10 Integrated Management of Aquatic Resources: a Bayesian Approach to Water Control and Trade-offs in Southern Vietnam

E. Baran,[1] T. Jantunen,[2] P. Chheng[3] and C.T. Hoanh[4]
[1]*WorldFish Center, Phnom Penh, Cambodia; e-mail: e.baran@cgiar.org;* [2]*Environmental Consultant, Phnom Penh, Cambodia;* [3]*Inland Fisheries Research and Development Institute, Phnom Penh, Cambodia;* [4]*International Water Management Institute, Regional Office for South-east Asia, Vientiane, Lao PDR*

Abstract
The BayFish–Bac Lieu model presented in this chapter is a Bayesian model that aims to identify optimal water control regimes and trade-offs between water uses in order to improve management of water-dependent resources in the inland coastal area of Bac Lieu Province, Mekong Delta, Vietnam. The model was developed between 2004 and 2007 and integrated local databases, outputs from the Vietnam River Systems and Plains (VRSAP) model and stakeholder consultations. The model facilitates analyses of the consequences of different water management scenarios (quantitative and qualitative) on rice, fish, crab and shrimp production in the province. However, beyond production, trade-offs between household income, food security or environmental protection were also identified during the model development process. Subsequently, the BayFish–Bac Lieu model allows detailing of: (i) annual production probabilities in the case of a baseline scenario; (ii) outcomes of four different sluice gate operation modes; and (iii) trade-offs between household income, food security and environment outcomes for each scenario. The model shows that through improved shrimp farming and fish production, total household income benefits directly from open sluice gates allowing saline intrusion. However, this has the opposite effect on rice production, and on food security. Results suggest that a suitable compromise involving at least one sluice gate open at all times should be adopted for optimized outcomes.

Introduction

The management of coastal zone development is challenging, not only because of the dynamic nature of coastal systems, but also because of competition and conflict between stakeholders involved in different economic activities. Understanding trade-offs inherent in the management of the system is, therefore, essential. This was particularly the case in Bac Lieu Province, Mekong Delta, Vietnam (Fig. 10.1), where multiple sluice gates were constructed by the government along the main coastal road to prevent the incursion of salt water, thus favouring the extension of rice farming in a freshwater environment. As a result, between 1994 and 2000, the area under rice cultivation in Bac Lieu increased (Hossain *et al*., 2006). However, at the same time, market forces prompted other farmers to invest in shrimp farming, which is dependent on salt water. Conflicts of interest grew and peaked in February 2001 when shrimp farmers breached the dyke system in Lang Tram to let salt water

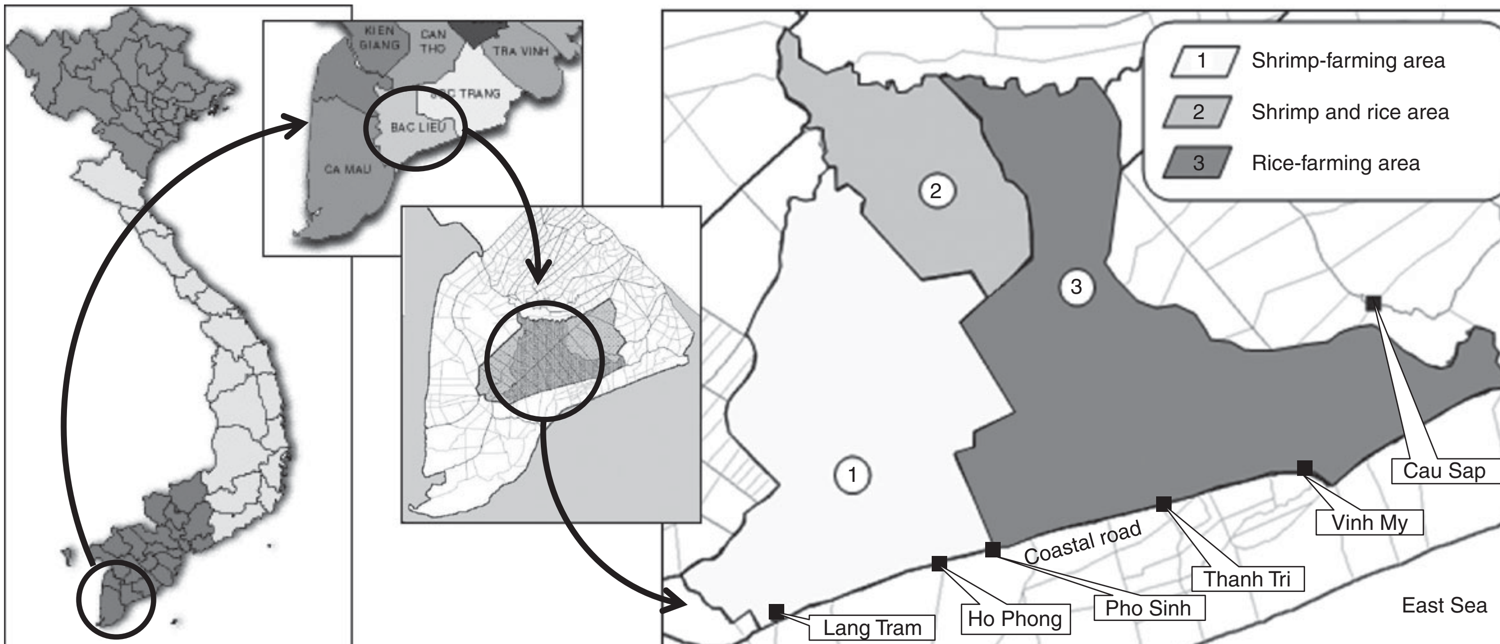

Fig. 10.1. Study area in Bac Lieu Province (black squares mark sluice gates).

into the protected area. Subsequently, a compromise operation mode for the sluice gates was adopted, thereby allowing the influx of salt water by opening certain gates at times or preventing its influx by not opening them. Now, the study area can be divided roughly into three zones (Fig. 10.1): zone 1, where water is quite brackish and dominated by shrimp farming; zone 2, brackish in the dry season, where shrimp and rice farming are combined; and zone 3, where water is mainly fresh (this is the predominantly rice growing area).

In addition to rice and shrimp farming, water management options have a significant impact on aquatic resources, fish being another significant commodity for the local population. Combined, agriculture, aquaculture and fisheries contribute 52.6% of GDP in the province. In this context, the need for a methodology assessing interactions and trade-offs among the various food commodities has been highlighted (Gowing *et al.*, 2006a).

BayFish–Bac Lieu, a Bayesian probabilistic model, has been developed to make explicit the cause–effect links in these production systems, to understand inherent trade-offs and, ultimately, to assist water management in the province. The objectives of the model are (from the most specific to the broadest):

1. To help optimize the operation of the sluice gates.
2. To assist decision making about water management options, through the modelling of different scenarios.
3. To identify stakeholders and inform them about the production trade-offs inherent in water management.
4. To involve stakeholders in the management process.

This chapter is a follow-up of a previous publication (Baran *et al.*, 2006), which presented the first steps in the model development process, i.e. the theoretical background of Bayesian modelling, the approach in BayFish–Bac Lieu, the stakeholder consultation process and the overall model structure. Since then, databases and results from other surveys and studies have been integrated into the model and scenarios have been produced and analysed. Data used, model development, parametrization and outcomes are detailed in Jantunen *et al.* (2007). In this chapter, we present a summary of the entire model development cycle, followed by a detailed discussion of the model outputs, with a particular emphasis on scenarios and trade-offs.

Model Development, Testing and Validation

Bayesian networks – also called Bayes' nets or Bayesian Belief Networks (BBN) – consist of a set of variables linked by probabilistic interactions (Charniak, 1991; Jensen, 1996; Cain, 2001). These variables can be quantitative or qualitative and a small number of classes are defined for each of them (e.g. 'rice farming area', <1000 ha or >1000 ha). Then probabilities, originating from data analysis or from consultation with experts, are attached to each class of each variable. When variables are linked (e.g. 'rice farming area' and 'rice productivity' being combined into 'rice production'), the resulting probabilities are calculated throughout the network using the Bayes' formula. For computation, we use Norsys' 'Netica' software since it is widely recognized, user-friendly and freely available on the Internet (www.norsys.com) for users to run the models developed.

In the case of the BayFish–Bac Lieu model, the structure is based entirely on stakeholder consultations held at the commune and provincial level. During the process, stakeholders identified the dominant factors (model variables) determining food production in the province and their cause–effect relationships (model linkages). Stakeholders also gave respective weights to factors at each level (probability elicitation). The model structure is shown in Fig. 10.2.

During the development process, it became clear that the initial objective – to propose an optimal sluice gate operation schedule that would maximize the production of all water-dependent commodities – was based on the improper assumption that harvest maximization (in terms of biomass) was the only expected outcome, regardless of economic or environmental considerations. Hence, the two latter variables were integrated as management outputs. On the input side, the sluice gate scenarios and corresponding hydrological data were

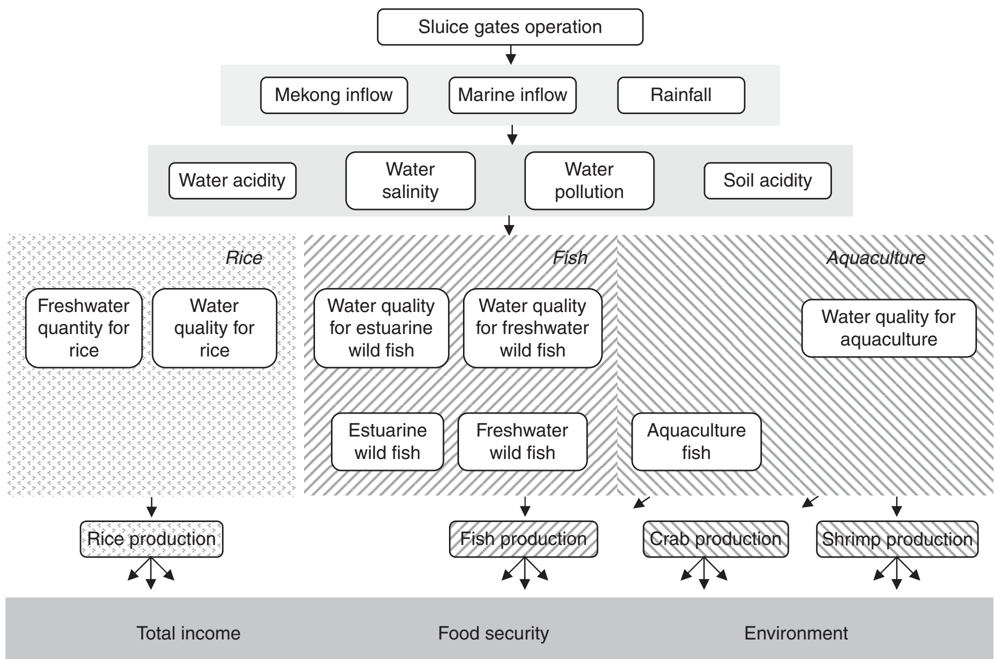

Fig. 10.2. Main variables and structure of the BayFish–Bac Lieu model.

derived from the VRSAP model (Hoanh, 1996). Five sluice gate managemement scenarios were considered (Jantunen *et al.*, 2007):

1. *Baseline*: current complex operation schedule for 2001, 2003 and 2004 in which Lang Tram and Ho Phong sluices, and some smaller sluices, are opened or closed depending on salinity at three upstream benchmarks.
2. *All open*: all sluice gates open at all times (saltwater scenario).
3. *LT open*: only southern Lang Tram sluice gate is opened.
4. *LT and HP open*: Lang Tram and Ho Phong sluice gates are opened.
5. *All closed*: all sluice gates are closed at all times (the freshwater scenario), but in practice gates are opened briefly at certain times to let excess freshwater out.

Model fine-tuning (in particular thresholding) was carried out in collaboration with the Southern Institute for Water Resources Planning and local experts (details are given in Jantunen *et al.*, 2007). Calibration was undertaken with a baseline scenario by relating provincial food production statistics with model output probability units. The resulting model is presented in Fig. 10.3.

Because the BayFish–Bac Lieu model focuses on water management options at the province level but does not integrate management options at the farm level (such as stocking density or use of fertilizers), the notion of 'production' could not refer to a number of tonnes only. Therefore, the land area used to produce a certain commodity was used as a proxy of production.

Figure 10.4 shows the relationships between model outputs (in probabilistic units) and land area used for agriculture and aquaculture; the model prediction for each production appears good.

In order to be readable, the model outputs, expressed in probabilistic terms, have been related to actual data for the years available, in particular for agriculture area and production and household income. These relationships are detailed below:

- Relationship between model units (x) and agriculture production (y, tonnes): $y = 7307.4x - 39{,}587$.

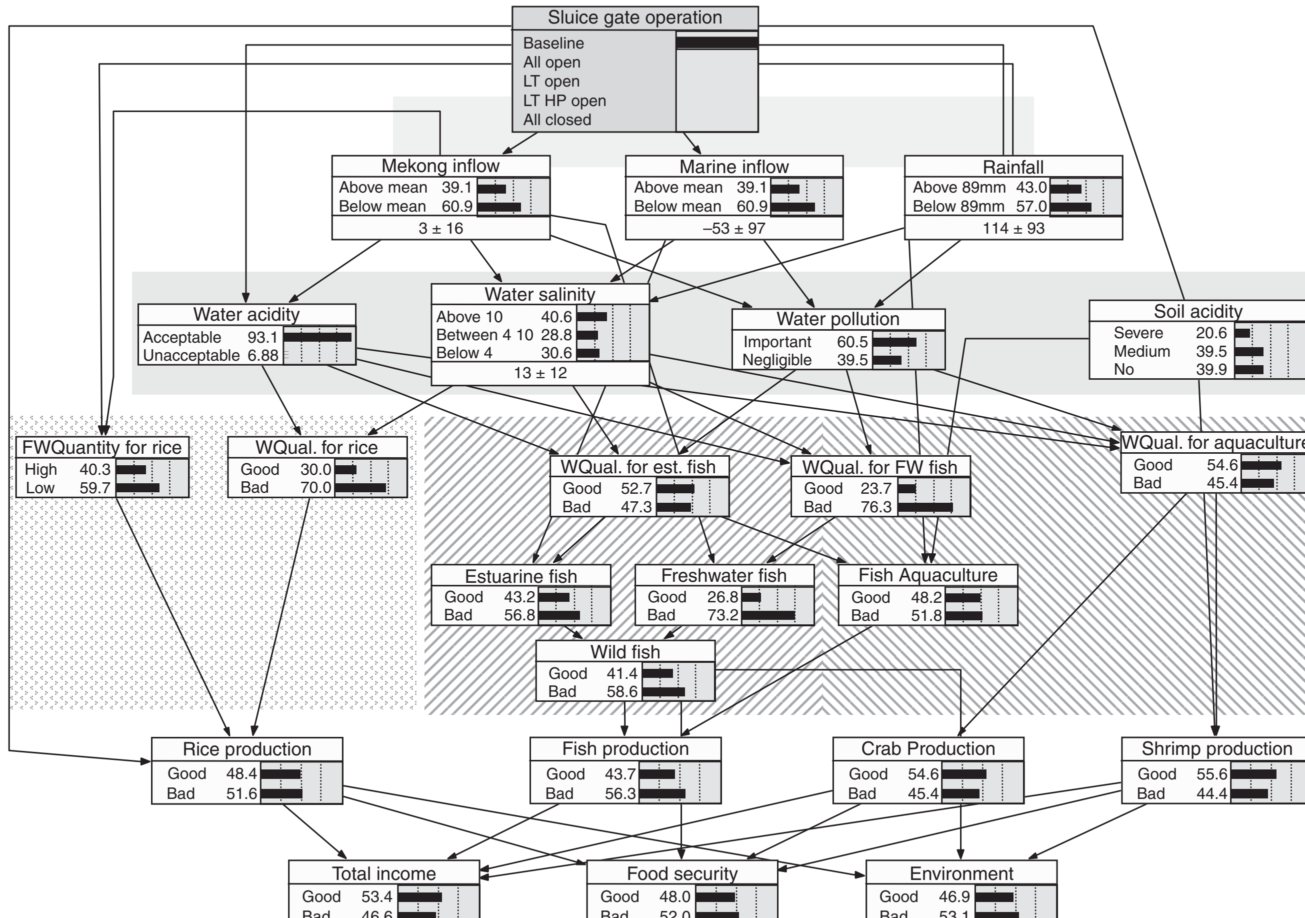

Fig. 10.3. Overview of the BayFish–Bac Lieu model. Values in boxes are probability units varying between 0 and 100%.

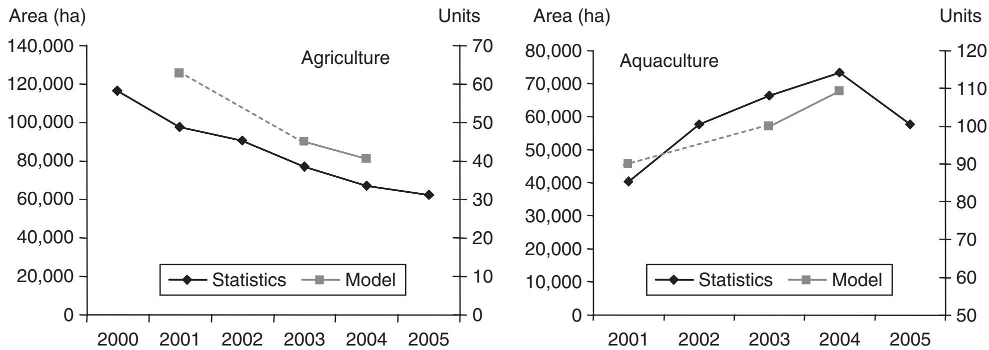

Fig. 10.4. Baseline scenario prediction (squares) compared to production area (lozenges) for agriculture and aquaculture.

- Relationship between model units (*x*) and agriculture area (*y*, ha): $y = 1916.4x - 18{,}009$.
- Relationship between model units (*x*) and aquaculture production (*y*, tonnes): $y = 1119.5x - 79{,}368$.
- Relationship between model units (*x*) and aquaculture area (*y*, ha): $y = 1977.9x - 13{,}7674$.
- Relationship between model units (*x*) and household income (*y*, US$): $y = 133.87x - 5306.9$.

Results

Water quantity and quality

The model was used to analyse the consequences of different sluice gate operation scenarios on water quality (Table 10.1). *Soil acidity* and *Rainfall* are not considered here as they are static nodes, i.e. scenarios do not affect their probabilities. The response of the model reflects closely the functioning of the environment. For all physical and chemical variables (except *Water pollution*), the *All gates open* and *All gates closed* scenarios provide the opposite extreme in response. When the *Baseline* scenario is compared to the *Lang Tram open* and the *Lang Tram and Ho Phong open* scenarios, the latter has much higher *Marine inflow*, but *Lang Tram and Ho Phong open* results in lower *Mekong inflow* probabilities. This means that having one main sluice gate (Lang Tram) open draws in more fresh water from the Mekong than enters in the *Baseline* scenario.

Water salinity levels do not increase much from the *Baseline* to the *Lang Tram open* scenario, whereas the *Lang Tram and Ho Phong open* scenario increases salinity significantly, especially above 10 ppt. *Water acidity* also behaves in opposition to salinity: the more *Marine inflow* is allowed, the less acidity is a problem in the province. *Water acidity* problems are also local, but they can be significant. The significance of acidity problems depends on soil type and excavation of new shrimp ponds; Gowing *et al.* (2006b) note that under

Table 10.1. Water quality depending on sluice gate operation scenarios. Results in probability units varying between 0 and 100%.

Variable	State	Baseline	All open	LT open	LT and HP open	All closed
Mekong inflow	Above 10 m^3/s	39.1	8.7	47.8	30.4	52.2
Marine inflow	Above 10 m^3/s	39.1	69.6	65.2	69.6	4.4
Water salinity	Above 10 ppt	40.6	59.9	43.3	51.2	27.3
	Between 4 and 10 ppt	28.8	24.0	30.1	27.4	27.8
	Below 4 ppt	30.6	16.1	26.7	21.3	44.9
Water acidity	Acceptable	93.1	96.5	92.2	94.1	91.7
Water pollution	Important	60.5	45.3	40.5	40.9	82.2

present circumstances, the release of acidity has a more significant impact on water quality than organic pollution.

Scenarios confirm that when sluice gates are all closed, there is no flushing of pollutants to the sea, which causes a high probability of pollution. Conversely, the *All gates open* scenario is not the best scenario for pollution either, since it corresponds to high-intensity shrimp farming (many authors argue that intensive shrimp farming is not sustainable, e.g. Gowing *et al*., 2006a; Hossain *et al*., 2006; Luttrell, 2006; Dung *et al*., 2009). In fact, the best scenarios pollution-wise are the *Lang Tram open* and *Lang Tram and Ho Phong open* scenarios. This is because these scenarios allow a fairly high inflow of both Mekong and marine water, thereby diluting the pollutants.

Scenarios and consequences

Results for each of the scenarios in the BayFish–Bac Lieu model are presented in Table 10.2. Probability units (ranging from 0 to 100% probability) are those attached to the variable state defined as 'Good'. *Total aquaculture* is the sum of *Shrimp production* and *Fish production* variables (statistics were not available for *Crab production*). Linear equations detailed above were used to compute indicative yield and area for each scenario.

All gates open

The *All gates open* scenario represents the system as it would be without any sluice gates. In this scenario, marine inflow is characteristically high, with minute *Mekong inflow*. This causes the province to have very high salinity concentrations. As a consequence, aquaculture production is very high (between 28,000 and 90,000 t/year for the 2001–2004 period, i.e. *Baseline* +100%), whereas *Rice production* decreases significantly to 210,000–280,000 t/year (i.e. *Baseline* −30%). Given the high price of shrimps, *Household income* is likely to rise to US$3000/household/year (+70%). This comes at the cost of reducing *Food security* significantly for the poorest of the province by limiting possibilities for rice cultivation, which is counterweighted to a degree by increased possibilities for *Fish production* through better access to open resources.

Table 10.2. Food production according to the different scenarios. Results in probability units (varying between 0 and 100%; focus on state 'Good' of each variable).

Variable	Baseline	All open	LT open	LT and HP open	All closed
Model output probabilities					
Fish production	43.7	59	56.7	58.9	26.4
Crab production	54.6	71.2	59.1	65.2	40.1
Shrimp production	55.6	68.9	59.2	64.1	44
Total aquaculture	99.3	127.9	115.9	123	70.4
Rice production	48.4	35.6	50.8	44	55
Total household income	53.4	63.2	57.7	60.7	43.7
Food security	48	41.5	52.6	47.8	49.3
Environment	46.9	47.2	45.9	46.4	47.8
Indicative production					
Aquaculture (ha)	58,731	115,299	91,565	105,608	1,570
Aquaculture (t)	31,798	63,816	50,382	58,331	−555
Agriculture (ha)	74,745	50,215	79,344	66,313	87,393
Agriculture (t)	314,091	220,556	331,629	281,939	362,320
Household income (US$)	1,842	3,154	2,417	2,819	543
Change from Baseline					
Aquaculture (ha)	0	96.3	55.9	79.8	−97.3
Aquaculture (t)	0	100.7	58.4	83.4	−101.7
Rice (ha)	0	−32.8	6.2	−11.3	16.9
Rice (t)	0	−29.8	5.6	−10.2	15.4
Income (US$)	0	71.2	31.3	53.1	−70.5

Lang Tram open

In this scenario, the *Marine inflow* is much higher than in the *Baseline* scenario, but less than in the *All gates open* or in the *Lang Tram and Ho Phong open* scenarios. *Water salinity* is a bit higher than in the *Baseline* scenario, resulting in an aquaculture production of 22,000–72,000 t/year for the 2001–2004 period (*Baseline* +55–60%). Surprisingly, rice production increases to 310,000–420,000 t/year (*Baseline* +5%), mainly because of higher *Mekong inflow*. It seems that opening this southern sluice gate does not allow salt water to penetrate far into the freshwater zone. This, however, allows more water exchange, which reduces *Water pollution* and *Water acidity*. *Household income* increases from *Baseline* level (US$1800/household/year) to US$2400/household/year (+30%) and *Food security* also increases in the province. However, this increased production pattern results in slightly more damage to the *Environment* than in the *Baseline* scenario.

Lang Tram and Ho Phong open

In this scenario, *Marine inflow* is as high as in the *All gates open* scenario. However, *Mekong inflow* is considerably higher than in the *All gates open* scenario, which results in a much lower *Water salinity*. Subsequently, aquaculture production reaches between 25,000 and 81,000 t/year for the 2001–2004 period (*Baseline* +80%). Because of higher *Marine inflow* and *Water salinity* levels, rice production decreases by 10% to 270,000–360,000 t/year. *Household income* increases from US$1800/household/year to US$2800/household/year (*Baseline* +50%), while almost holding *Food security* and *Environment* in the province at the same level as the *Baseline* scenario.

All gates closed

When all sluice gates are closed, *Marine inflow* is very low, whereas *Mekong inflow* is high. This holds *Water salinity* very low, but at the same time causes problems with increased *Water acidity* and *Water pollution*. The lack of *Marine inflow* results in aquaculture production sinking by 100% to 7000–23,000 t/year for the 2001–2004 period. At the same time, rice production increases by only 15% to 350,000–460,000 t/year, reflecting problems caused by extensive acidity. In this scenario, the low production intensities cause the least damage to the environment, but *Household income* decreases significantly to US$500/household/year, which is not even balanced by a significant increase in *Food security*. Omission of open-access fish catches in provincial statistics, i.e. self-consumed fish production, is demonstrated by a −555 t result in terms of aquaculture production. This also illustrates that yield probabilities are indicative rather than definite.

Shrimp versus rice versus fish

The government agenda of creating a regional ‘rice bowl’ by closing all sluice gates to suppress saline intrusion and favour rice production is impractical and does not benefit production, the people or the environment, as demonstrated by the *All gates closed* scenario. On the other hand, shrimp production is risky as it is susceptible to sudden failure because of shrimp diseases (Luttrell, 2006; Dung *et al*., 2009). In addition, intensive shrimp cultivation is detrimental to the environment, similar to intensive rice cultivation. Overall, it is clear that the shift from extensive to intensive systems brings trade-offs between economic benefit and environmental and social impacts (Gowing *et al*., 2006a). Hossain *et al*. (2006) point out that shrimp provides more postharvest employment opportunities than rice, which can contribute to poverty reduction and increased income at the provincial level. Fluctuating market prices of shrimp, however, introduce uncertainty in postharvest employment and the market price of shrimp is more volatile than that of rice (Hossain *et al*., 2006). However, 2008 saw a sharp increase in rice prices over a short period, which was not reflected in this model as it was designed and calibrated earlier on. Actually, economic sustainability can be improved by adopting a combined shrimp–rice cultivation system, which is possible under a *Lang Tram gate open* scenario. Indeed, ‘even if the relative price of shrimp had declined by 50% from

Table 10.3. Predictions of the model for the fish component. Results in probability units varying between 0 and 100%.

Model output	State	Baseline	All open	LT open	LT and HP open	All closed
Water quality for estuarine fish	Good	52.7	66	60.6	63.8	39.6
Water quality for freshwater fish	Good	23.7	13.8	21.4	17.6	33.4
Estuarine fish	Good	43.2	68.5	63.8	67.8	14.9
Freshwater fish	Good	26.8	12.8	26.6	20.1	37.1
Wild fish	Good	41.4	62.3	59.7	62.5	26.4
Fish aquaculture	Good	48.2	52.6	50.8	51.9	43.8
Fish production	Good	43.7	59	56.7	58.9	26.4

the level of 2001, the rice–shrimp system would remain more profitable than the intensive rice production system' (Hossain *et al.*, 2006, p. 42).

From an aquatic resources viewpoint, 'Fish have always been abundant and are considered a commodity, like water and air, that will always be there, but there is evidence that changes within the protected area have had an impact on fishery resources' (Gowing *et al.*, 2006b, p. 59). It is clear from the *All gates closed* scenario (Table 10.3) that the sluice gates have a significant impact on fish production in the province. Direct impacts include acting as a barrier to fish movements and indirect impacts such as altering *Mekong inflow* and *Marine inflow* and subsequently affecting salinity levels. Fish production is currently dominated by larger and more abundant estuarine fish species (Baran *et al.*, 2007) and the *All gates closed* scenario practically eradicates them from the canals. Fish production in estuarine systems is always higher than in freshwater systems because of the incursion of marine species and of the high productivity of robust permanent estuarine species, as opposed to the lower overall productivity of temporary freshwater species (Baran, 2000); thus, the water management option of closing gates to estuarine species results in a substantial overall loss of aquatic productivity. Fish make an important contribution to food security since they are an open-access resource. Open-access resources are essential in providing income and sustenance for the poor for whom aquaculture is not an accessible livelihood option (Gowing *et al.*, 2006b; Hossain *et al.*, 2006; Luttrell, 2006). The *All gates open* scenario results in the highest fish production, but there is actually little difference with *Lang Tram open* and *Lang Tram and Ho Phong open* scenarios because of trade-offs between fish aquaculture production and estuarine fish input. In terms of fisheries production, and thus in terms of food security, these two latter scenarios are quite acceptable.

Conclusion

Analysis of the scenario results clearly shows that neither *All gates open* nor *All gates closed* are a desirable operation mode (Fig. 10.5). The *All gates closed* scenario devastates aquaculture production, while not providing added benefits (in particular no significant increase in rice production), and it also decreases overall water quality. On the other hand, the *All gates open* scenario affects *Food security* seriously through reduced rice production, while encouraging unsustainable and environmentally damaging intensive shrimp aquaculture. Even though the *All gates open* scenario seems to provide the best household income, it causes increased reliance on monoculture.

Of the four scenarios tested here, *Lang Tram open* and *Lang Tram and Ho Phong open* seem to offer the best potential for the province, with significant improvements from the *Baseline* scenario in terms of aquaculture production and household income. In addition, *Lang Tram open* increases *Food security* and *Environment* outputs, whereas the *Lang Tram and Ho Phong open* scenario shows a marginal decrease in both compared to the *Baseline* scenario. Overall, *Lang Tram open* provides a more balanced approach, with a moderate increase in household income and aquaculture, yet providing a small increase in rice production

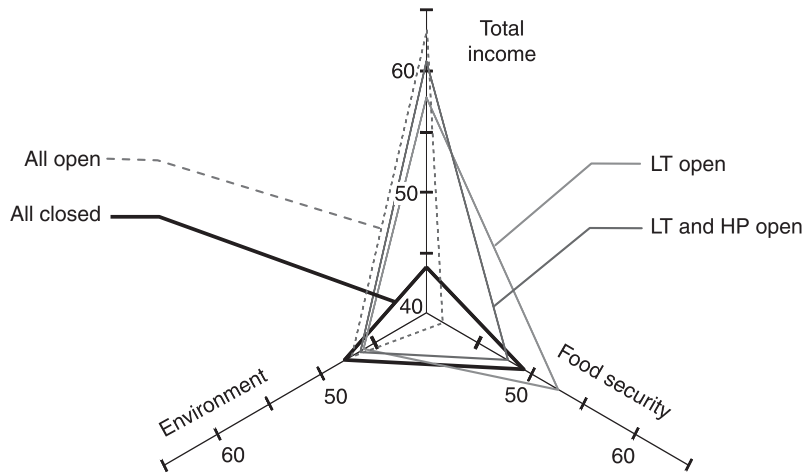

Fig. 10.5. Star graph comparing the outcomes of four sluice gate management scenarios in terms of income, food security and environment. Results in probability units varying between 0 and 100%.

as well. Moreover, it allows both freshwater and estuarine fish to prosper in the canals, when *Lang Tram and Ho Phong open* causes a decrease in freshwater fish production.

Based on the results of this study, the opening of *Lang Tram* sluice gate is seen as the optimum choice in the current circumstances. This confirms that the change in sluice gate operation mode that took place from 2001 to 2004 has been positive. However, given the dynamics of change in Bac Lieu Province, it is recommended that planning is not undertaken more than 3 years in advance.

As a tool allowing the integration of expert knowledge, databases and model output data, BayFish–Bac Lieu has proved to be a useful platform, illustrating the usefulness of a Bayesian approach in planning and managing natural resources. The qualities and shortcomings of this approach have been detailed in Baran *et al.* (2006). From a local management perspective, the current model is constrained by its broad scope and could be refined by: (i) a division into smaller unit models to reflect the characteristics of each area better; (ii) using daily and/or weekly input data instead of the current monthly input data, in particular for water quality; and (iii) analysing temporal issues on the basis of a lunar calendar to reflect tidal influence better, which is crucial in this region.

Another major improvement would be the development of detailed scenarios focusing on the opening and closure schedule of Lam Than and Ho Phong sluice gates. However, Bayesian networks do not accommodate iterations and thus should not be expected to model dynamic processes at small temporal scales. Nevertheless, unlike dynamic environmental models, Bayesian networks allow the analysis of the consequences of sluice gate management to encompass income, food security or environmental dimensions. In conclusion, the modelling approach presented also highlights trade-offs between management outcomes, highlighting the need for clear identification of the political choices driving environmental management.

References

Baran, E. (2000) Biodiversity of estuarine fish faunas in West Africa. *NAGA* 23(4), 4–9.

Baran, E., Jantunen, T. and Chheng, P. (2006) Developing a consultative Bayesian model for integrated management of aquatic resources: an inland coastal zone case study. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones*. CAB International, Wallingford, UK.

Baran, E., Chheng, P., Warry, F., Vo, T.T., Ha, P.H. and Hoanh, C.T. (2007) Aquatic resources and environmental variability in Bac Lieu Province (Southern Vietnam). Final report of the Coastal Lands Challenge Program Project No 10 Managing Water and Land Resources for Sustainable Livelihoods at the Freshwater/Saline Interface in Vietnam and Bangladesh. WorldFish Center, Phnom Penh.

Cain, J. (2001) *Planning Improvements in Natural Resources Management. Guidelines for Using Bayesian Networks to Support the Planning and Management of Development Programmes in the Water Sector and Beyond*. Centre for Ecology and Hydrology (CEH), Wallingford, UK.

Charniak, E. (1991) Bayesian networks without tears. *Artificial Intelligence* 12(4), 50–63 (http://www-psych.stanford.edu/~jbt/224/Charniak_91.pdf, accessed 31 August 2009).

Dung, L.C., Hoanh, C.T., Le Page, C., Bousquet, F. and Gajaseni, N. (2009) Facilitating dialogue between aquaculture and agriculture: lessons from role-playing games with farmers in the Mekong Delta, Vietnam. Water Policy, Special Issues on Trade-off and Synergies in Water Management Across Scales. *Water Policy* 11(S1), 80–93.

Gowing, J.W., Tuong, T.P. and Hoanh, C.T. (2006a) Land and water management in coastal zone: dealing with agriculture–aquacultre–fishery conflicts. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones*. CAB International, Wallingford, UK.

Gowing, J.W., Tuong, T.P., Hoanh, C.T. and Khiem, N.T. (2006b) Social and environmental impact of rapid change in the coastal zone of Vietnam: an assessment of sustainability issues. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones*. CAB International, Wallingford, UK.

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. PhD thesis, Wageningen Agricultural University and International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, the Netherlands.

Hossain, M., Ut, T.T. and Bose, M.L. (2006) Livelihood systems and dynamics of poverty in a coastal province of Vietnam. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones*. CAB International, Wallingford, UK.

Jantunen, T., Baran, E., Chheng, P., Warry, F., Hoanh, C.T. and Binh, N.T. (2007) Sluice gate operation, outcomes and trade-offs: BayFish–Bac Lieu, a model for integrated management of inland coastal resources in southern Vietnam. Final report. CGIAR Water and Food Challenge Program Project PN 10 Managing Water and Land Resources for Sustainable Livelihoods at the Interface Between Fresh and Saline Water Environments in Vietnam and Bangladesh. WorldFish Center, Phnom Penh.

Jensen, F.V. (1996) *An Introduction to Bayesian Networks*. UCL Press, London.

Luttrell, C. (2006) Adapting to aquaculture in Vietnam: securing livelihoods in a context of change in two coastal communites. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones*. CAB International, Wallingford, UK.

11 Soil Characteristics of Saline and Non-saline Deltas of Bangladesh

M.A. Saleque,[1] M.K. Uddin,[2] M.A. Salam,[2] A.M. Ismail[3] and S.M. Haefele[3]
[1]Bangladesh Rice Research Institute Regional Station, Barisal, Bangladesh; email: asaleque_brri@yahoo.com; [2]Bangladesh Rice Research Institute (BRRI), Gazipur, Bangladesh; [3]International Rice Research Institute (IRRI), Metro Manila, Philippines

Abstract
The delta soils of Bangladesh occur in the coastal region of the Ganges tidal flood plain, the young Meghna estuarine flood plain, the old Meghna estuarine flood plain and the Chittagong coastal plains. Although delta soils constitute some of the most productive lands of the country, their characterization has received little attention, often because of limited accessibility. However, this information is necessary to maximize their use for agriculture to enhance national food security. Soil characteristics of farmers' fields from saline and non-saline delta zones were evaluated to understand their soil fertility status, salt content and distribution in these soils and their potential for the cultivation of modern rice varieties. Electrical conductivity in the saturation extract of the topsoil in the saline zone varied from 1 to 20 dS/m, whereas it ranged from 0.7 to 1.6 dS/m in the non-saline zone. The pH of these coastal soils ranged from moderately acidic to mildly alkaline (5.8–7.8) and soil organic matter varied between 1.2 and 3.6%. The tested soils had a wide range of available phosphorus (2–59 mg/kg) and exchangeable potassium varied from 0.2 cmol/kg to as high as 2.5 cmol/kg soil. Across the soils, potassium saturation was always higher than 2% of the base saturation. Soil analysis indicated widespread zinc deficiency (less than 2 ppm available Zn) in coastal delta soils. Wet-season rice is grown in most of the saline and non-saline areas and, given the moderate percolation rate of these soils and availability of good-quality river water in most of these coastal areas, the land is suitable for rice cultivation. Recently developed salt-tolerant rice varieties (BRRI dhan 40 and BRRI dhan 41 for the wet season; BRRI dhan 47 for the dry season) should be evaluated in these delta areas to replace the currently grown landraces with low productivity, and packages of proper crop and nutrient management options for these modern rice varieties need to be established.

Introduction

Deltas are depositional bodies that form at the point where a river empties into a lake or the sea. The combined actions of river and marine processes determine whether a depositional body can form at the mouth of a river and what kind of body will form. If the rate of sediment input from the river exceeds marine sediment redistribution, the depositional sequence will progress seaward to form a delta. The delta of the Ganges–Brahmaputra river system in Bangladesh is a tide-dominated delta plain. In Bangladesh, about 30% of the net cultivable area (9.5 million ha) lies in the coastal zone. Coastal soils are in a state of disequilibrium with the physical environment because of the destructive, transportive and constructive activities of waves, tides, currents, rivers and winds acting throughout the year. Many of the coastal lands are subjected to detrimental river erosion, while others experience continuous sedimentation.

The coastal lands of Bangladesh are categorized into highlands (≤0.5 m flood depth), medium highlands (≤0.9 m flood depth), medium lowlands (0.9–1.8 m flood depth) and lowlands (1.8–3.0 m flood depth). Highlands

 Tropical Deltas and Coastal Zones: Food Production, Communities and Environment at the Land–Water Interface (eds C.T. Hoanh *et al.*)