaluated as high technical standard (Halcrow, 2001), and has been widely used in many studies (ESSA *et al.*, 1992; NEDECO, 1992; Dong, 2000; KOICA & KARICO, 2000). 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 model applies the concept of advection and dispersion (Harleman, 1971) to simulate salinity intrusion, and using the implicit finite difference scheme (Delft Hydraulics, 1989; Jin & Fread, 1997) to compute water level and salinity for each node and each field, and discharge for each segment. A segment can be a reach of a river/canal or a hydraulic structure (such as a sluice) identified by two nodes at two ends. A sluice can be operated in various ways such as completely closed, or opened, for one direction flow, or fully opened for both in- and out-flows. 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, either uncontrolled or controlled by structures, between them. To apply to water management in the Region, the model has been refined with new options of operating sluices for the intake of saline water for shrimp production, and pumping saline water into shrimp fields.

3. Model application in exploring water management options

3.1. Planning issues and water management options

During the Planning phase (1989–1991), the focus was on options for expanding the rice area into the saline coastal zone. The objective of this phase was to establish a well integrated development strategy in land and water management in the Region (Mekong Secretariat, 1988). The proposed water control system consists of dams and sluices, primary, secondary and tertiary canals, and on-farm systems for the purpose of protection from salinity intrusion, acid water leaching and water drainage and increased fresh water supply in the dry season.

Three main questions in this planning phase are:

- how to provide the Region with fresh water and protect from salt water?
- where is the boundary of the agricultural intensifying area?

- what are the effects of salt water protection and irrigation on the hydrological conditions in the Region and surrounding area, in particular salt water intrusion into the Bassac river?

Three water management options were studied (Figure 2) (Sonntag & McNamee, 1989):

- Option 1: protection against salt water intrusion for each small unit bordered by lateral canals; irrigation of some units near the main streams;
- Option 2: protection against salt water intrusion and irrigation of the central part of 250,000 ha by construction of 12 large sluices along the national highway;
- Option 3: protection and irrigation of the whole Region by construction of a large dike and sluice system along the seashore.

3.2. Application of the suite of models

In this planning phase, the VRSAP model was developed for the Ca Mau peninsula and run with a time step of one hour for a scheme of 372 nodes, 455 segments and 190 fields representing the canal network (Figure 1). It was calibrated for three hydrological measurement campaigns: 08–22 October, 1989 (flood season); 9–22 February, 1990 (dry season); and 9–23 June, 1990 (beginning of rainy season). An example of water level and salinity simulated by the VRSAP model and observed in the campaign is given in Figure 3.

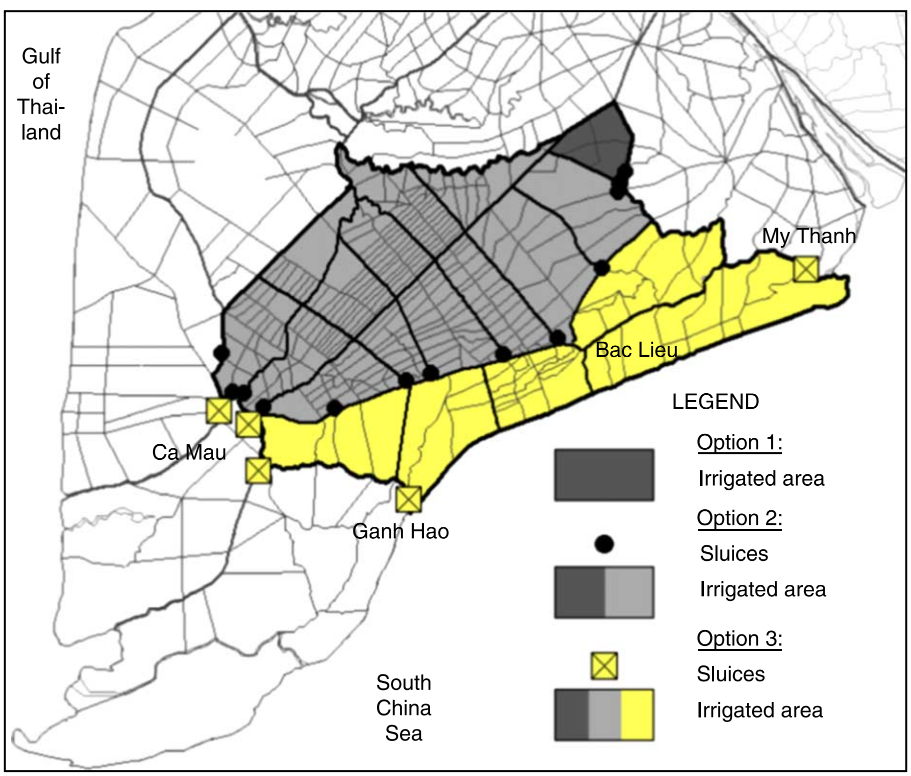

Fig. 2. Three water management options.

The model was then run to predict canal water levels, field water levels, canal salinity and tidal fluctuation for each half month period in February, April, June, August, October, and December for each of the 221 sub-WMUs determined by overlaying the administrative boundary with the canal system in the Region.

To select the most suitable option, the outputs of the VRSAP model were incorporated into an integrated planning model, the Quan Lo Phung Hiep (QLPH) by applying the Adaptive Environmental Assessment and Management (AEAM) methodology (Holling, 1978; Mekong Secretariat, 1982; Walters, 1986; Roux *et al.*, 1999; Bunch 2003). The selection was recommended on the basis of costs/benefits, compatibility with the existing engineering and management capabilities (in the 1990s), and environmental impact (Sonntag & McNamee, 1989). The cost/benefit analysis involved four steps: (i) identification of costs and benefits (qualitative analysis); (ii) calculation of costs and benefits (quantitative analysis); (iii) selection of appropriate discount rate and project life; and (iv) identification and accounting for constraints. In the first step, all costs and benefits associated with each of 19 different economic activities under the headings of agriculture (9 activities), forestry (3 activities) and fisheries (7 activities) were identified. In the second step, for any development scenario, the total cost for construction of a water control system and inputs for agriculture, forestry and fisheries, and total benefits from these economic activities were estimated. In the third step, an appropriate discount rate revealed the importance of allocating costs and benefits to the appropriate years in the project life. The net present value and internal rate of return of the project were calculated at a discount rate of 12% with a project life of 30 years to select the most economically feasible scenarios. Finally, while land use figures implicitly included all physical constraints on project development, other constraints on project development such as social, political, financial or technical, were reviewed.

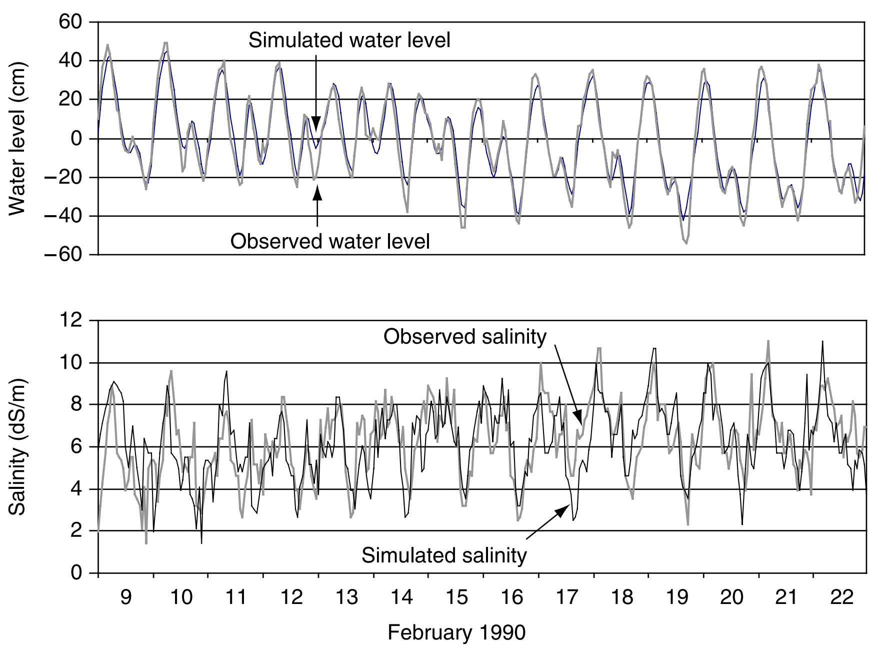

Fig. 3. Comparison of simulated and observed water level and salinity at Xom Cui station in WMU 36.

3.3. Application of model outputs in addressing planning issues

The answers to planning questions derived from the model results are shown in Table 1. The results indicated that Option 1 does not satisfy the ultimate development targets set up by the national and regional authorities. The challenge of Option 3 is not only the risk in deeper salt water intrusion into the Bassac and Cai Lon rivers (Table 1), but also the loss of mangrove forests in WMUs 40 to 44 that are an important habitat for the marine and brackish water fisheries. A sequential strategy in water management was suggested to begin with Option 1 (applied at the end of the 1980s), then moving to Option 2 after some time and, if appropriate, eventually moving to Option 3. After each step, evaluation and information collected may generate a new, previously unstated, option which has more appeal than the originally developed options. This sequential approach makes adaptive management possible in the Region (Sonntag & McNamee, 1989).

4. Model application in selection of an investment plan

4.1. Formulating development scenarios for the feasibility study phase (1991–1992)

The follow-up phase was a pre-feasibility study for a water control project, financially supported by the Government of Vietnam and the Canadian International Development Agency (CIDA) and accomplished in 1992 (ESSA *et al.*, 1992). At the same time, the Mekong Delta Master Plan also

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

	Answers to planning questions		
Option	Question 1	Question 2	Question 3
A	Build many small sluices in secondary canals. Enlarge canals connecting WMUs 28 and 29 (Figure 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 Figure 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.

considered this project as a high priority project for a feasibility study (NEDECO, 1993). The VRSAP and QLPH planning models were refined (Hoanh, 1996) to analyze Option 2 in more detail, to find a suitable investment strategy.

Four land use strategies were suggested (Table 2) and, based on these strategies, 28 development scenarios were formulated by combining 7 construction schedules (Table 3). These scenarios were compared with scenario "zero", in which water conditions and land use patterns are assumed to remain as they were in 1990, with the exception that more land is allocated for specific use (housing, urban, roads, etc.), as a consequence of population growth.

During the feasibility study phase, the VRSAP model was used to predict the changes in water level and salinity in each WMU every half-month over 30 years, as a consequence of construction and operation of water control system and land use change. Outputs from the VRSAP model were used in the QLPH planning model to analyse the effects on agricultural, fish and forest production, economic returns and some environmental impact indicators such as total pesticide use and exploited acid sulphate soil area.

4.2. Evaluating alternative scenarios

The scenario analysis (ESSA Ltd *et al.*, 1992) showed the Min-Acid strategy combined with schedules A to C show significantly higher economic returns than other scenarios, due to the concentration of effort on enhancing acid water drainage in the low productivity area on the west side of the Region. Short construction periods, as in schedule B, do not always lead to high economic returns and production because investments in land use changes by farmers are not in pace with those for water control by the Government.

Taking into account constraints and impacts of expansion of rice production in the acid sulphate soil area in the western part, option F was recommended by environmentalists. However, due to the high priority setting for agricultural development in the 1990s, the Government approached the World Bank for a loan to implement schedule C. To address the effects of acid water in the western part of the Region, the project was split into three phases (Haskoning, 1998): phases I and II cover the areas of non-

Table 2. Four land use strategies in the Region.

Strategy	Description
1. Max-rice: maximize rice production	Rice production is the focus and the rice cropping system yielding the highest rice production is selected
2. Max-income: maximize income from rice production	Rice production is the focus, but the rice cropping system yielding the highest net income is selected
3. Diversification: crop diversification for highest income	Crops, including aquaculture and forestry, yielding the highest net income are selected
4. Min-acid: minimize effects of acid water	Acid tolerant crops cultivated in areas of slightly and moderately active acid sulphate soils, and no land use changes are allowed on strongly active acid sulphate soils

Table 3. Construction schedule (in years) of the water control system.

Schedule	Main features	Investment sources	Main sluices	Secondary canals
A	Main sluices built sequentially from east to west over 7 years	Internal	7	9
B	Main sluices built simultaneously in two provinces over 5 years	External	5	5
C	As B, but over 7 years	Internal	7	9
D	As A, with early construction of secondary canals in acid sulphate soil areas	Internal	7	8
E	As B for main sluices and D for secondary canals	External	5	3
F	Construction work separated in 2 parts with approximately 5 years in between to allow for environmental, social, economic, and institutional assessment, and completed in 10 years.	Internal	10	12
G	Construction work separated in 3 parts and completed in 17 years	Internal	17	17

acid and slightly acid soils in the east and the west, and phase III covers the area with severe acid soils in the northwest (WMUs 39, 52 and 54).

5. Model application in managing conflicts between agriculture and aquaculture

5.1. Analysis of conflicts management strategies during the operation phase (1993 to present)

The construction of the first three large sluices in the east was completed in 1993. The effects on water conditions and subsequently on land use have been observed since 1994, showing an increase of 15,000 ha (5% of the target protected area) in double rice cropping in the area protected from salt water. In 1996, the double rice area was up to 82,000 ha (28% of the target protected area) (SIWRP, 1997). During this period, under the "reform" policy, rice production has shifted from a subsistence economy to a market economy, and farmers' income from rice cultivation has gradually increased. In 1997, when 7 sluices were built, social assessment and environmental impacts were reviewed to decide the implementation of phase III (SIWRP, 1997; Haskoning, 1998). By 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 was up to 101,000 ha (35% of the target protected area).

In areas with acid sulphate soils and which are medium- to deep-flooded, farmers practiced shrimp culture (*Metapenaeus* spp. fry recruited from incoming sea water) or a shrimp-rice system in the 1980s. From the mid 1990s onwards, shrimp farmers, attracted by the high profits (two to ten times higher, compared to 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 fringe of the study area became operational after 1998, thereby advancing the salinity-protected area westward (Figure 4), the supply of brackish water required for shrimp production was cut off, and many farmers were forced to abandon aquaculture and to convert to less profitable rice farming. Hence, in 2000, the area of shrimp culture decreased to approximately 25,000 ha (SIWRP, 2003).

However, the water control system to support the expansion of rice and upland crops into the Region causes conflicts between agriculture and fishery-aquaculture because of their different water quality requirements: agricultural crops need fresh water, while aquatic production is higher in a brackish water environment. Some shrimp farmers resisted and attempted to maintain favorable conditions by blocking secondary canals and pumping brackish water into their fields, but this created conflicts with rice farmers who depended on fresh water to irrigate their fields. Such conflicts were serious in the 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. Land use zoning was carried out by consulting with the provincial authorities, local stakeholders and national scientists. A boundary between an intensive agriculture zone (rice based) and a mixed agri-aquaculture zone (shrimp-rice based) was outlined, and three benchmarks with specific salinity requirement were identified along the arterial Phung Hiep canal (Figure 4). The most important benchmark is the Ninh Quoi site where water salinity should be $<$ 10 dS/m throughout the year.

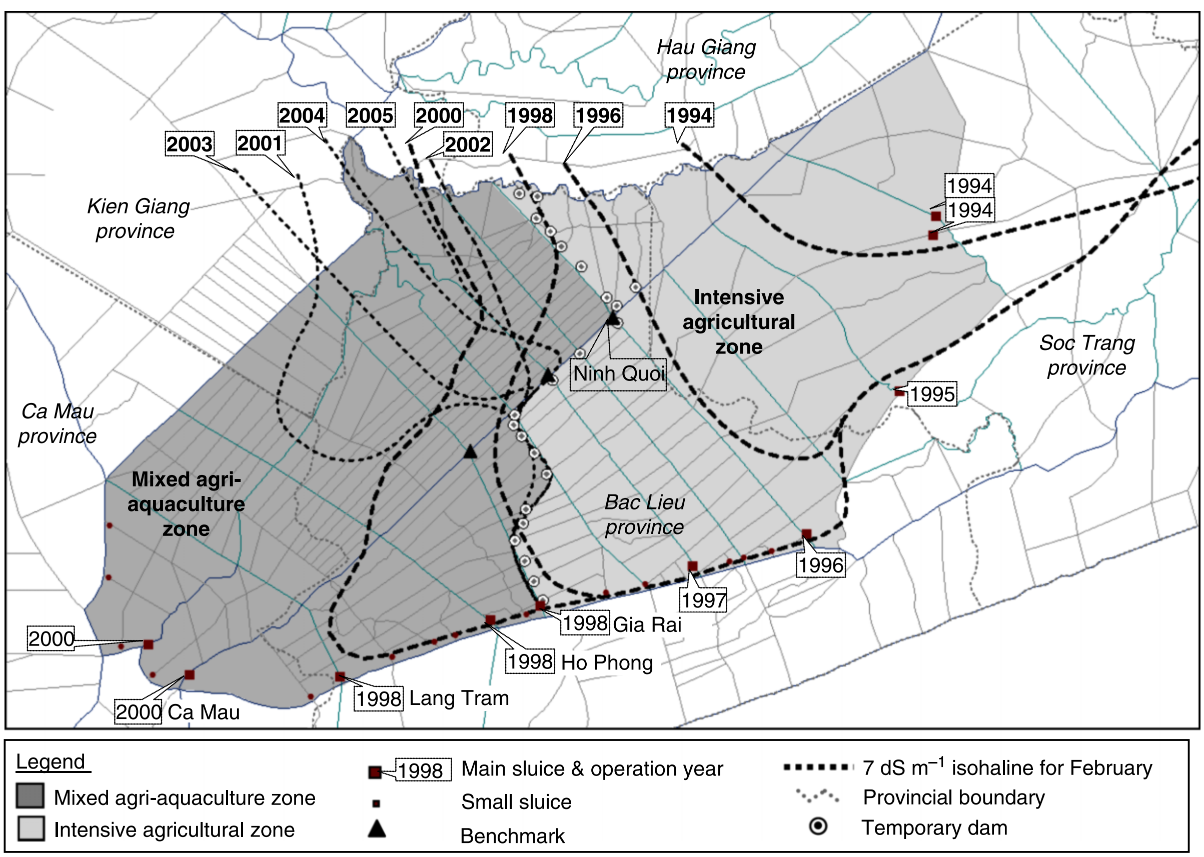

Fig. 4. Effect of existing sluices on salinity in February each year.

An urgent question raised by the authorities of Bac Lieu province was how to operate the sluice system to simultaneously maintain both brackish and fresh water conditions in different parts of the project area that are suitable for intensive rice, shrimp-rice and shrimp cropping patterns. To answer this question, the VRSAP was applied with an updated scheme of 1,638 segments, 1,032 nodes and 648 fields to reflect a denser canal network (Figure 4), to find a suitable sluice operation schedule. Using the knowledge gathered from such modelling exercises, a number of scenarios comprising different combinations of sluice operation were formulated: (1) opening all the sluices to the west of Ho Phong to allow salinity intrusion; (2) opening the Ho Phong sluice at ebb tide to curtail excessive salinity intrusion into the intensive agriculture zone; and (3) adjusting the opening duration of each sluice to control the movement of the salinity boundary. For example (Figure 5), if the Lang Tram sluice (see Figure 4) was opened, the 10 dS/m isohaline would move progressively eastward and intrude into the intensive agriculture zones (Figure 5(b)). However, simultaneously opening the Ho Phong sluice (see Figure 4) 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 (Figure 5(c)). This is because drainage at Ho Phong would induce more fresh water to flow from the Bassac river into the study area through the arterial Phung Hiep canal, and hence the requirement of salinity at Ninh Quoi could be satisfied.

The sluice operation scenarios were assessed to see if the resulting salinity distributions satisfied the water quality requirements at benchmarks, and the most suitable alternative was selected. In each month in the dry season, sluices from Lang Tram to Gia Rai were opened for only flowing out during 3 days to release the polluted water and sediment inside the sluices, then opened for only flowing in to take in saline water over the following 7–10 days. The model outputs also help in identifying when temporary dams (Figure 4) should be built along secondary canals to protect the intensive agriculture zones from saline water during the dry season.

5.2. Application of model outputs in conflicts management

These scenarios were given to the water management authorities in Bac Lieu province to guide the actual sluice operation and the construction of temporary dams from 2001 onwards. Changes in the salinity boundary from February 2001 to 2005, due to changes in sluice operation, are compared with that in the precedent in Figure 4. It shows that salinity was controlled as expected. Changes in sluices operation under new water management policies has had a strong effect on land use (Gowing *et al*., 2006), in particular aquaculture, with a significant expansion of the shrimp cultivation area from 51,000 ha in 2001 to 64,000 ha in 2002 (SIWRP, 2003).

Through this exercise, the provincial governments of five provinces recognized the importance of collaborating in the operation of sluices for the benefit of the whole region, therefore a regional water alliance (RWA) was established. Different water management scenarios have been analyzed by applying the model and presented to the RWA. The extreme scenario is opening all the sluices in the mixed agri-aquaculture zone throughout the year to avoid a complex operation schedule. However, the model outputs indicate that salinity becomes too high in the intensive agriculture zone. Another scenario is to operate the Ca Mau sluice in Ca Mau province (see Figure 4), at present fully opened or closed during the dry season, to support the control of salinity in Bac Lieu province. The model outputs show that by operating this sluice, saline water could be supplied earlier to the upper part of the mixed agri-aquaculture zone. Hence, a harmonic sluice operation in the whole Region is needed.

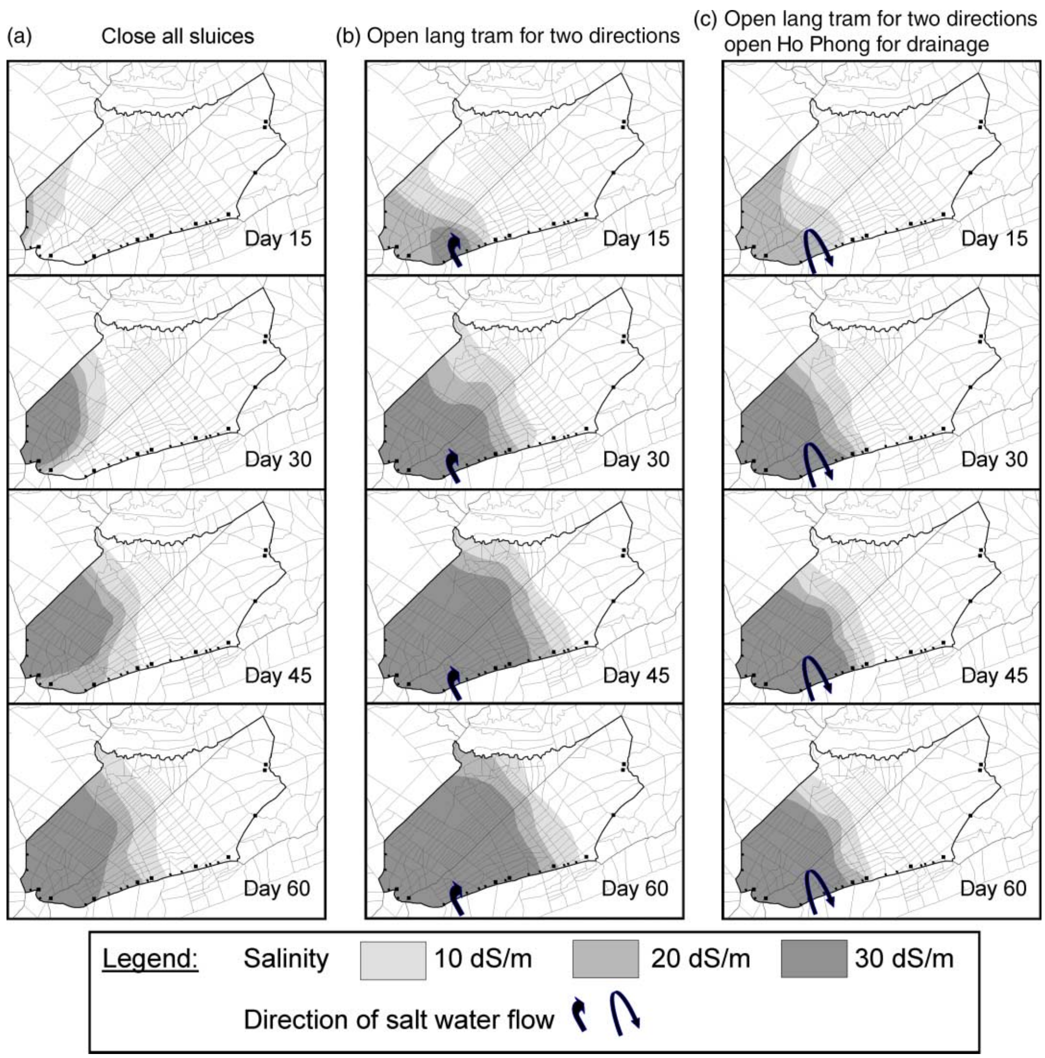

Fig. 5. An example from analysing the role of main sluices on salinity intrusion in the protected area.

6. Conclusions and implications

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 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 a feasibility study, a main question is how to achieve the highest economic returns from an investment in a 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 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 raising shrimp 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 (Metz *et al.*, 1999). 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 by acid sulphate soil 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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References

Brennan, D., Clayton, H. & Be, T. T. (2000). Economic characteristics of extensive shrimp farms in the Mekong Delta. *Aquaculture Economics and Management*, *4*(3/4), 127–140.

Bunch, M. J. (2003). Soft systems methodology and the ecosystem approach: a system study of the Cooum River and environs in Chennai. India. *Environmental Management*, *31*(2), 182–197.

Cuthbertson, A. J. S., Davies, P. A. & Guo, Y. (2006). Model study of the influence of submerged tidal barriers on estuarine mixing and exchange processes. *Journal of Hydraulic Engineering*, *132*(10), 1033–1043.

Delft Hydraulics (1989). *SAFLOW Manual: A Program to Calculate One-Dimensional Channel Flow Including Salinity*. Delft Hydraulics, Delft, The Netherlands.

Dong, T. D. (2000). VRSAP model and its applications. In *Proceedings of the Workshop On Hydrologic and Environmental Modelling in the Mekong Basin*. Al-soufi, R. W. (ed.). Technical Support Division, Mekong River Commission, Phnom Penh, Cambodia.

ESSA Ltd, Stothert, Pegasus, Ward & Associates, and IEM, Inc (1992). *Water Control Project for the Quan Lo Phung Hiep Area, Mekong Delta, Vietnam: A Pre-Feasibility Study (Executive Report)*. Prepared by ESSA Environmental and Social System Analysts Ltd, Vancouver, B.C., Canada, for Ministry of Water Resources, Socialist Republic of Vietnam.

Faeh, R. (2007). Numerical modeling of breach erosion of river embankments. *Journal of Hydraulic Engineering*, *133*(9), 1000–1009.

Gowing, J. W., Tuong, T. P., Hoanh, C. T. & Kheim, N. T. (2006). Social and environmental impact of rapid change in the coastal zone of Vietnam: an assessment of sustainability issues. In: *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture-Fishery Aquaculture Conflicts*. Hoanh, C. T., Tuong, T. P., Gowing, J. W. & Hardy, B. (eds). CABI Publishing, UK.

Halcrow Group Ltd (2001). *Working Paper No. 4 – Review of Available Models. Water Utilisation Project Component A: Development of Basin Modelling Package and Knowledge Base (WUP-A)*. Mekong River Commission, Phnom Penh, Cambodia.

Harleman, D. R. F. (1971). *One-Dimensional Model; Estuarine Modeling: an Assessment*. TRACOR, Inc, New York, NY, USA.

Haskonning, B. V. (1998). *Mekong Delta Water Resources Development Project. Environmental Review of Quan Lo Phung Hiep Sub-Project*. Prepared for Central Project Office, Ministry of Agriculture and Rural Development, Vietnam. Haskonning B.V. Consulting Enginneers and Architects in Association with EuroConsult and Delft Hydraulics. Nijmegen, The Netherlands.

Hoanh, C. T. (1996). *Development of a Computerized Aid to Integrated Land Use Planning (CAILUP) at regional level in irrigated areas. A case study for the Quan Lo Phung Hiep region, Mekong Delta, Vietnam*. Ph.D. Thesis. ITC Publication Number 38, International Institute for Aerospace Survey and Earth Sciences, Enschede, The Netherlands.

Holling, C. S. (ed.) (1978). *Adaptive Environmental Assessment and Management*. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Jin, M. & Fread, D. L. (1997). Dynamic flood routing with explicit and implicit numerical solution schemes. *Journal of Hydraulic Engineering, ASCE*, *123*(3), 166–173.

Khue, N. N. (1986). *Modelling of Tidal Propagation And Salinity Intrusion in the Mekong Main Estuarine System*. Technical paper of Mekong Delta Salinity Intrusion Studies, Phase II. Mekong Secretariat, Interim Mekong River Committee, Bangkok.

Klein, R. J. T. (2002). *Coastal Vulnerability, Resilience and Adaptation To Climate Change: An Interdisciplinary Perspective*. The Mathematisch-Naturwissenschaftliche Fakultät of the Christian-Albrechts-Universität zu Kiel, Germany.

KOICA & KARICO (2000). *Flood control planning for development of the Mekong Delta (basinwide): Final Report, Volume 1, Main Report*. Korea Water Resources Corporation and Korea Agricultural and Rural Infrastructure Corporation. Mekong River Commission, Phnom Penh, Cambodia.

Mekong Secretariat (1982). *Environmental Impact Assessment: Guidelines for Application to Tropical River Basin Development*. Mekong Secretariat, Interim Committee for Coordination of Investigations of the Lower Mekong Basin, ESCAP, Bangkok, Thailand.

Mekong Secretariat (1988). *Preliminary Environmental Assessment of Quan Lo/Phung Hiep Development*. Mekong Secretariat, Interim Committee for Coordination of Investigations of the Lower Mekong Basin, ESCAP, Bangkok, Thailand.

Metz, B., Davidson, O. R., Martens, J.-W., van Rooijen, S. N. M. & McGrory, L. V. W. (eds.) (1999). *Methodological and Technological Issues in Technology Transfer–IPCC Special Report*. Intergovernmental Panel on Climate Change (IPCC), IPCC Secretariat, Geneva, Switzerland.

NEDECO (1992). *Thematic Study on Management of Water Resources, Hydraulic Modelling. Vol. 4*. State Planning Committee-Government of Vietnam, World Bank, Mekong Secretariat, United Nations Development Programme (UNDP), Bangkok, Thailand, Mekong Delta Master Plan Project (VIE/87/031).

NEDECO (1993). *Master Plan for the Mekong Delta in Vietnam: A Perspective for Sustainable Development of Land and Water Resources*. State Planning Committee-Government of Vietnam, World Bank, Mekong Secretariat, United Nations Development Programme (UNDP), Bangkok, Thailand, Mekong Delta Master Plan Project (VIE/87/031).

OTA (1982). *Use of Models For Water Resources Management, Planning, and Policy*. Office of Technology Assessment (OTA), Congress of the United States, Washington, DC.

Prandle, D. (2004). Saline intrusion in partially mixed estuaries. *Estuarine Coastal and Shelf Science*, *59*(3), 385–397.

Preliminary Foresight Study on Hydrological Science (2003). *Hydrology: A Vital Component of Earth System Science*. Preliminary Foresight Committee on Hydrological Science in The Netherlands (Koninklijke Nederlandse Akademie van Wetenschappen), The Netherlands.

Roux, D. J., Kleynhans, C. J., Thirion, C., Hill, L., Engelbrecht, J. S., Deacon, A. R. & Kemper, N. P. (1999). Adaptive assessment and management of riverine ecosystems: the crocodile/elands river case study. *Water SA*, *25*(4) South African Water Research Commission.

Savenije, H. H. G. (1993). Predictive model for salt intrusion in estuaries. *Journal of Hydrology*, *148*(1-4), 203–218.

SIWRP (1997). *Report on Social and Environmental Study Update for the Quan Lo Phung Hiep project*. Sub-Institute for Water Resources Planning, Ministry of Agriculture and Rural Development, Vietnam.

SIWRP (2003). *Study of Scientific Base for Adjustment of Production Systems and Environmental Protection in the Quan Lo Phung Hiep region*. Sub-Institute of Water Resources Planning (SIWRP), Ministry of Agriculture and Rural Development, Vietnam (in Vietnamese).

Sonntag, N. C. & McNamee, P. J. (1989). Eco-development planning for the Quan Lo Phung Hiep area of the Ca Mau Peninsula. Final report by ESSA Environmental and Social Systems Analysts Ltd for Mekong Secretariat, Vietnam.

van der Tuin, H. (1991). *Guidelines on the Study of Seawater Intrusion Into River*. Prepared for the International Hydrological Programme, UNESCO, Paris, France.

Walters, C. W. (1986). *Adaptive Management of Renewable Resources*. MacMillan Publishing Company, New York.

WRI (1996). World resources institute, united nations environment programme, united nations development programme and the World Bank. In *World Resources 1996–97: A Guide to the Global Environment–The Urban Environment*. Oxford University Press, Oxford, UK.

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