Spatial modelling for optimisation of bivalve culture: A case study for Green Mussel (*Perna viridis*) and Blood Cockle (*Anadara granosa*) culture in Pattani Bay, Thailand.

A Thesis Submitted to the University of Stirling

For the degree of Doctor of Philosophy

By

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Statement of Originality

I hereby confirm that this is an original piece of work conducted independently by the undersigned and all work contained here has not been submitted for any other degree.

All research material has been duly acknowledge and cited

Signature of Candidate

Supat Khongpuang

Date: 30 September 2011

Abstract

This study focused on (1) Green mussel (*Perna viridis*) growth determination and harvestable area models and (2) optimisation model for cockle (*Anadara granosa*) culture in Pattani Bay, Thailand. The main objectives of this study are:

(a) Development of a mussel growth determination model,
(b) Development of a harvestable area model for mussels,
(c) Development of a suitable area model for cockle farming.

Four main, geo-referenced input data sets were developed, comprising (1) water quality parameters, (2) sediment quality parameters, (3) empirical mussel growth and (4) secondary data related to the target species and the bay ecology including satellite images of study area were employed. Data on twelve water quality parameters and four sediment parameters were collected in the field between June 2009 and February 2010 while mussel growth data was collected between June and September 2009.

Different combinations of data from these groups were managed and manipulated within the IDRISI™ environment to address the different study objectives and to formulate databases, analyse data, and develop and illustrate spatial models. The main output models of the study were (1) mussel growth determination models, (2) suitable mussel culture and harvestable area models and (3) models for optimisation of suitable cockle culture area.

Principal Component Analysis (PCA) and Multiple Linear Regressions (MLR) were employed to determine optimised conditions for mussel growth determination. The main determinants for mussel growth were particulate organic matter (POM), chlorophyll-a and salinity. All three together can predict 85.2% of mussel growth while chlorophyll-a and salinity could predict 84.9% and salinity alone could predict 83.4% of observed mussel growth.

The optimum suitable area for mussel farming was estimated using overlaying techniques to combine three main components comprising salinity, water depth and shipping route. Of the 58 km^2 of the total water space in the bay, a potential optimised

area for mussel farming of 13 km^2 was found. The remaining area was limited for culture due to low salinity, inadequate water depth and presence of shipping routes. Based on the empirical growth function of mussel, the mussel harvestable areas were projected and illustrated periodically. The harvest period of mussel within the potential culture site extends over 2 months. The spatial analysis showed that <50% of the current mussel culture operations within the bay are located within the optimal area and the models also identified >12.5 km^2 that could be developed further.

The suitable cockle farming area was estimated using a Multi-Criteria Evaluation (MCE) approach based on sediment and water factors reclassified as a fuzzy data set. The maximum water surface area suitable for cockle culture was 48 km^2, but this decreased to around 13 km^2 when water depth, water current and sediment suitability were taken into account. The overall suitable cockle culture area was found in the middle part of the bay and approximately 75% (10.4 km^2) of existing cockle farms were locate in this area. The remaining existing farms were in more vulnerable areas which experienced low salinity, low pH and high water current. It was noted that relocation of cockle culture areas in the bay is technically feasible and could be considered in future management plans.

Suitable site selection and management is very important for an unfed culture system. This study indicates the usefulness of GIS technology for spatial planning and area optimization for mollusc culture in the study area. The study results also provide supportive information for spatial management of the bay aimed at sustainable resource use. Not only in the Pattani Bay, the same study protocols could be applied for the others bays, potential coastal culture sites in Thailand and other tropical countries.

Acknowledgement

It is a pleasure to thank my supervisors; Prof. Lindsay G. Ross and Dr. Trevor Telfer, for their useful suggestion, comment, criticism and valuable help during study and writing up periods. I also appreciate my examiners; Prof. Aas Smaal and Prof. Dave Little, for their additional suggestion to fulfil my thesis content.

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Importantly, this thesis would not be possible unless my parents, sisters, brothers and teachers who give me the moral support consistently.

LIST OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

Chapter 1
Introduction

1.1 World fisheries and aquaculture

The fishery and aquaculture sector is of importance to local and national communities, not only as a human food source but also by creating income and generating employment through the actual activity and ancillary services, such as fish processing and trading. Particularly, the employment rate generated by the fishery sector is higher than that of traditional agriculture and the global population growth. At the national level, the fishery sector can also generate foreign currency earnings. In 2008, Asian countries accounted for 85.5% of global fishers and fish farmers. The rest were from Africa (9.3%), Latin America and the Caribbean (2.9%), Europe (1.4%), North America (0.7%) and Oceania (0.1%) (FAO, 2011). Globally, approximately 142.3 million tonnes of fishery production was reported in 2008 while that in 2004 was 134.3 million tonnes. Production in 2008 comprised 52.5 and 89.7 million tonnes from aquaculture and capture sectors, respectively (or 99.2 and 43.1 million tonnes from marine and inland sectors). Of all fishery production, seafood for human consumption increased from 104.4 million tonnes in 2004 to 115.1 million tonnes in 2008 while the global population increased from 6.4 to 6.8 billion. Per capita food fish also increased from 16.2 to 17.1 kg. In contrast to all previous indicators, non-food use of fish decreased from 29.8 million to 27.2 million tonnes (FAO, 2011). In 2007, fish contributed 15.7% of the total animal protein or 6.1% of the animal protein consumed by world population.

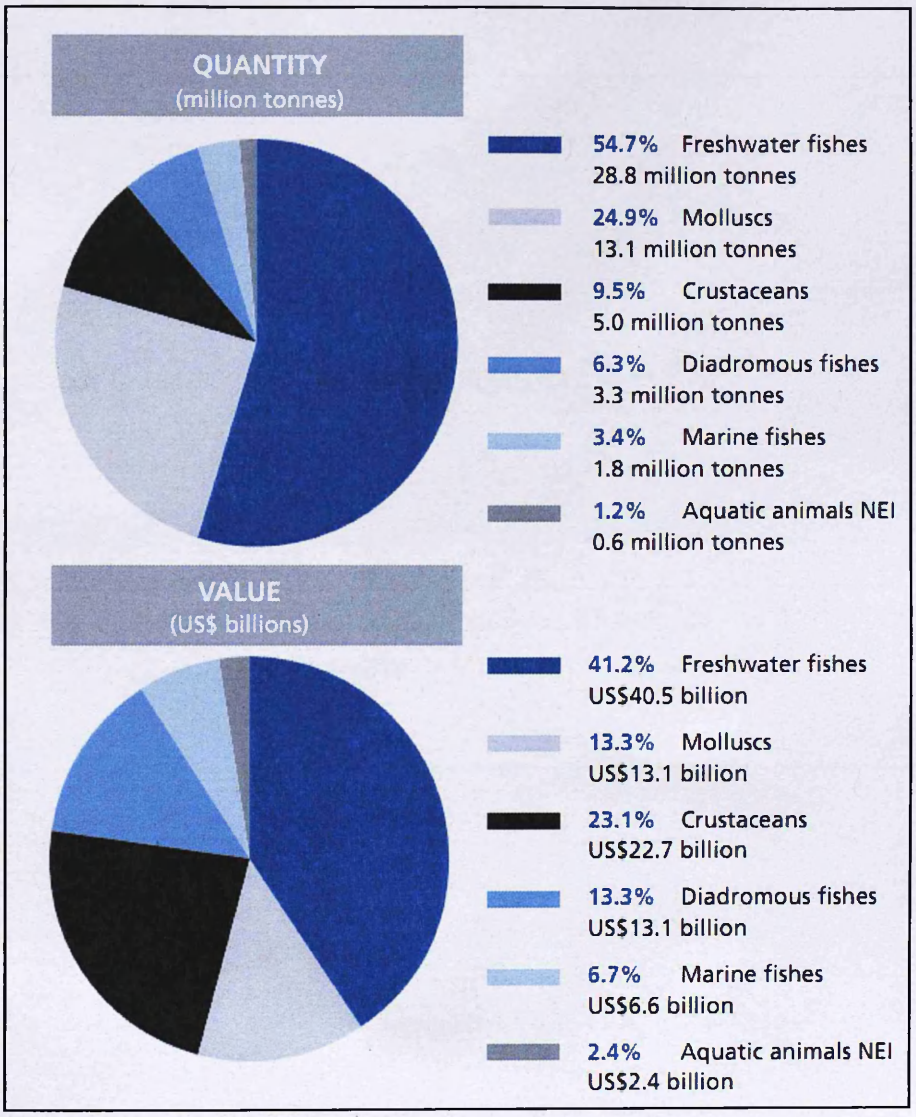
As world fisheries are under pressure and declining, aquaculture is the only possible way to increase seafood supply (Gibbs, 2004; Dumbauld, Ruesink, & Rumrill, 2009). The sector maintains fast-growing animal food production and *per capita* supply has increased from 0.7 kg in 1970 to 7.8 kg in 2008. Its average annual growth rate is 6.6% while that of food fish production and world population are 8.3% (6.3% excluding China) and 1.6%, respectively. In the last 50 years, world aquaculture products have increased from <1 million tonnes in 1950 to 52.2 million tonnes in 2008 or three times higher than that of meat production. Global aquaculture production excluding plants in 2000 was 32.4 million tonnes while in 2008 it had reached 52.5 million tonnes. As a result, the contribution of this sector to the global seafood consumption has increased from 33.80% to 45.70%. The percentage contribution is projected to be 50% by the year 2012 (FAO, 2011). The total value of aquaculture excluding plants in 2008 was 98.4 billion USD. Production quantity and value are shown in Fig. 1.1. Of all major species in terms of production quantity molluscs are the second largest next to freshwater fish species (Fig. 1.2). From around 1987 onwards, the production of molluscs and diadromous fish species contribute almost similar percentage to the total world aquaculture product including aquatic plants (Fig. 1.3) (FAO, 2011). The production of cultured molluscs has increased fourfold in the last 15 years (Berthou, Goulletquer, & Dao, 2011)

Table 1.1. World fisheries and aquaculture production and utilisation.

	2004	2005	2006	2007	2008	2009
	(Million tonnes)					
PRODUCTION						
INLAND						
Capture	8.6	9.4	9.8	10.0	10.2	10.1
Aquaculture	25.2	26.8	28.7	30.7	32.9	35.0
Total inland	**33.8**	**36.2**	**38.5**	**40.6**	**43.1**	**45.1**
MARINE						
Capture	83.8	82.7	80.0	79.9	79.5	79.9
Aquaculture	16.7	17.5	18.6	19.2	19.7	20.1
Total marine	**100.5**	**100.1**	**98.6**	**99.2**	**99.2**	**100.0**
TOTAL CAPTURE	**92.4**	**92.1**	**89.7**	**89.9**	**89.7**	**90.0**
TOTAL AQUACULTURE	**41.9**	**44.3**	**47.4**	**49.9**	**52.5**	**55.1**
TOTAL WORLD FISHERIES	**134.3**	**136.4**	**137.1**	**139.8**	**142.3**	**145.1**
UTILIZATION						
Human consumption	104.4	107.3	110.7	112.7	115.1	117.8
Non-food uses	29.8	29.1	26.3	27.1	27.2	27.3
Population (*billions*)	6.4	6.5	6.6	6.7	6.8	6.8
Per capita food fish supply (*kg*)	16.2	16.5	16.8	16.9	17.1	17.2

Note: Aquatic plants are excluded whilst the data for 2009 is based on projected estimates.

Source: FAO (2011).



NEI = not elsewhere included.

Fig. 1.1. World production in 2008 by quantity and value based on major species. Source: FAO (2011).

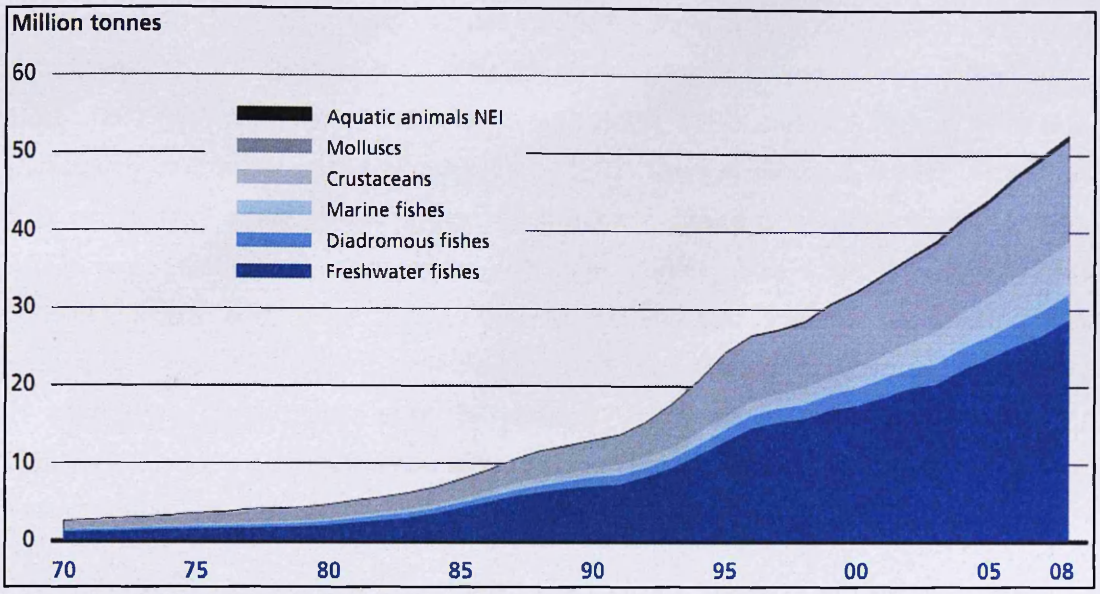


Fig. 1.2. World aquaculture production trends by major species 1970-2008.
Source: FAO (2011).

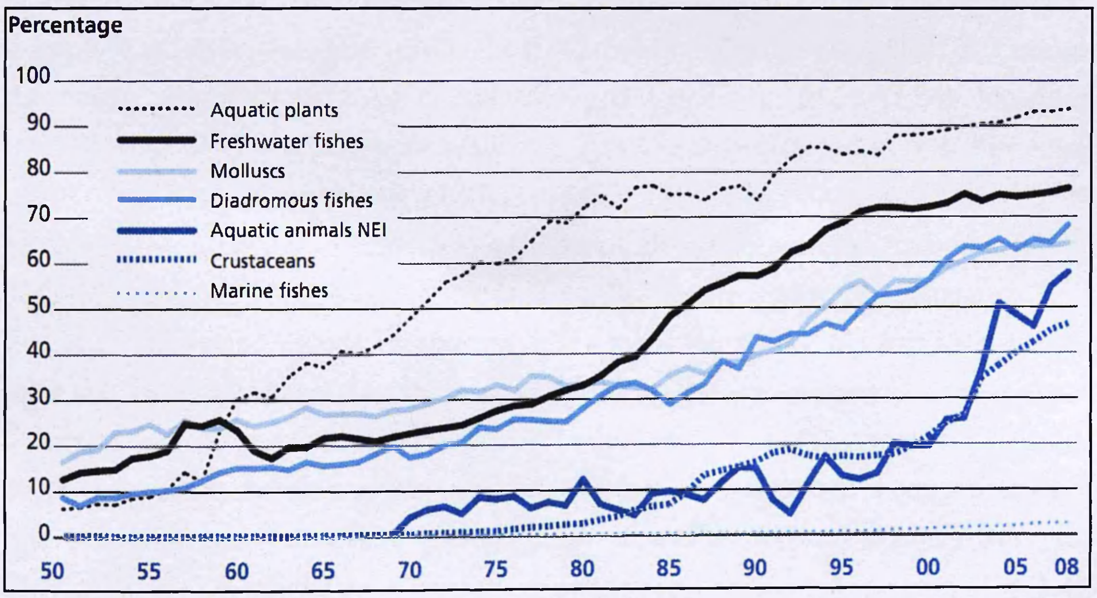


Fig. 1.3. Contribution to world aquaculture products by major species 1950-2008.
Source: FAO (2011).

Among the various aquatic species that are cultured, bivalve molluscs, such as mussels and cockles (Vakily, 1989; Rajagopal, Venugopalan, van der Velge, & Jenner, 2006b), are an excellent choice to promote because they rely mainly on natural food sources such as phytoplankton, microzooplankton and suspended organic matter

(Grant, 1996; Gibbs, 2007; Berthou *et al.*, 2011), withstand environmental fluctuation (Rajagopal, Venugopalan, Nair, van der Velde, & Jenner, 1998a; Shin, Yau, Chow, Tai, & Cheung, 2002; Rajagopal *et al.*, 2006b), have high growth and survival rate (Zhong-Qing, 1982; Navakalomana, 1982; Davy & Graham, 1982),and high reproductive rate, particularly in tropical zones (Zhong-Qing, 1982; Davy & Graham, 1982). Moreover, they are a most effective way to convert organic matter into valuable food (Korringa, 1979) and provide an inexpensive and high protein food source (Vakily, 1989). Globally, there are more than 1,500 edible mollusc species, comprising 720 gastropods and 790 bivalves, collected for food. 128 species of those are considered of commercial importance while 64 species are used in culture. In addition to commercial aspects, molluscs are also of importance to local people in terms of food security (Berthou *et al.*, 2011).

1.2 Fishery and aquaculture production in Thailand

Thailand is ranked in the top ten of the world's fishing nations with a yearly production of approximately 2.0 million tonnes (Yashiro, 2008) and is ranked third as an exporter in terms of quantity and value (FAO, 2011). The marine capture production of Thailand decreased sharply from 2004 (2,636 thousand tonnes) to 2008 (1,645 thousand tonnes) while coastal aquaculture production has increased (Department of Fisheries, 2010). The Royal Government of Thailand has promoted fishery development, as stated in The 5th National Economic and Social Development Plan, over the period 1982-86 (Saraya, 1982; Yashiro, 2008). Total fishery production of Thailand in 2008 was 3,204 thousand tonnes comprising 1,331 thousand and 1,873 thousand tonnes from culture and capture sectors, respectively. Coastal aquaculture contributed 808 thousand tonnes and inland aquaculture contributed 522.5 thousand tonnes. For capture fisheries, the main contributor was marine capture (1,645 thousand tonnes) with the remainder from inland sources (229 thousand tonnes) (Fishery Statistics Division, 2008). The percentage contributions to total product are illustrated in Fig. 1.4.

For many years, Thailand has generated a financial surplus from the import and export of fishery products. This surplus increased from 34,638 million THB in 1989 to 147,089 million THB in 2008 based on exported quantities of 875,293 and 1,907,056 tonnes, respectively (Fishery Statistics Division, 2008).

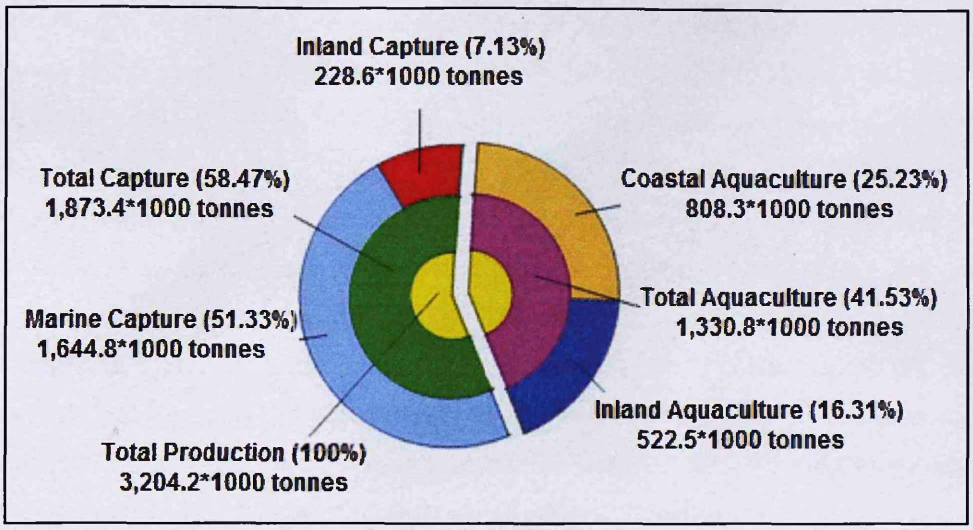


Fig. 1.4. Fisheries production in 2008 in quantity by sub-sectors.
Source: Reproduced from the Fishery Statistics Division (2008).

1.2.1 Coastal aquaculture

Coastal aquaculture in Thailand has long been established but the most significant development began 50 years ago, where over the period 1969 and 1976, when there was success in the mass production of marine shrimp (banana shrimp, *Penaeus merguiensis* and black tiger shrimp, *P. monodon*) and Asian seabass (*Lates calcarifer*). Currently, there are 19 Coastal Fishery Research and Development Centers (CFRDC), three Coastal Aquaculture Research and Development Stations (CARDS) and 24 Provincial Fisheries Offices (PFO) in 24 coastal provinces. These organisations are responsible for coastal aquaculture and enforce the fisheries laws and regulations. The national policy on aquaculture is summarised as follows (Yashiro, 2008).

- Increase aquaculture production sufficiently in both quantity and quality for domestic consumption and export;
- Accelerate research for supporting commercial aquaculture industries to increase trade volume, improve quality standards and reduce production costs;
- Develop sustainable marine shrimp culture systems for domestic trade as well as for export; and
- Develop the production and marketing of ornamental fish and aquatic plants for export to increase the income from aquaculture.

Geographically, Thailand has a total coastline of 2.6 thousand kilometers, with 1,875 kilometers along the Gulf of Thailand from the Province of Trat to Narathiwat provinces (Fig. 1.5) and the remaining 894 kilometers along the Andaman Sea coast, from the Province of Satun to Trang (Saraya, 1982; Yashiro, 2008). The area of intertidal flats within 2 km width from the shoreline covers approximately $5.2*10^5$ ha (3.26 million rai) and is considered as an area for potential mollusc, fish-cage and shrimp-pen culture. Additionally, abandoned mangrove areas of around $3.0*10^5$ ha could be used for shrimp and fish pond culture (Saraya, 1982). In 1988, a holistic report on mollusc culture was produced and the potential national area for mollusc culture was roughly evaluated. The potential area for oyster culture was 35,933 ha and there was an existing farmed area of 7,046 ha. In Pattani, an existing farm area of 200 ha and a potential culture area of 2,500 ha were reported (Brohmanonda, Mutarasint, Chongpeepien, & Amornjaruchit, 1988a). For cockle culture, the existing area was 8,876 ha while the potential area was 63,036 ha with no specific data for Pattani Province (Tookwinas, 1983).

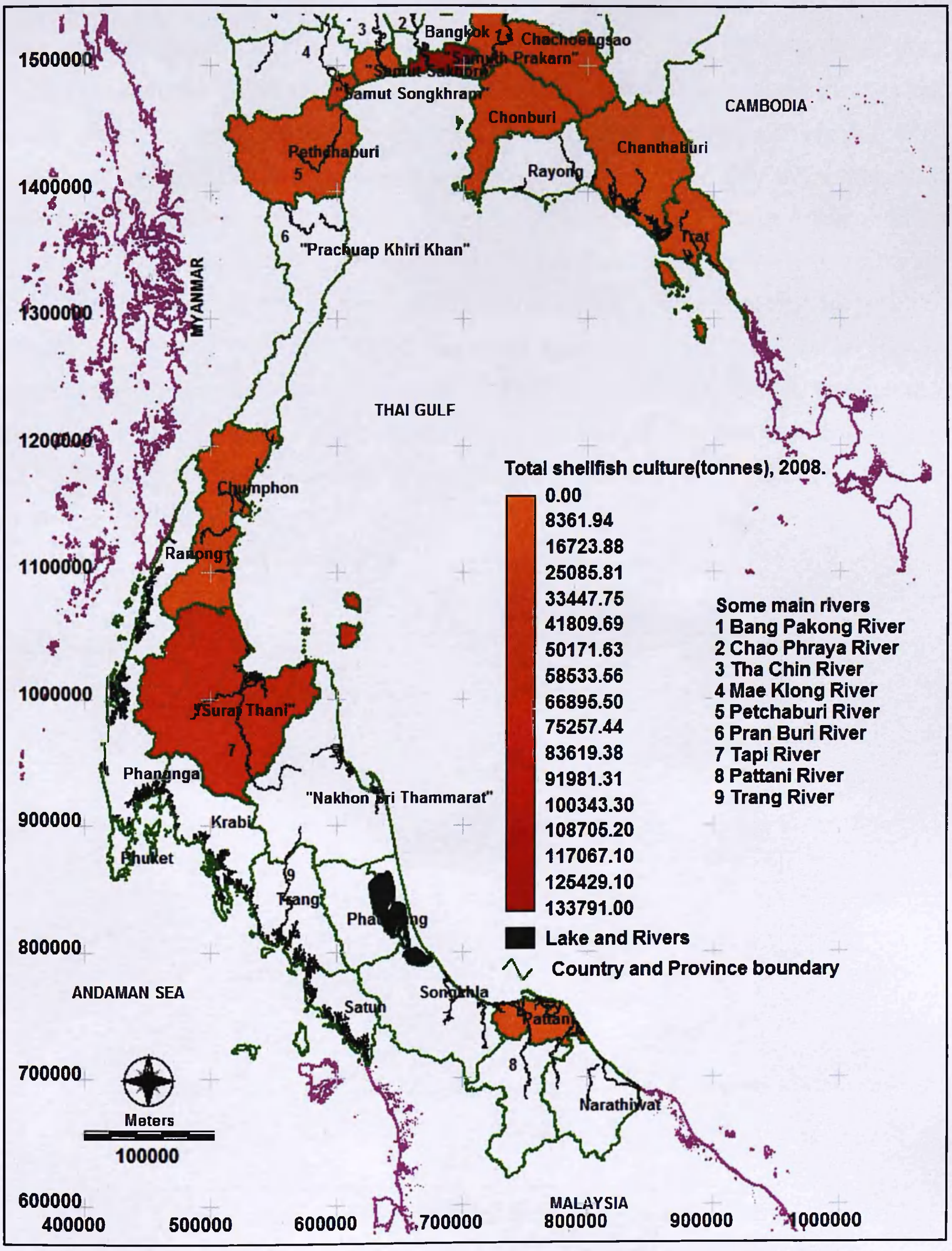


Fig. 1.5. Coastal provinces of Thailand highting the main area of shellfish culture in 2008.

Source: Based on data provided by Chalermwat *et al.* (2003) and the Fishery Statistics Division (2008).

Quantitatively, total coastal aquaculture production between 1981 and 1987 was fairly stable; however from 1988 to 2007, it steadily increased. Shrimp is the most important contributor, followed by shellfish and fish, respectively. Shrimp culture has long been the main contributor since 1988, except for 2002 and 2003, when shellfish fluctuated, and then gradually increased from 1981 to 2000. The sharp increase in the shellfish sector started in 2000, reaching a peak in 2002 and then slightly declining until 2007 (Fig. 1.6). The considerable change in shellfish production in the year 2001 was partly because of the inclusion of mussel production from bamboo stake traps (Fishery Statistics Division, 2007a; Fishery Statistics Division, 2007b; Department of Fisheries, 2010). Total coastal aquaculture production increased exponentially from 67.50 thousand tonnes in 1981 to 845.30 thousand tonnes in 2007 (Table 1.2) with an average rate of increase of approximately 12.72% *per annum*. In 2008, total coastal aquaculture decreased to 808.4 thousand tonnes, of which 2% was from fish culture, 62.7% from shrimp culture and 35.3% from shellfish culture (Fig. 1.7) (Department of Fisheries, 2010).

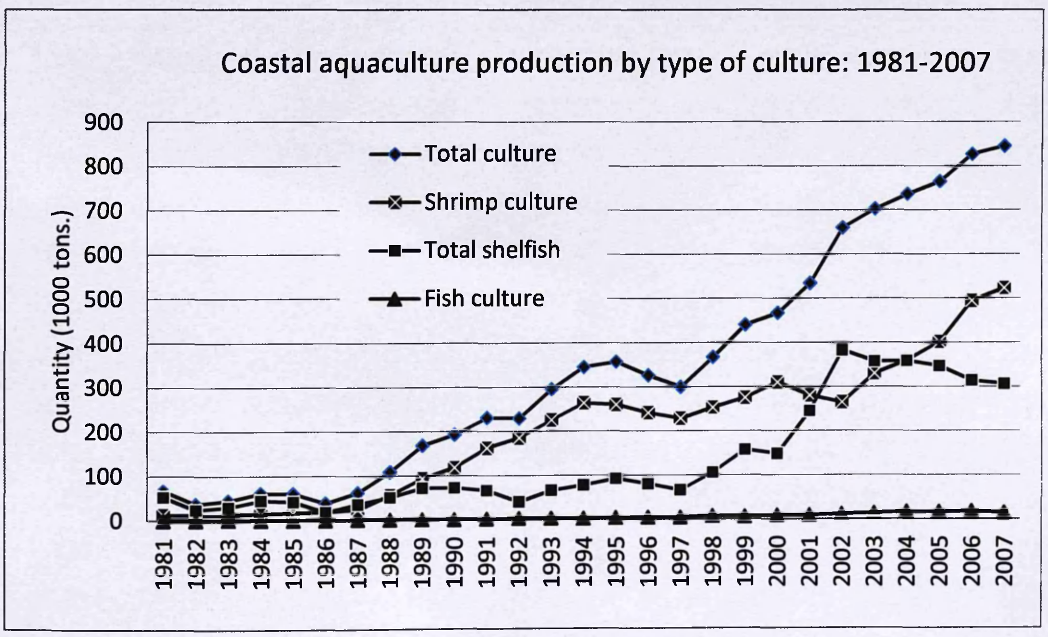


Fig. 1.6. Annual coastal aquaculture production by type, 1981-2007.

Source: Based on data provided by the Fishery Statistics Division (2007b).

Table 1.2. Yield from coastal aquaculture by type of culture 1981-2007.

Quantity: 10^3 tonnes.

Year	Total culture	Fish	Shrimp	Total shellfish	Cockle	Mussel	Oyster	Horse mussel
1981	67.50	0.20	13.60	53.70	8.20	36.60	7.60	1.30
1982	36.80	0.10	12.80	23.90	3.70	16.10	3.50	0.60
1983	44.70	1.20	13.70	29.80	7.10	18.70	3.40	0.60
1984	61.60	0.80	15.60	45.20	12.50	26.20	4.90	1.60
1985	60.60	0.70	17.70	42.20	12.40	25.90	3.50	0.40
1986	39.10	0.90	19.30	18.90	6.90	11.10	0.60	0.30
1987	61.80	1.50	24.50	35.80	9.60	23.90	1.50	0.80
1988	108.90	1.40	56.10	51.40	4.70	44.20	1.90	0.60
1989	168.70	1.80	94.00	72.90	12.80	58.70	1.40	0.00
1990	193.20	1.60	118.60	73.00	12.30	58.40	1.40	0.90
1991	230.40	2.00	162.10	66.30	26.40	35.50	3.30	1.10
1992	229.30	3.50	185.20	40.60	18.80	14.00	3.80	4.00
1993	295.60	3.50	225.70	66.40	20.60	24.40	17.80	3.60
1994	345.80	3.20	264.10	78.50	11.30	43.10	19.30	4.80
1995	357.50	4.50	260.20	92.80	14.40	51.20	23.00	4.20
1996	326.00	4.80	241.00	80.20	15.80	35.50	23.40	5.50
1997	299.70	4.90	228.40	66.40	8.30	43.00	15.10	0.00
1998	367.60	8.20	253.30	106.10	44.20	39.50	22.40	0.00
1999	441.10	7.20	275.70	158.20	61.70	67.30	29.20	0.00
2000	467.00	9.00	310.00	148.00	45.70	88.80	13.50	0.00
2001	534.50	9.40	280.10	245.00	75.90	148.5	20.60	0.00
2002	660.10	12.20	265.00	382.90	80.80	291.0	11.10	0.00
2003	703.30	14.60	330.80	357.90	67.40	263.9	26.60	0.00
2004	736.30	17.20	360.30	358.80	69.50	261.7	27.60	0.00
2005	764.70	16.80	401.30	346.60	56.80	270.7	19.10	0.00
2006	826.90	18.40	494.40	314.10	65.70	229.7	18.70	0.00
2007	845.30	15.40	523.40	306.50	55.60	228.3	22.60	0.00

Note: From 2001onwards, mussel production from bamboo stake traps are included.

Source: Fishery Statistics Division (2010).

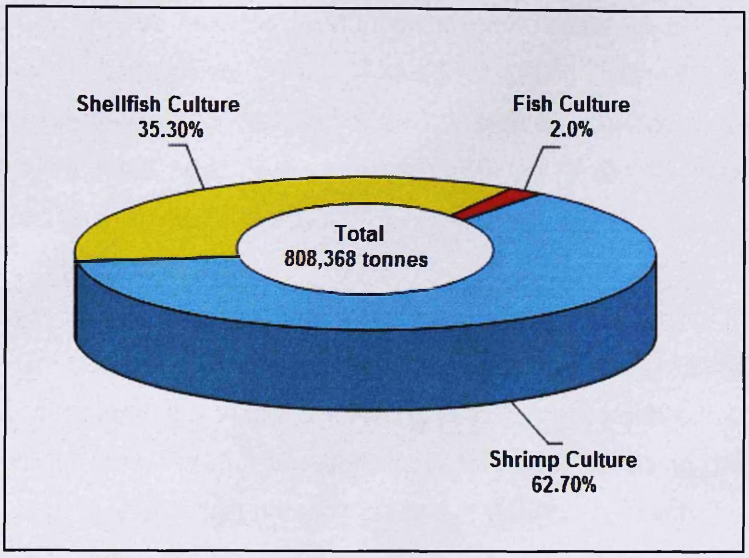


Fig. 1.7. Total volumn of aquaculture products from Thailand in 2008.
Source: Department of Fisheries (2010).

1.2.2 Mollusc culture

Mollusc culture has been practiced in Thailand for over 100 years and the culture techniques have gradually developed to become more capital intensive (Saraya, 1982). Initially, molluscs were collected from natural sources but there was then a gradual shift to the culture sector because of a reduction in natural supply (Brohmanonda *et al.*, 1988a). Thereafter, many culture techniques were developed, including pole culture, raft (hanging method), tray method and bottom culture. Many substrates, such as cement blocks, tyres, asbestos sheets, roof tiles and bricks, have been applied (Amornjaruchit, 1988; McCoy, Tuaycharoen, Vakily, & Boonchuwong, 1988). A diversification of processed mollusc products was reported (Lovatelli, 1988b), and the shellfish industry is fairly well established (Office of Agricultural Economics, 2009) as well as the relevant marketing channels (Amornjaruchit, 1988; Sahavacharin, Chindanond, Amornjaruchit, Nugranad, Silapajarn, Chawivanskorn, & Limsurat, 1988; Vakily, 1992; Chalermwat, Szuster, & Flasherty, 2003).

The main cultured bivalve species are the blood cockle (*A. granosa*), oyster (*Saccostrea calculate, Crassostrea belcheri, and C. iredalei*), the green mussel (*Perna viridis*) (Amornjaruchit, 1988) and the horse mussel (Arcuatula arcuatula), the latter being used only for animal feed. Among gastropods, only Babylonia and Abalone are reared for commercial purposes. However, 39 species of commercial mollusc are sold in the market alongside 13 other locally-consumed species (Chalermwat *et al.*, 2003).

Approximately 70% of Thai mollusc production is contributed by the culture sector (Office of Agricultural Economics, 2009). Mollusc marketing channels, structure and organisation, represented by the cockle market, are well established and cockle seed and adults have been imported to fill the domestic demand (Brohmanonda, Mutarasint, Sukwongse, & Thanakumcheep, 1988b).

Mussels are initially found in the brackish water zone at the inner part of the Thai Gulf, Chachoengsao, Chonburi and Chumphon Provinces (McCoy *et al.*, 1988). They have been collected from natural and stationary fishing gear (bamboo stake trap) until about 60 years ago whereafter, seed collection and pole culture using bamboo were developed. The rearing period (from seed) takes 6-8 months to reach the marketable size. Most production areas remain near major rivers (Bang Pakong, Chao Praya, Mae Klong and Tha Chin Rivers) , but have extended to the southern (Prachuap Khiri Khan, Surat Thani, Songkla and Pattani Provinces) because some original culture sites are effected by industrialisation and pollution (Chaitanawisuti & Menasaveta, 1987; Thamasavate, Silapajarn, Nugranad, Pattharapinyo, Sangrungruang, Limsurat, & Yangponlakan, 1988; Brohmanonda *et al.*, 1988b). Studies have been made of seed transportation (Thamasavate *et al.*, 1988; Brohmanonda *et al.*, 1988b), transplantion of cultured seed for consumption and natural productivity enhancement (McCoy *et al.*, 1988). The considerable success of transplanted seed culture makes the mussel production of Sawi Bay, Chumphon the second largest production area (by quantity) of the whole country (Tookwinas, 1983; Siripan, 2000).

Cockle culture began at least 100 years ago in Ban Laem District, Petchaburi Province, using traditional methods (Tookwinas, 1983). Due to the increased domestic demand, the culture area expanded to other areas, such as Satun, Trang, Ranong, Nakhon Sri Thammarat and Surat Thani Provinces. Initially, culture technology and seed supply was transferred from Malaysia (Hansopa, Thanormkiat, Chongpeepien, Mongkolmann, & Tuaycharoen, 1988). Farming using transplanted seed was also developed in many areas, such as, Nakhon Bay (Thamasavate *et al.*, 1988) and Sawi Bay (Brohmanonda *et al.*, 1988a), to increase the culture area and production level.

Oyster culture was established by Chinese immigrants in Chonburi, Rayong and Chanthaburi Provinces. It was then distributed to the southern provinces of Prachuap Khiri Khan, Surat Thani, Songkla and Pattani (Fishery Statistics Division, 2007a; Fishery Statistics Division, 2007b).

Mollusc production varied between 1981 and 1997 from around 20 thousand to over 100 thousand tonnes. It increased sharply to 383 thousand tonnes in 2002 and gradually decreased to 307 thousand tonnes in 2007 (Table 1.2 and Fig. 1.8). The total culture area of molluscs is 15,399 ha (96,241 rai), occupied by cockles, mussels and oyster of 11,424, 2,967 and 1,006 ha (or 71,404 18,546 and 6,291 rai), respectively. Total mollusc production in 2008 was 285,739 tonnes, contributed by cockles (65,852 tonnes), mussels (203,213 tonnes) and oysters (16,674 tonnes) while horse mussels made no contribution (Department of Fisheries, 2010).

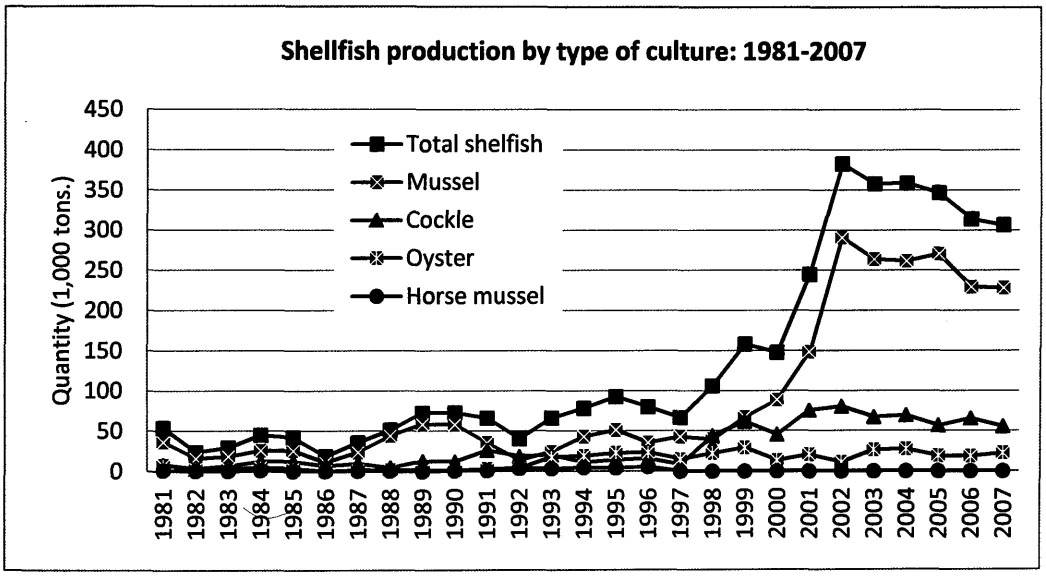


Fig. 1.8. Annual coastal aquaculture shellfish production by type, 1981-2007.

Source: Based on data provided by Fishery Statistics Division (2007b).

1.3 GIS and its application for fishery resources management

1.3.1 Definition and principle of GIS

A Geographical Information System (GIS) is a computer-assisted system for storing, capturing (acquisition), integrating, analysing and displaying geo-referenced information (Wadsworth & Treweek, 1999; Carocci, Bianchi, Eastwood, & Meaden, 2009). It comprises computer hardware, software and personnel. The hardware (or physical component) is the central processing unit, mass storage, wide area network LAN/WAN), and data input units (digitiser, mouse, keyboard, and other mobile devices). Personnel are normally trained in both computer science and geographical analysis skills (Wadsworth & Treweek, 1999) while the software facilitates users to capture, store, manage, manipulate, analyse and display data (Eastman, 2006a). GIS software has many components/systems (Fig. 1.9), however the database is the most important part of the system and contains two types of data, spatial and attribute data. Spatial data illustrates the shape and position of features on the Earth's surface while attribute data describes the quality (landuse, owner and property valuation) of surface features (Eastman, 2006b).

An advantage of GIS is the ability to carry out spatio-temporal analyses in various scales and resolutions. There are many kinds of input data, including maps, tables, data loggers, databases, remote sensing data and acoustic sonar. For any specific problem, area and time, various data can be an input to the system. The system itself carries many functions designed to serve the users requirements. Similar to the input, the GIS offers various types of outputs; report, maps, photographs, statistics, tabular data, GIS models, *etc*. A conceptual diagram of a GIS system, input, function and output is illustrated in Fig. 1.10.

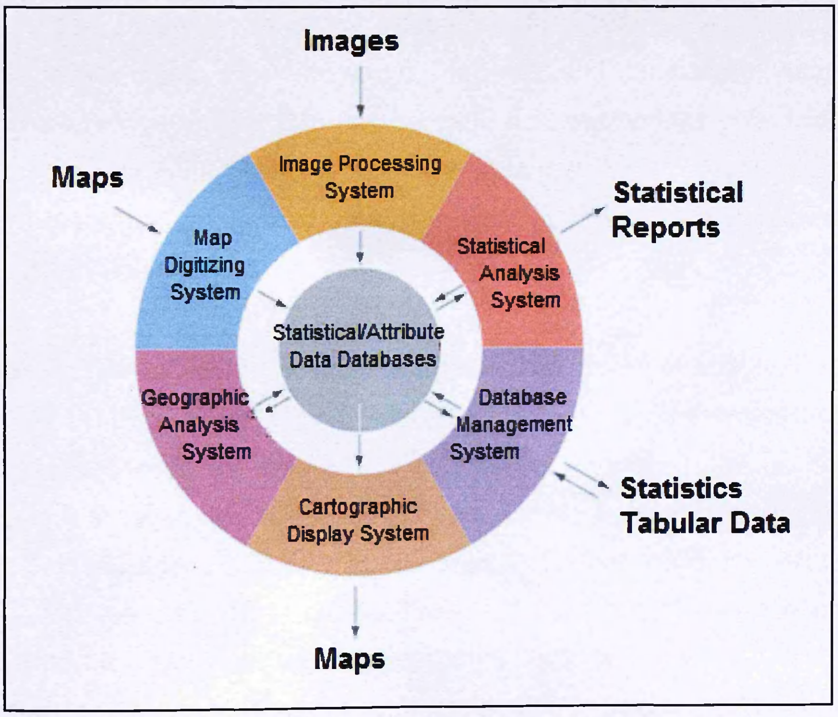


Fig. 1.9. Main components/systems of GIS software.
Source: Nath *et al.* (2000).

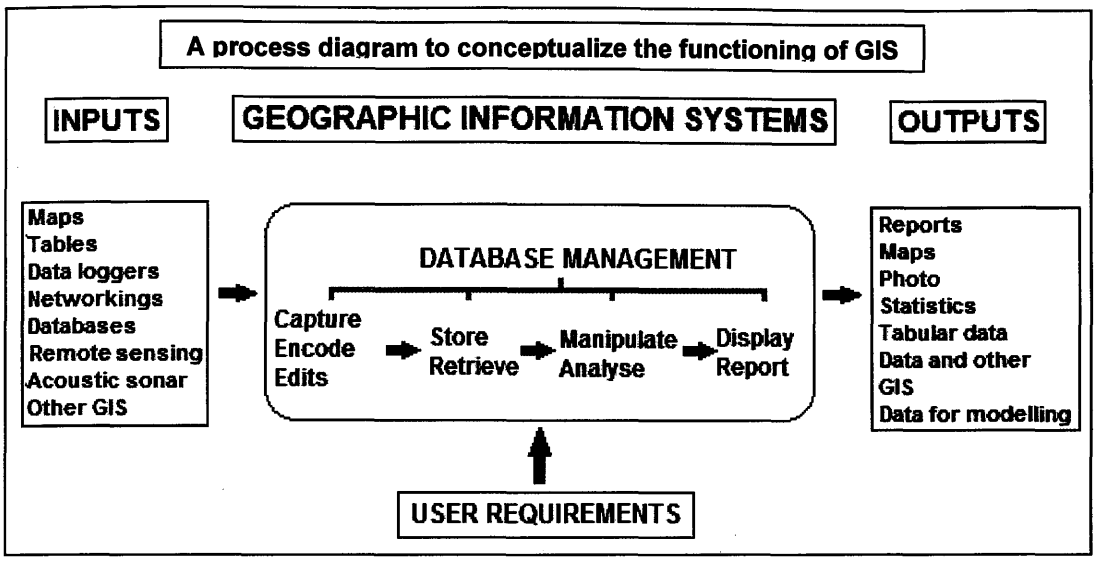


Fig. 1.10. Conceptual diagram of GIS input, functions and output.
Source: Nath *et al.* (2000).

1.3.2 GIS application for fishery resources and aquaculture

GIS has long been applied for both capture fisheries and aquaculture activities for various purposes. Based on geographical boundaries, it can be involved in local (or farm), aquaculture zone (or watershed), national and continental scales (Ross, Mendoza, & Beveridge, 1993). GIS can serve to address various objectives, such as site selection (Nath, Bolte, Ross, & Aguilar-Manjarrez, 2000), environmental impact assessment, resource use conflicts, and trade-offs and food security alleviation (see Nath *et al.*, 2000; Salam, 2000).

GIS applications in the sector include a chronological review of published documents during 1987-2000 (Kapetsky & Aguilar-Manjarrez, 2007), application for multi-sectoral planning and application for marine shellfish culture (Pérez, Telfer, & Ross, 2003; Salam, Ross, & Beveridge, 2003; Pérez, Ross, Telfer, & del Campo Barquin, 2003; Giap, Yi, & Yakupitiyage, 2005; Karthik, Saharan, & Biradar, 2005; Radiarta, Saitoh, & Miyazono, 2008; Hossain & Das, 2010). From 2000 onward, GIS has maintained an important role in fisheries and aquaculture affairs covering site selection (Anuchiracheeva, Demaine, Shivakoti, & Ruddle, 2003; Seekao, 2006; Alexandridis, Topaloglou, Lazaridou, & Zalidis, 2008), mapping (Pérez, Telfer, Beveridge, & Ross, 2002; Corner, Brooker, Telfer, & Ross, 2006; Shih, Chou, & Chiau, 2009), environmental modelling, aquaculture impact assessment (Herlyn, 2005; Vincenzi, Caramori, Rossi, & De Leo, 2006), yield/production estimation (Chakraborti, Kaur, &

DePinto, 2002), growth determination (Crawford, Commito, & Borowik, 2006; Rios-Lara, Salas, Javier, & Ayora, 2007), spatial distribution of target species (Anuchiracheeva *et al.*, 2003; Jarernpornpipat, Pedersen, Jensen, Boromthanarat, Vongvisessomjai, & Choncheanchob, 2003; Scott, 2003; Kullavanijaya, 2005; Asmah, 2008; De Freitas & Tagliani, 2009; Houssain, Chowdhury, Das, Sharifuzzaman, & Sultana, 2009), aquaculture and fishery development/management (Pillay & Kutty, 2005).

The objectives or goals of conventional aquaculture activities are varied. At the farm scale, conventionally, the objective is to maximise production or maximise profit/economic benefit while social benefits may sometimes be included. For state or national levels, the goals vary depending on the socio-economic and environmental policy in the country. As a result, the goals of aquaculture may include some of the following; self sufficiency, replacing capture production, increasing employment, foreign money earning and agro-industrial promotion (Inglis, Hayden, & Ross, 2000; McKindsey, Thetmeyer, Landry, & Silvert, 2006). In order to achieve and sustain these goals over a long term period, sustainable resource use or carrying capacity of the system must be assessed. According to Inglis *et al.* (2000), the carrying capacity (CC) comprises 4 aspects; physical, production, ecological and social aspects. These can be connected to aquaculture in the following way;

- Physical carrying capacity: Physical CC relates to size and area of marine farms that can be located within an available physical area. The area is restricted by size, geography and existing plan (navigation area and zoned area, for example), farm development requirement (water depth, distance to handling facilities, *etc*) (McKindsey *et al.*, 2006).This concept is dependent on the overlap between the requirement of each species and the physical parameters of the area *i.e.* substrate, depth, hydrodynamics, temperature. Some basic chemical parameters such as salinity and dissolved oxygen could be included, but not organo-chemical variables (particulate organic carbon or chlorophyll concentration). Field data during the growing period may need to be collected to ensure adequate conditions for growth (Inglis *et al.*, 2000)

- Production carrying capacity: Production CC relates to the stocking density which provides maximum harvest in the long term. For mollusc culture it is normally limited by the amount of plankton biomass and supply rate to a particular farm area. This group of models describes the rate of natural food conversion to productive tissue

(Gibbs, 2007). Briefly, it is the maximum sustainable yield of culture that can produced in a region (McKindsey *et al.*, 2006). This model (aspect) still has some limitations because seed collection, harvesting and processing processes are not included (McKindsey *et al.*, 2006).

- Ecological carrying capacity: Ecological CC covers a broader scope. Interactions among culture systems, physical and biological processes are included. These interrelations affect the transfer of organic material among the different benthic and pelagic components in the ecosystem. In summary, the ecological carrying capacity deals with the suitable stocking or farm density, which avoids unacceptable impacts on the surroundings (Gibbs, 2007) or the level of culture achievable without significant change to ecological processes, species, populations and communities in the growing environments (McKindsey *et al.*, 2006). The scope of models involves all culture activities including seed collection, ongrowing, harvesting and processing stages (McKindsey *et al.*, 2006).

- Social carrying capacity: This is the level of farm development that avoids unacceptable social impacts such as effects on visual amenity and displacement of other activities (McKindsey *et al.*, 2006). This concept plays an important role in integrated coastal zone management (ICZM) because it is the combination of all the first three concepts and considers the trade-offs among different stakeholders (McKindsey *et al.*, 2006). The conceptual model, some related factors and inter-relation between all CC concepts is illustrated in Fig. 1.11.

Basically, shellfish culture affects ecological systems in three ways; (1) by material process, it produces food and emits waste to the environment, (2) by physical structure, farming introduces shellfish and farm structures to the culture area whereas other species habitats may be replaced, and (3) by pulse disturbance, maintenance and harvesting activities remove cultured organisms and have an effect on resource and habitat availability (McKindsey *et al.*, 2006). The production processes (seed collection, ongrowing, harvesting and processing), and the potential impacts from shellfish culture on environment are illustrated by McKindsey *et al.* (2006).

Theoretically, and in practice, in order to achieve ecological sustainability aquaculture management goals and strategies have to change from the conventional to the ecosystem approach aquaculture (EAA) (see Soto, Anguilar-Manjarrez, Brugere, Angel, Bailey, Black, Edwards, Costa-Pierce, Chopin, Deudero, Silvert, Marba, Mathe, Norambuena, Simard, Tett, Troell, & Wainberg, 2008). This approach promotes both human and ecological well-being by developing aquaculture in the context of other sectors, policies and goals (Anguilar-Manjarrez, Karakassis, & Soto, 2010). Hence, multi-dimensional spatial management is necessary and GIS is an indispensible support tool, because it facilitates spatial management for aquaculture at least in three categories; (1) identification of optimal location and resource use, (2) resolution of conflicts of space and natural resources utilisation and (3) quantification of production levels according to market, infrastructures and economic drivers (Silva, Ferreira, Bricker, DelValls, Martín-Díaz, & Yáñez, 2011). However, data availability appears to be one of the main limitations for applying GIS. As a result, social CC modelling is relatively rare or just in infancy stage (McKindsey *et al.*, 2006).

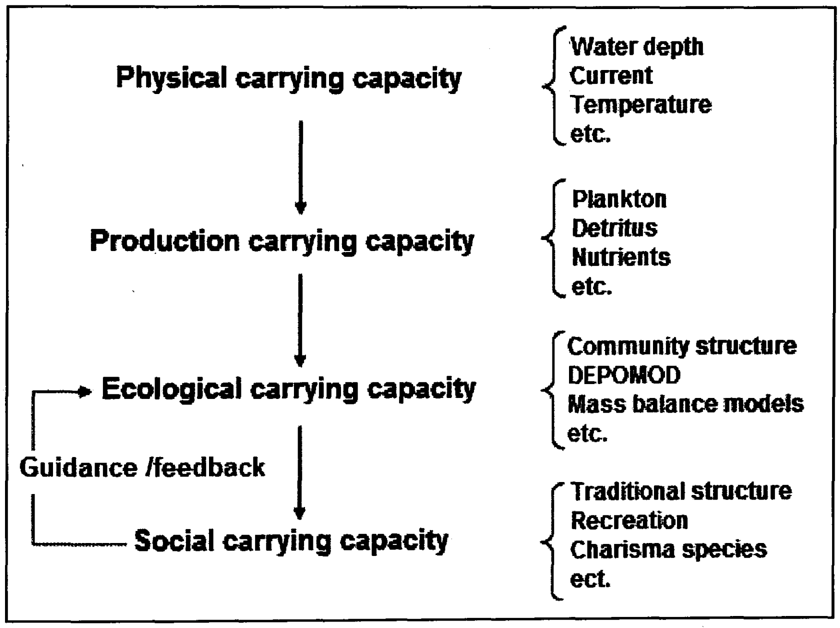


Fig. 1.11. Hierarchical diagram of the carrying capacity.
Source: McKindsey *et al.* (2006).

Although Thai fishery products have been exported worldwide and Thailand has become known as one of the most prominent world exporting countries, the application of GIS for fisheries and aquaculture is quite limited. The main government sector, the Fishery Geo-Informatics Group, Department of Fisheries, has established a web-based GIS database, which contains three main data groups comprising GIS for inland, coastal and marine fisheries. However, the information provided is mainly in the form of base maps, basic fisheries statistics, culture site distribution of some economic important species, fishing ports, seafood factories, socio-economics of fisheries household, photographs and some video related to fishery and aquaculture (see: http://www.fisheries.go.th/it-gis/). Some applications of the GIS at local scale have been used, such as remote sensing for fishing gear (set net) management in Samut Prakarn, Chachoengsao and Chonburi Provinces (Jarernpornpipat *et al.*, 2003), GIS application for shellfish resource management in Bandon Bay (Anuchiracheeva *et al.*, 2003) and the application for fisheries management in Bangsapan Bay (Siripong, Matsumura, Singhruck, Lirdviriyaprasit, & Sojisuporn, 2000). The study in the Bandon Bay showed proposed sites for cockles, green mussel and oyster plus previous culture area of cockles. McCoy *et al.* (1988) conducted a study on variation of chlorophyll-a and suspended sediment by remote sensing.

Pollution risks in the some main bivalve production areas, Samut Songkhram and Samut Prakarn Provinces (as illustrated in Fig. 1.5), which are located near populated areas and industrial zones have been reported (Jarernpornpipat *et al.*, 2003). For Surat Thani, the main production area (Bandon Bay) faces many problems, such as waste water discharge, overfishing, vulnerable fishing gears (push net and fine-mesh net), fishing in spawning season and increasing numbers of fishers (Broom, 1985; Sukansil, 2000). Similar to other bivalve culture areas, Pattani Bay serves for many fishing activities and aquaculture (Hajisamae, Yeesin, & Chaimongkol, 2006), it is a nursery ground of fish (Pitaksalee, Hajisamae, Yeesin, Chaimongkol, & Nuimuang, 2003a) and shrimp (Hengchuan, 2004; Ruangchuay, Luaeangthuwapranit, & Pianthumdee, 2004; Pianthumdee, 2004), and also has natural sea grass and seaweed beds. Moreover, the bay is located near fishing communities, industrial and commercial areas including being the outlets of two main rivers. As a result, the interactions of possible impacts generated in the surrounding area are unavoidable.

Based on general survey and anecdotal discussion, it is clear that the abundance of sea grass and seaweeds has declined considerably. The quantity of economically important seaweeds, *Gracillaria spp.*, which was the biggest national production area, is no longer viable to collect for sale. For aquaculture, some fish cage culture sites have been abandoned while mussel culture areas have expanded into new areas, and are no longer limited to the previous culture areas where farming activities have been established (more details are given in Chapter 2). Among culture activities in the bay, cockles are the main cultured species, which occupies the most water space and is the major contributor in terms of income. Total cockle culture farms decreased to around 60 farms in 2005-2007 while yearly cockle production in that period was around 3,390-

4,160 tonnes (Fishery Statistics Division, 2007a; Fishery Statistics Division, 2007b). At present, cockle culture still plays an important role in both production and financial terms for coastal culture households. But, unexpected deaths of cockles and mussels are found occasionally. Additionally, because of the high financial return from cockle culture to operators, there can be conflicts among different stakeholders who rely upon the bay for a living. Local people believe that all fishery resources are provided by God and must be shared by everybody and most stakeholders feel that there is unequal sharing of benefits, particularly where use is intensive.

Theoretically, fishery resources are considered as common-pool resources with open access because it is owned by no one or, in the other hand, by everyone (Ostrom, 2003; Ostrom, 2008). Pattani water space and fishery resources are also in the same condition with some restrictions. According to the Fishery Act., B.E. 2490, the area within 3,000 m from shoreline is restricted to small scale fisheries with no destructive gears, a trawl net, for example. As a result, reliable supporting data and an effective basis for planning must be established for unified direction in the near future to enable a better management strategy and help with conflict reduction and sustainable use.

1.4 Study objectives

This research project focuses on mussel and cockle culture in Pattani Bay for several reasons. In terms of water body utilisation (*i.e.* fishing, aquaculture and other resource beds.), inshore land use and other services provided by the bay, Pattani Bay would be the representative of other bays and semi-enclosed areas in Thailand. In terms of aquaculture, both targeted species are the most important molluscs and have market acceptance nationwide, the main production areas of the selected species are in semi-enclosed areas, various culture techniques have already been developed, and marketing channels and structures for mollusc are well established. Locally, the selected species have long been reared by both artisanal and commercial methods. Mussel seed is available from nearby areas while some cockle seed has also been found. Although a cockle seed shortage is reported, it can be imported from other provinces as well as from Malaysia. Socio-economically, fishermen have family labour and a boat with an engine, which can be involved in both capture and culture activities. Additional inputs such as wood, bamboo, net rope and *etc.*, are all available locally. As a result, farming of these two species have the potential to provide additional income and food security to villagers who rely mainly on fishing and collecting wild molluscs.

The research question of this study is to understand if the target species farming is sustainable. This study focuses mainly on the physical carrying capacity of the bay base on the following research objectives.

The main objectives and proposed outputs of this study are;

(1) Development of a mussel growth determination model,
(2) Development of a harvestable area model for mussels,
(3) Development of a suitable area model for cockle farming.

For Pattani Bay, these study outputs will provide the suitable culture area of the target species and proposed harvesting time for mussels. Furthermore, this study outputs may be applied to evaluate the possible production quantity and value of the targeted species. Trade-offs between fishing opportunity cost and proposed income from aquaculture within the proposed farming area can be compared to evaluate if it is financially viable. As the coastal fishery resource is used competitively by many stakeholders, it is also hoped that the outcomes from this project will partly benefit integrated coastal management and promote sustainable coastal resources management in the bay. Moreover, there is the potential to apply the findings of the study to other semi-enclosed and coastal areas in Thailand as well as in other tropical areas.

Chapter 2

The study area

2.1 Pattani Province

2.1.1 Topography

Pattani Province is in Southern Thailand and occupies an area of 2,013 km^2. It lies between latitudes 6°32' and 6°57' N, and longitudes 101°01' and 101°45' E. In the north it borders the Thai Gulf while in the south, west and southwest it connects to Narathiwat, Songkhla and Yala Provinces, respectively. The dominant landscape is lowland plain area with scattered small hills, located at the southern part of the province area (Chaiwanawut, Hatta, & Duangmala, 2005). Coastal flood plains occupy one third of the total area and are located mainly in the northern and middle parts of the province (Fig 2.1). Pattani Province comprises 12 districts (Amphoe), as shown in Fig 2.2, 5 of which (Nong Chick, Mueang, Yaring, Panarae, Saiburi and Mai Kaen) border the sea. Pattani Bay is surrounded by the first three districts. According to Hoecharoen *et al.* (1998), only fishermen from the these three districts are involved directly in fisheries in the bay.

2.1.2 Catchment areas

There are 2 main rivers in the catchment; the Pattani and Yaring Rivers. The Pattani River is a long river collecting water from the Pattani River basin, which covers most of Yala Province. The river flows north through the Yarang and Mueang Pattani Districts of Pattani Province and approaches the sea at the Pattani Bay opening. The Pattani Basin occupies a small area in Pattani Province adjacent to the Pattani River's banks. There are two dams along the Pattani River; Banglang Dam in Yala Province and Pattani Dam in Yarang District, Pattani. The rest of the area in Pattani Province is occupied by Yaring River Basin. The outlet of The Yaring River is at the East end of the bay. The total area of the two basins is approximately 4,388 km^2 (area identification and calculation based on satellite images, DEM and river system layer) (Fig 2.3).

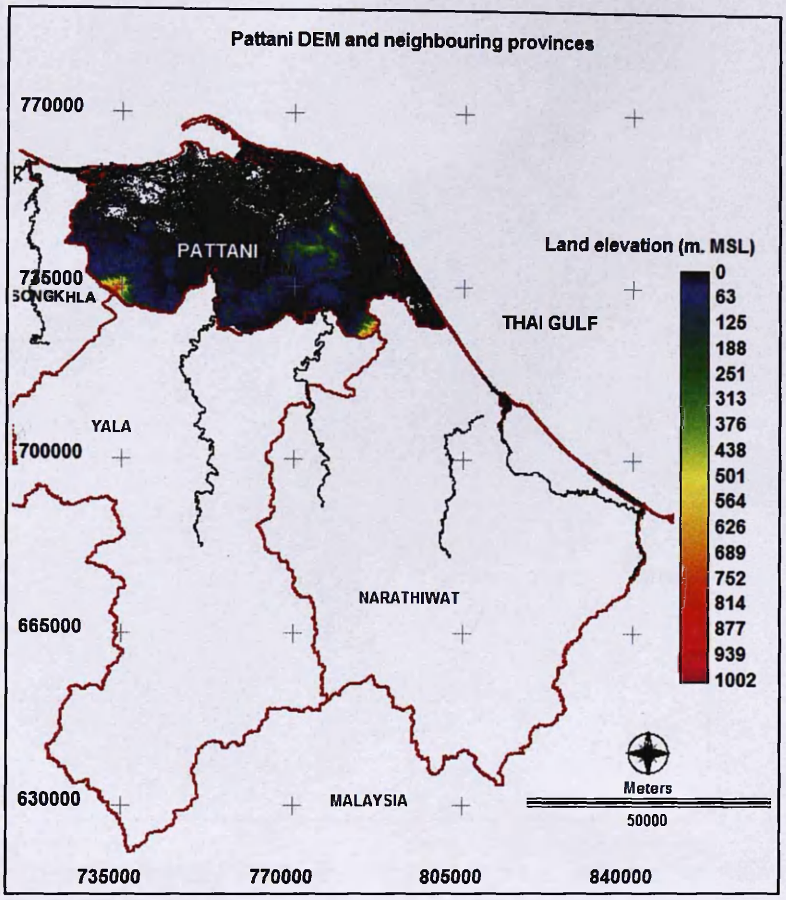


Fig. 2.1. Pattani land elevation and neighbouring provinces, Thailand.
Source: Based mainly on data provided by LDD (pers. comm.).

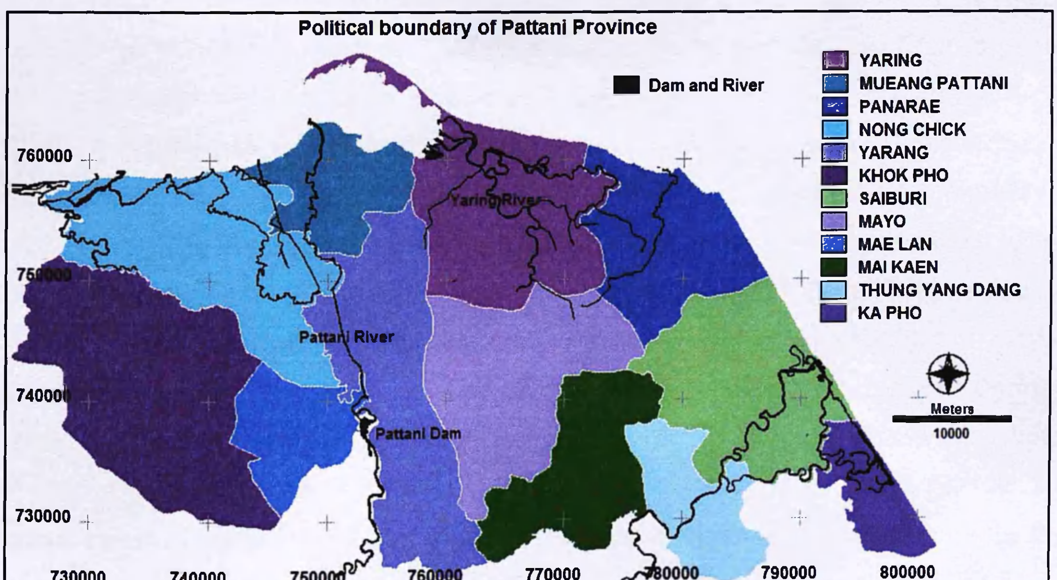


Fig. 2.2. Political boundary of Pattani Province and districts.
Source: Based mainly on data provided by LDD (pers. comm.).

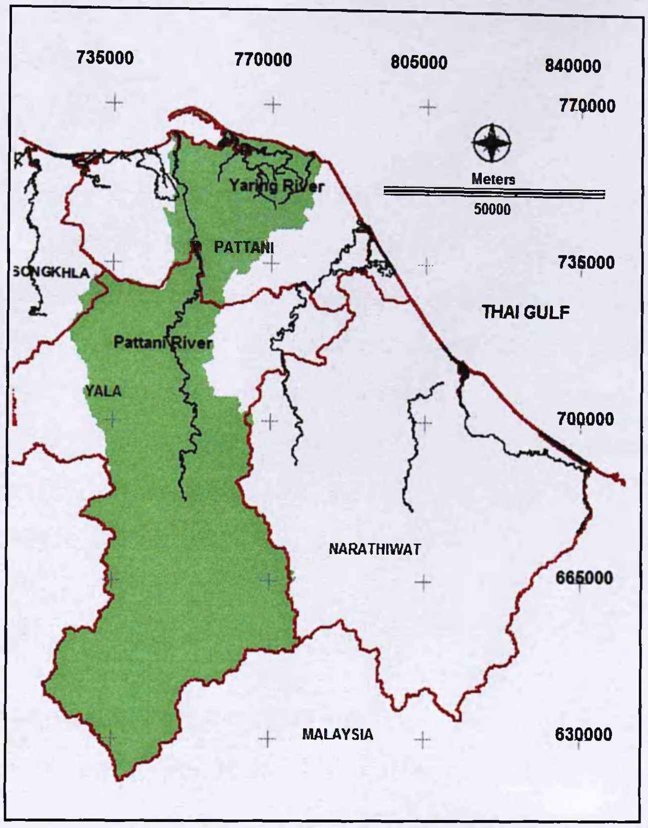


Fig. 2.3. Catchment area of Pattani Bay, the green area defines the main river basin. Source: Based mainly on data provided by LDD (pers. comm.).

2.1.3 Climate

Thailand, generally, has 3 different seasons, which are dry season (mid February- mid May), rainy season (mid May – mid October) and cold season (mid October - mid February). There are two monsoon seasons; the Northeast monsoon season during mid October – mid February and the Southwest monsoon season during mid May – mid October. The dry season takes place during the change from the Northeast to the Southwest monsoon. The hottest period is normally in May (Thai Meteorological Department, 2007). Based on rainfall data, Pattani area has three different rainfall characteristics throughout the year. Dry or low rainfall period covers 3-4 months from January-April. Moderate rainfall period is from May to September. During this time, amount of rainfall gradually increases from May until September. High rainfall, the highest rainfall intensity, is during October to December. These are the same for the eastern coastline of the Southern Thailand, particularly from the south of Surat Thani Province (Hemsuhree, 1997). This is consistent with the observations of Chaiwanawut *et al.* (2005) who confirmed that Pattani had 5 months of relative drought and 8 months of rainy period on average.

Yearly rainfall of Pattani Province during 1997 - 2007 was in the range of 1,281– 2,568 mm. For the year 2007, the total annual rainfall was 1,841 mm and number of rainy days was 152 days. The highest monthly rainfall was in October with 316 mm and the lowest was in February, with 0 mm. The highest daily rainfall was in the 7th January 2007 with 118 mm.Temperature range of Pattani in 2007 was 19.5-37.0 °C. The highest temperature being found in March at 37.0 °C and the lowest was 19.50 °C in January and February. Average yearly temperature was 27.30 °C (The Office of Strategy Management, 2011).

2.1.4 Population and socio-economics

The total registered population of Pattani Province increased from 2005 (634,376) to 2009 (647,624) at a yearly rate of 0.2-0.7%. The number of households gradually increased, from 141,511 households in 2005 to 153,323 households in 2009, while the average member per household decreased from 4.48 to 4.22 ind/household (National Statistic Organization, 2011a). The Gross Primary Product (GPP) in the Province during 2005-2009 varied from 32,842 to 40,089 million THB. The fisheries sector shared approximately 24-30% of the total GPP or 8,913-10,483 million THB. Per capita GPP varies from 50,775-58,724 THB (National Statistic Organization, 2011b). In 2007, the Per capita GPP was ranked in the 9th of the Southern Region and the 29th of the country (The Office of Strategy Management, 2011). It's considered as a relatively poor province in the Southern Thailand, which comprises 14 provinces in total.

Based on data from the Department of Provincial Administration (2011), the most populated areas are located near Pattani Bay. Total population of the three most populated sub-districts (Rusamiale, Bana and Sabarung) is 16,683, 18,724 and 24,003 people (Fig. 2.4) from the total number of 7,238, 6,542 and 7,034 households, respectively (Fig. 2.5) (Department of Provincial Administration, 2010). As a result, the populated areas may affect the bay ecology and productivity. On the other hand, an effective use or a suitable management plan of the bay may benefit the majority people in the province.

2.2 Pattani Bay

2.2.1 General data

Pattani bay, a small bay in Southern Thailand, is located at longitude 101° 14' 49"- 101° 21' 15" E and latitude 6° 57' 0"- 6° 51' 45" N. It has a water surface area of approximately 51 km^2 and the 4 km bay mouth is in the west and bounds to the Thai Gulf. The maximum west to east length is approximately 11.6 km. There are two rivers supplying fresh water to the bay; Pattani River, 150 km in total length, collects water from Pattani Basin and enters the bay at the bay opening while Yaring River connects to the distal end of the bay (Fig. 2.6). Sand deposition generates a sand spit near the bay opening. The highly productive mangrove area of the bay is around 9,143 rai (6.25 rai = 1 ha) at Yaring River mouth, part of which (2,913 rai) is man-made mangrove forest (Predalumpaburt & Chaiyakam, 1994).

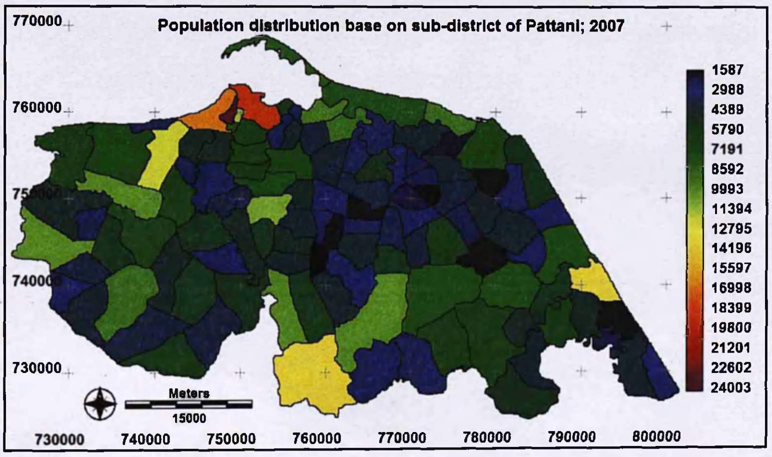


Fig. 2.4. Total population base on sub-district of Pattani Province in 2007.
Source: Based on data provided by Department of Provincial Administration (2010).

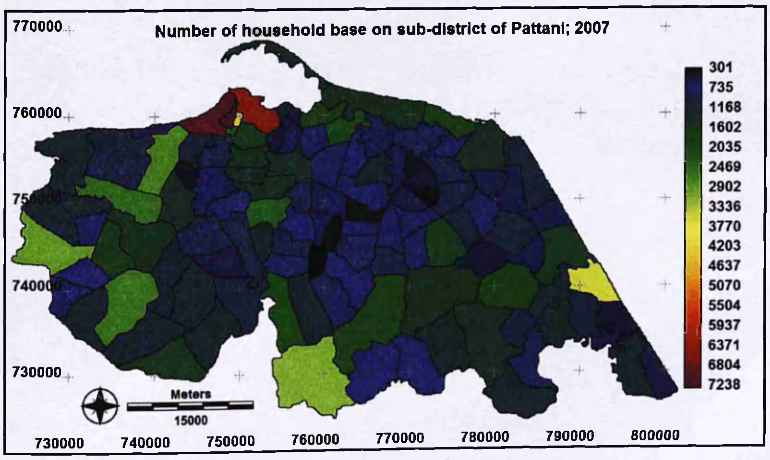


Fig. 2.5. Total households in the sub-districts of Pattani Province in 2007.
Source: Based on data provided by Department of Provincial Administration (2010).

Fig. 2.6 illustrates reference sites, villages and related locations around the bay which are referred to throughout this study. From the bay tip (Laem Tachi) to Lighthouse is a wilderness area, although there is access by road. The other three villages; Budee, Talo Samilae and Da To, are fishing villages. Some shrimp farms are found at Budee while integrated catfish and coconut tree farming is observed at Da To in addition to artesanal fish cake production which is the dominant processing activity of the village. If seaweeds (*Gracilaria sp.*) are available, sun-dried seaweeds are also produced by the villagers. The Yaring River Delta, from Da To to Bang Pu, is reserved mangrove area (see the boundary of the area in Fig. 4.4). Bang Pu, Tanyong Lulo, Bana and Laem Nok are also fishing villages. Dried seaweeds are found in Tanyong Lulo and Bang Pu seasonally, which is similar to Da To. Some coastal areas of Bana and Tanyong Lulo are occupied by shrimp farms. Laem Nok is outstanding for mollusc culture and local fish processing, both in terms of production capability and investment intensity. Both sides of the Pattani River bank are occupied by city area, industrial area, fishing port, land fill area, government and educational organisations. Rusamilae and the next few villages (not shown in this report) are also fishing villages.

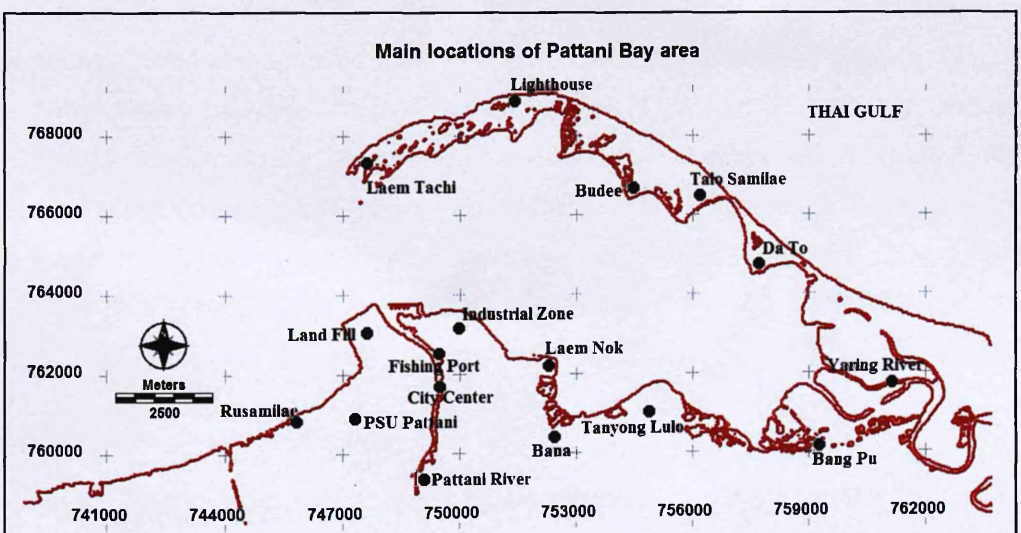


Fig. 2.6. Main locations of Pattani Bay, Thailand.

2.2.2 Water and sediment quality

2.2.2.1 Water quality

Water and bottom sediment quality studies have been conducted in the area on several occasions with varying study purposes. Predalumpaburt & Chaiyakam (1994) conducted an environmental survey for use in a sea farming feasibility study, mainly focussing on water and bottom soil. However, their 10 sampling stations of soil and water parameters were set up only in near shore locations, although water current, had 13 stations and covered a deeper zone area covering from the bay opening to the vertical line between Tanyong Lulo to Budee villages. The mean monthly minimum and maximum of some water quality parameters is summarised in Table 2.1. Salinity drop was found twice per year, in June (12 ppt) and in December (10 ppt). Water current was observed for both ebb and flood tides on waxing moon time. The current during flood tide at the bay opening area was 0.20-0.29 m/s while that of at Budee and Tunyoug Lulo areas were very low, between 0.04-0.08 m/s. During low tide, the current at the bay opening was 0.22-0.28 m/s and that of at Budee and Tunyoug Lulo areas was 0.06-0.08 m/s. The different water elevation between high and low tides was 0.71 m. This study suggested that the area from Tanyong Lulo and Da To to Yaring River is suitable for natural seaweeds while off shore of Tanyong Lulo to Laem Nok area is suitable for cockle farming and small areas near Laem Tachi are technically feasible for mussel and fish cage cultures.

Water quality parameters in the cockle farm area were investigated by (Tookwinas & Perngmark, 1986) who showed that the range of salinity, dissolved oxygen, BOD and chlorophyll-a was between 15.8-29.00 ppt, 3.85-6.20 mg/l, 0.05-1.62 mg/l and 6.87-54.73 mg/m^3, respectively. At mussel farming sites, Brohmanonda *et al.* (1988b) observed water quality in pilot culture site for 16 months (October 1979-January 1981) and found the range of monthly temperature, salinity, turbidity, pH, CO_2, DO and $CaCO_3$ of 26.53-31.85°C, 23.25-33.63 ppt, 31-98 cm, 7.30-8.63, 0.79-2.52 mg/l, 4.95-7.96 mg/l and 85.85-151.87 mg/l, respectively (Table 2.2).

2.2.2.2 Bottom sediment quality

The major bottom characteristic of the bay is muddy sediment, although the sediment at 2 stations near the bay opening is sandy. The sediment pH is between 6.68-7.32. Nitrite, nitrate and ammonia ranges of the sediment are 0.00-0.04, 0.33-0.90 and 3.44-20.13 mg/kg, respectively. Sediment organic matter is between 1.91-11.06%. Sediment particles were classified based on percentage of size classes, >2.5 mm, >0.25 mm, >0.125 mm, >0.053 mm and <0.053 mm (Predalumpaburt & Chaiyakam, 1994). Classification based on USDA Standards showed that sediments are mainly silty clay loam and silty clay. These two sediment types show broadest spatial distribution. Sand, loamy sand and sandy loam is rarely found and only on the northern coastline of the bay (Fig. 2.7) (Pitaksalee, Khongpuang, & Promdam, 2003b).

Table 2.1. Average of monthly minimum and maximum values of some water parameter in Patanni Bay, Thailand.

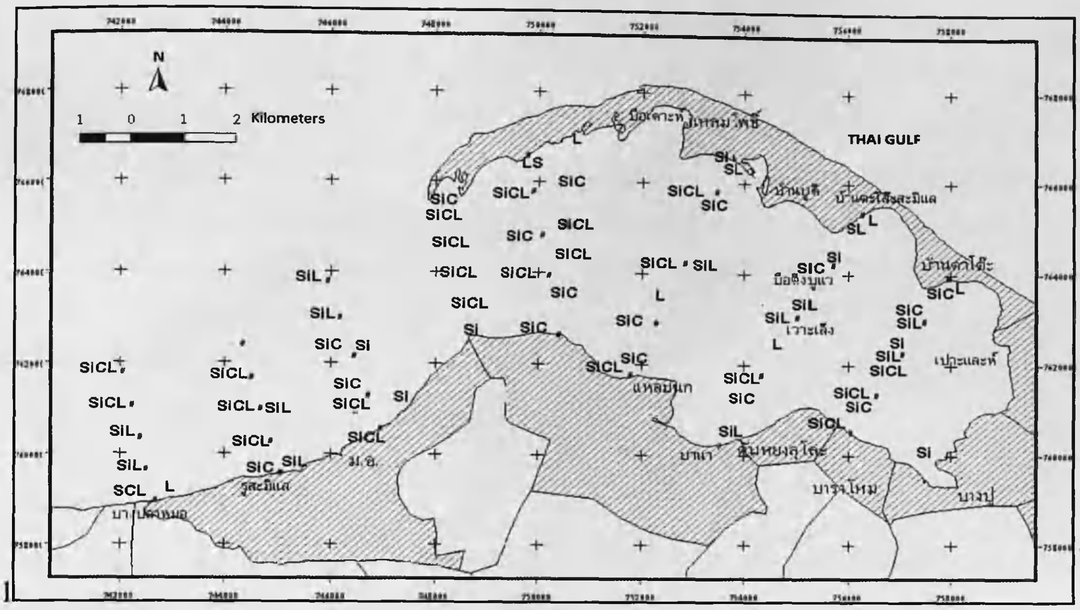
Parameter	Max±SD	Month	Min±SD	Month
Depth (m.)	1.03±0.27	Apr	0.60±0.44	Jun
Transparency (m.)	0.86±0.32	Apr	0.22±0.09	Aug
Temperature (°C)	30.20±0.26	Oct	29.2±0.50	Dec
pH	8.97±0.17	Apr	7.43±0.31	Feb
Salinity (ppt.)	31.50±2.9	Apr	18.10±7.50	Dec
DO (mg/l.)	6.62±0.89	Oct	5.63±0.68	Apr
NO_2 (ppm.)	0.026±0.06	Aug	0.001±0.003	Oct
NO_3 (ppm.)	0.078±0.067	Dec	0.016±0.013	Oct
Total NH_3 (ppm.)	0.507±0.861	Feb	0.034±0.052	Oct
PO_4 (ppm.)	0.071±0.084	Aug	0.295±0.372	Apr
Total suspended solid (ppm.)	279±424.5	Aug	0.002±0.003	Jun
Total phosphorus (ppm.)	0.157±0.094	Feb	0.058±0.012	Apr
BOD (ppm.)	4.43±0.73	Dec	0.29±0.44	Apr

Source: Predalumpaburt & Chaiyakam (1994).

Table 2.2. Some water quality from cockle and mussel culture sites.

Cockle*		Mussel**	
Parameters	Range	Parameters	Monthly Range
Salinity (ppt.)	15.80 - 29.00	Temperature (°C)	26.53 - 31.85
DO (mg/l.)	3.85 - 6.20	Salinity (ppt.)	23.25 - 33.63
Chlorophyll-a (°C)	0.05 – 1.62	Turbidity (cm)	31.00 – 98.00
		pH	7.30 – 8.63
		CO_2 (mg/l)	0.69 – 2.52
		DO (mg/l)	4.95 – 7.96
		$CaCO_3$ (mg/l)	85.85 – 151.87

Source: Tookwinas & Perngmark (1986)* and Brohmanonda *et al.* (1988b)**



L ; Loam SiCL; Silty Clay Loam SiC; Silty Clay SL; Sandy loam
Si; Silt SCL; Sandy Clay Loam SiL; Silty Loam LS; Loamy Sand

Fig. 2.7. Bottom sediment distribution in Pattani Bay, Thailand.
Source: Pitaksalee *et al.* (2003b).

The ranges of sediment pH, organic carbon and available phosphate in farmed areas of Pattani Bay are 7.0-7.5, 1.22-1.35% and 0.15-0.16 mg/kg, respectively. The dominant sediment type is silty loam while the percentage of sand, silt and clay particles is 29.87-55.67%, 33.46-63.23% and 10.87-13.47%, respectively. However, the high percentage of sand particles in sediment is found at only one station and indicates that different sediment types exist in farmed areas (Sangsakul & Tookwinas, 1986).

The concentration of heavy metals (Cadmium;Cd, Copper;Cu, Zinc;Zn and Manganese; Mn) between two sites (Laem Nok and Rusamilae) are very similar, but the concentration of Lead (Pb) at Laem Nok is significantly higher than that of Rusamilae (Suwanjarat, Pituksalee, & Thongchai, 2009). Mercury (Hg), Cadmium, Lead and Arsenic (As) from 9 different land use types around the bay are investigated. The dominant land uses are agriculture and shrimp farm and the main agricultural activity is rice paddy. The municipal area, industrial zone and dockyard have a big effect on heavy metals, particularly Pb and As, especially concentration in both topsoil (0-20 cm) and subsoil (21-50 cm) layers. At two sampling sites of dockyard and Pattani River mouth, high concentration of Pb were found at 386 and 557 mg/kg, respectively.

Based on the United States Environmental Protection Agency (USEPA) standard for residential area, the Pb at the last station exceeded the standard level of 400 mg/kg, as well as the value of As at the dockyard, Pattani River mouth, and industrial zone, which are 4.46, 4.75, and 3.48 mg/kg, respectively, over the standard value of 4 mg/kg. Other land use types, shrimp farming and traditional land uses (salt flat, paddy field, orchard, and mangrove forest) has low metal concentrations (Sowana, Shrestha, Parkpian, Pongkhuan, & Finkl, 2010).

2.2.3 Fishery resources

2.2.3.1 Molluscs

There are at least 90 species of molluscs in Pattani Bay and these can be classified into 3 classes (Bivalvia, Gastropoda and Scaphoda) and 25 families. Of all reported molluscs, 12 species from 5 families and 2 classes are classified as economically important molluscs as shown in Fig. 2.8. Of these, there is only one species of gastropod (*Pugilina cochidium*) and the others are bivalve molluscs. Blood cockles (*A. granosa and A. nodifera*), green mussel and white scar oyster, are obtained from both culture and capture activities. The remaining molluscs come from capture (Pitaksalee *et al.*, 2003b; Pitaksalee, Khongpuang, & Saravisutra, 2003c). The northern coastline is the most important habitat of natural molluscs (Fig. 2.9).

The density of economic molluscs varies from 2.25-10,654 individuals/m^2 and the average standing crop production varies from 98.5-2,491 g/m^2 (Pitaksalee *et al.*, 2003c). The abundant natural seed supply of green mussel in the bay is one factor promoting mussel farming. During the spat fall peak around October-March, the average density of mussels spat is 797 individuals/m^2 (559 – 1,174 individuals/m^2) of substrate surface (Bamboo stake) (Niyomdecha, 2009).

The blood cockle, *A. granosa* , exists both inside and outside the bay areas, including near shore of PSU Pattani until Rusamilae village (Pitaksalee *et al.*, 2003b; Suwanjarat *et al.*, 2009). Maturation of mussel at Laem Nok and Rusamilae areas is found all year round with slightly different periods. The peak breeding season is during July-August and harvesting in this period should be avoided with the most suitable harvesting period being February-June (Suwanjarat *et al.*, 2009).

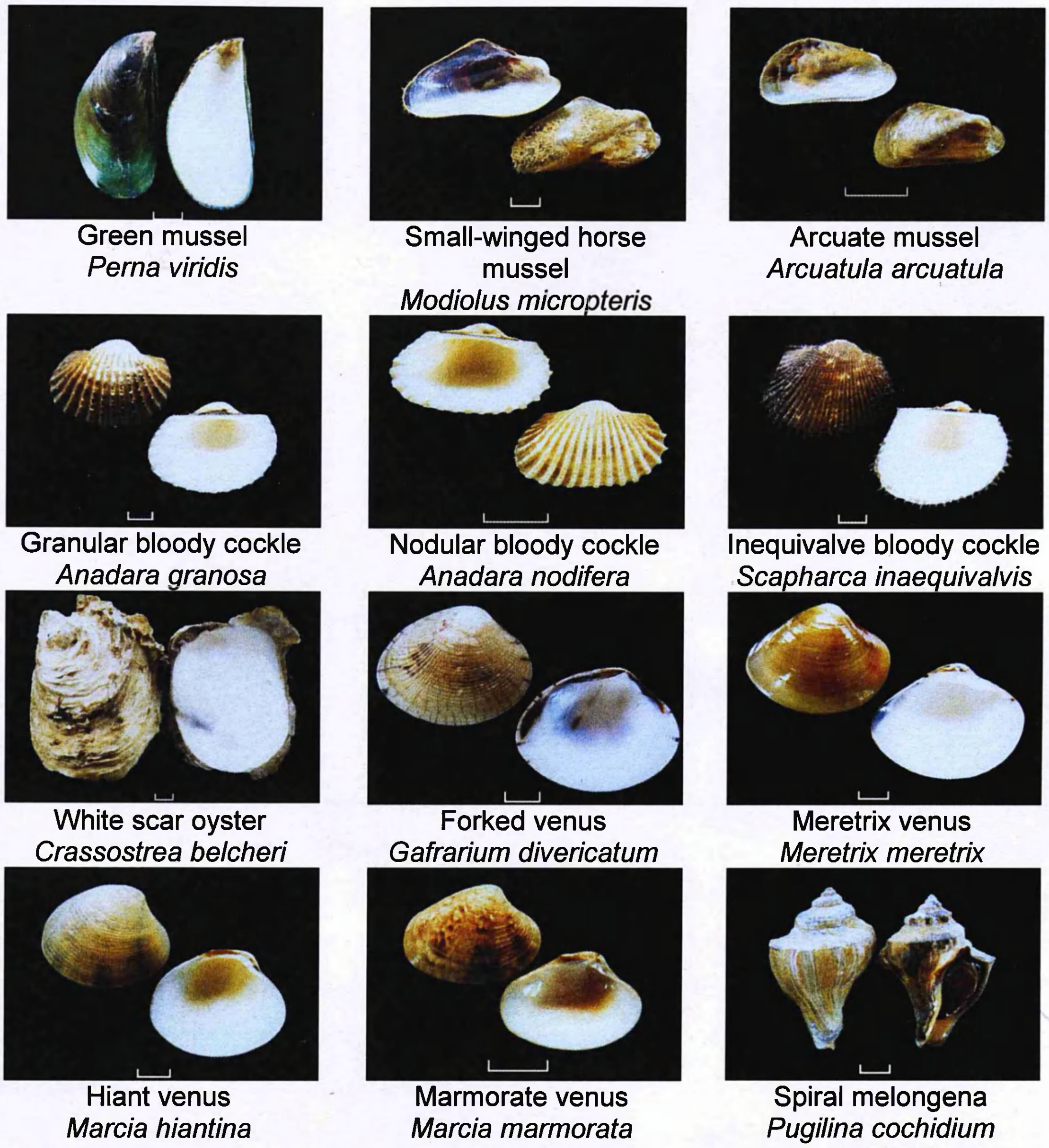


Fig. 2.8. Economically important molluscs in Pattani Bay, Thailand.
Note: Scale bar = 1 cm. Source: Pitaksalee *et al.* (2003b).

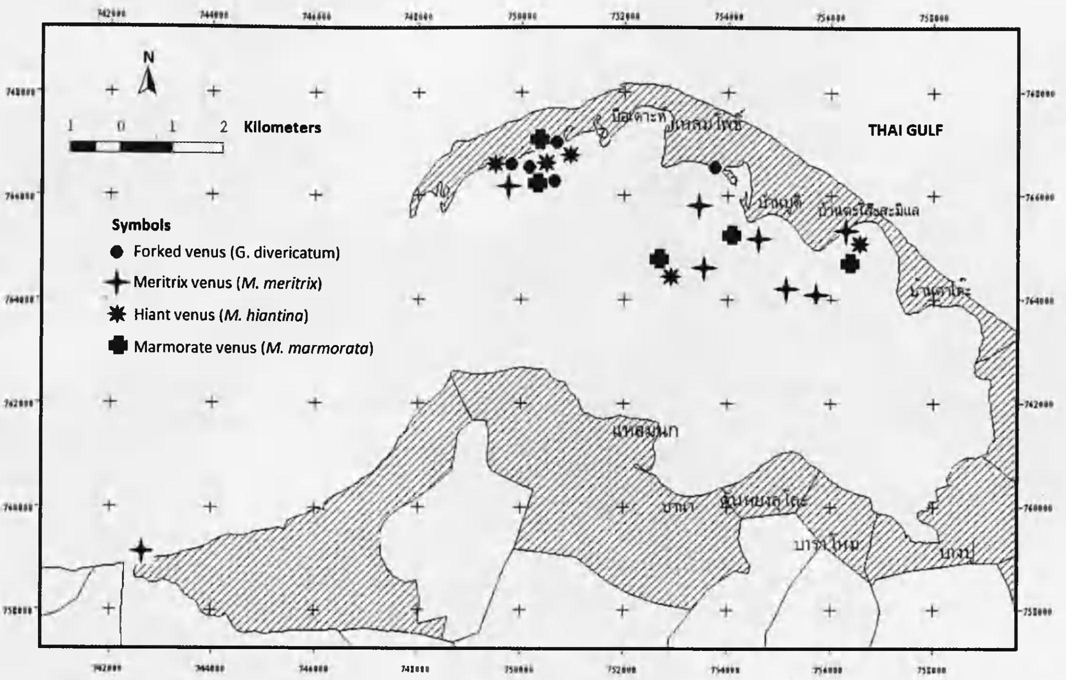


Fig. 2.9. Spatial distribution of natural molluscs (Family Arcidae) in Pattani Bay, Thailand.

Source: Pitaksalee *et al.* (2003b).

2.2.3.2 Fish

At least 108 fish species were found in a one year period (March 2003-February 2004), from 11 sampling sites (Hajisamae *et al.*, 2006) although in a previous study by Hoecharoen *et al.* (1998) only 55 species of fish were caught from the bay. Of the 30 most dominant species, some occupy specific habitats, but most are widely distributed (Hajisamae *et al.*, 2006). Although the majority of fish are small-sized, approximately 83% of those fishes are considered economically important species and the bay plays an important role for both food supply to villagers and as a nursery ground for many species. The average fish density was 399 individuals/1,000 m^2 (85-978 individuals/1,000 m^2) and the mean biodiversity index (H') was 2.35 (0.89-3.06). Based on the economical value, the percentage of fish of high (≥100 THB/kg), medium (30-100 THB/kg), low (<30 THB/kg) and non-economic values is 8%, 56%, 19% and 17% of all fish, respectively (Fig.2.10) (Hajisamae, Yeesin, & Chaimongkol, 2003), however, the sampling stations of this study were mainly located in shallow water (Fig. 2.11).

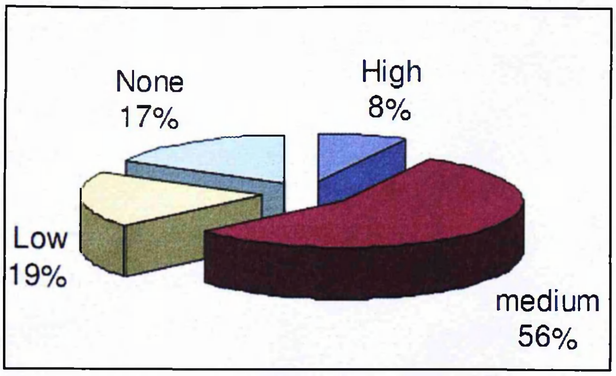


Fig. 2.10. Percentage of fish found in the bay base on the economic value.
Source: Hajisamae *et al.* (2003).

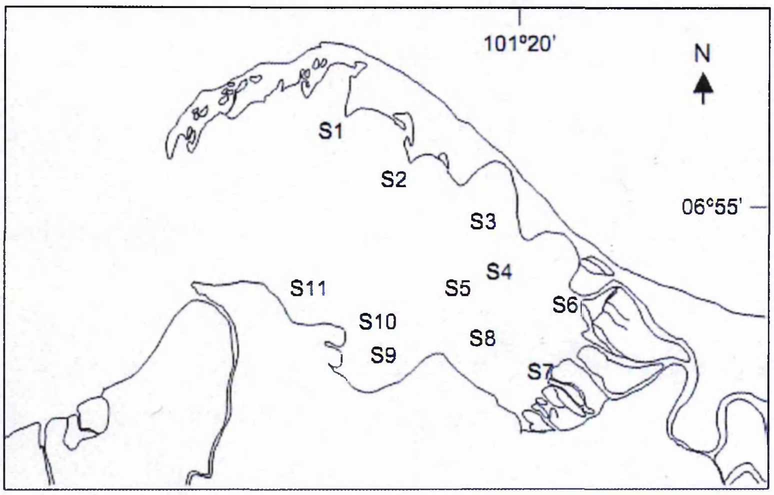


Fig. 2.11. Shallow water sampling sites for fish habitat in the bay.
Source: Hajisamae *et al.* (2006).

2.2.3.3 Shrimp

Hajisamae *et al.* (2006) found the mean density of shrimp in the bay to be 166 individuals/1,000 m^2 represented by 13 species from 3 families (Penaeidae, Palaemonidae and Sergestidae); the most prevalent are shown in Table 2.3. The majority of shrimp is found in the muddy bottom area, ranging from Bang Pu to Bana although near Laem Pho (Lighthouse), green tiger prawn is found because of the different community structure related to the high density of sea grass. Density of shrimp of the top five stations varies from 168-537 individual/1,000 m^2. Average size of shrimp at the northern coast is higher than that of the southern coast. Yellow shrimp is the main economic shrimp of the bay, costing around 60-80 THB/kg. The higher economic value shrimp (*Penaeus sp.*) is found in only at a small size, while the marketable size is caught offshore of Pattani Province (Pitaksalee *et al.*, 2003a).

Table 2.3. The top five of shrimp species found in Pattani Bay.

Family / Species	Common name**	Thai name	Density /1,000 m^2
Penaeidae			
Metapenaeus ensis	Greasy-back shrimp	Kungtakat-hangdang	194.3
Penaeus semisulcatus	Green tiger prawn	Kungkulalai	59.8
Metapenaeus brevicornis	Yellow shrimp	Kunghuaman/Kunglueang	44.8
Metapenaeus dobsoni	Yellow shrimp	Kungtakat	55.8
Sergestidae			
Acetes spp.	Opossum shrimp	Kungkhoei	147.6

Note: ** http://www.fisheries.go.th/rgm-samutsa/content_list.asp?Cat_ID=4&subcat_id=13&content_id=8

Source: Pitaksalee *et al.* (2003a).

2.2.3.4 Seaweeds and sea grass

16 species of seaweed are found in the bay (Fig. 2.12 and 2.13). The highest diversity of 12 species is found at Talo Samilae where an economically important seaweed ,*Gracilaria spp.* (Fig. 2.14) are found in almost sampling times. *G. tennuistipitata* has the maximum standing crop of 3.9 kg wet wt./m^2 and shows the highest total biomass of all sampling period, at 210.48 g dry-weight/m^2. No seaweed exists at Bana and Laem Nok for all year and have no seaweeds found in the bay during November - December. Seven species are considered as high biomass seaweeds (Ruangchuay *et al.*, 2004; Pianthumdee, 2004).

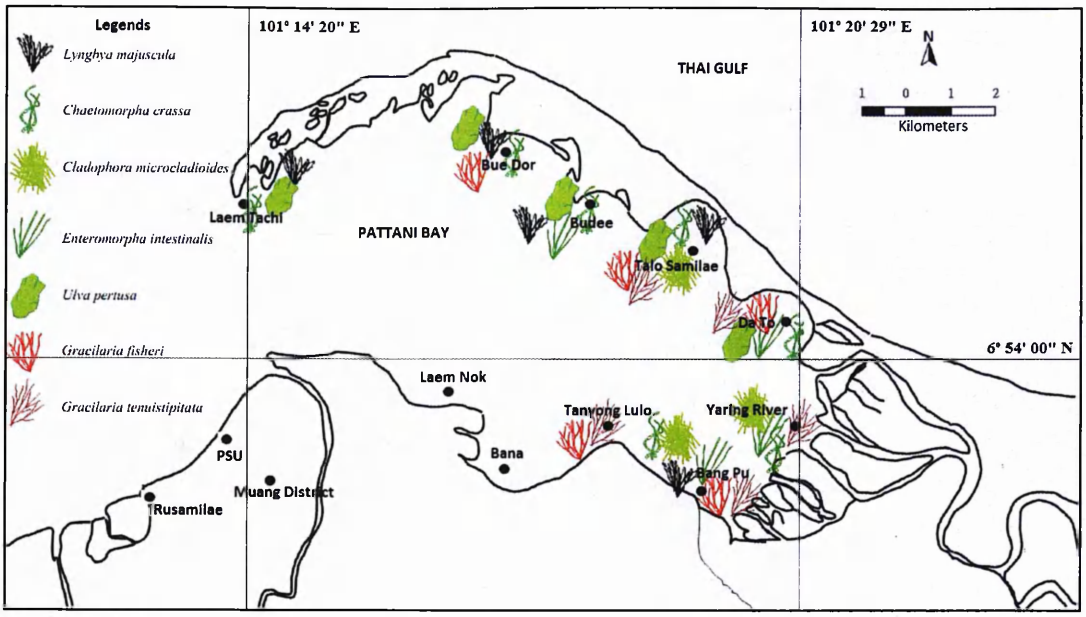


Fig. 2.12. Spatial distribution of high biomass seaweeds in Pattani Bay, Thaland. Source: Reproduced from Ruangchuay *et al.* (2004).

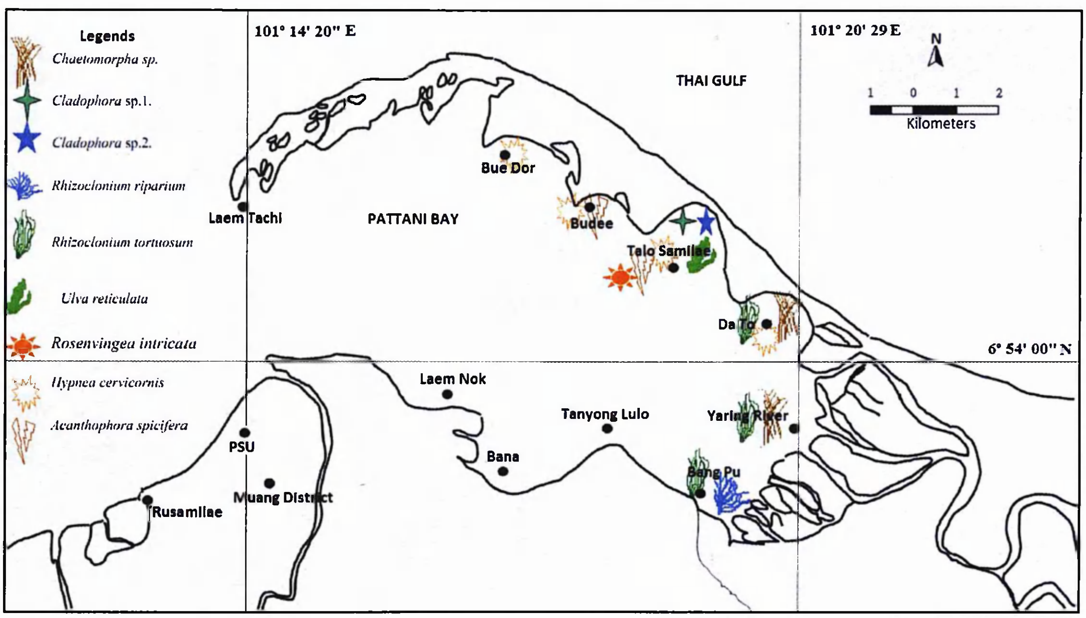


Fig. 2.13. Spatial distribution of low biomass seaweeds in Pattani Bay, Thailand. Source: Reproduced from Ruangchuay *et al.* (2004).

(a) Gracilaria tenuistipitata *(b) Gracilaria fisheri*

Fig. 2.14. Economical seaweed species in Pattani Bay, Thailand.

Source: Pianthumdee (2004).

Four species of sea grass, *Halodule uninervis, Ruppia maritima, Halophila ovalis* and *Halophila beccarii* are found in the bay. The average productivity by wet weight of those species varies from 23.14-138.92 g/m^2. There is no sea grass at Laem Tachi, Laem Nok, Bana and Tanyong Lulo. Generally, the growth rate of sea grass at silty bottom area is better than that of sandy bottom. The broadest distribution specie is *Halophila ovalis* follow by *H. Beccarii, Halodule uninervis* and *Rupia maritime* (Hengchuan, 2004). Various kinds of sea grass and seaweeds inhabit the shallow water zone near reserved mangrove area and Da To. The distribution of sea grass in other areas is illustrated in Fig. 2.15 (Hengchuan, 2004; Pianthumdee, 2004).

2.2.4 Capture fisheries

The bay has long been utilized for various fishing activities particularly by the inhabitants of Nong Chick, Mueang and Yaring Districts from which approximately 21% of the population are involved in fisheries (Hoecharoen, Hajisamae, Kamlangdee, Karntanut, & Punphol, 1998). The principle catch is of fish, shrimp, crab and cockle. The main fishing gears for fish, shrimp and crab are gill net or trammel net. A hand-drawn map of fishing areas in the bay was produced using a participatory research approach (Sukansil, 2000) from which the different fishing grounds were digitized.

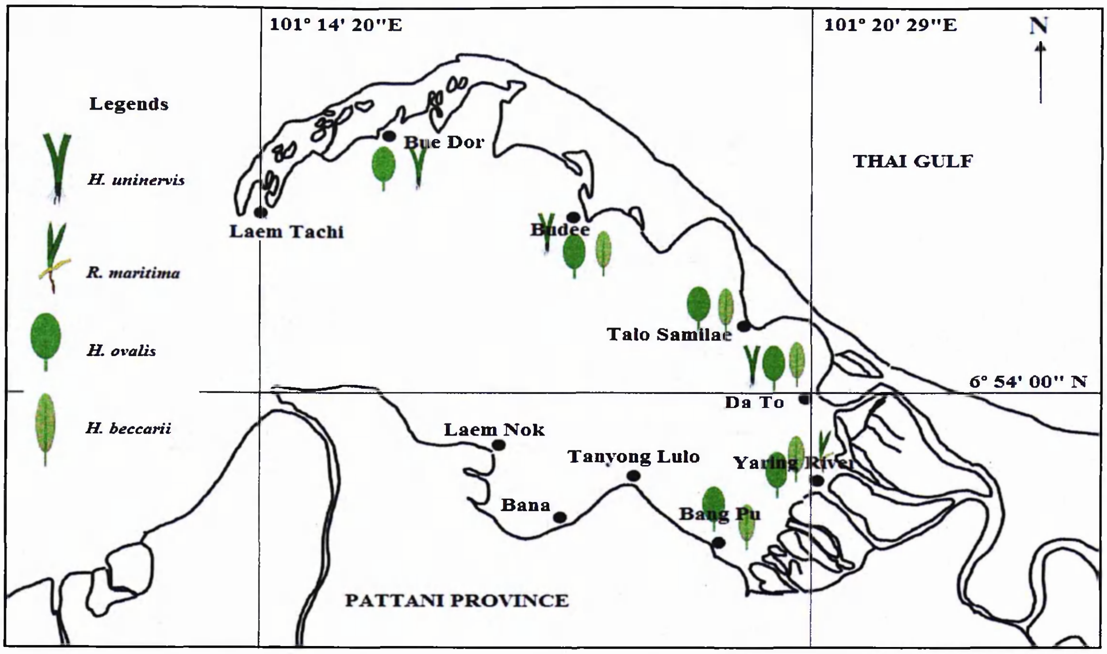


Fig. 2.15. Spatial distribution of sea grass in the Pattani, Thailand.
Source: Hengchuan (2004).

2.2.4.1 Crab

The main fishing gear is crab gill net and the total fishing area of 32.5 km^2 covers almost all of the bay, except the southern coastline from Laem Nok to Pattani River mouth (Fig. 2.16).

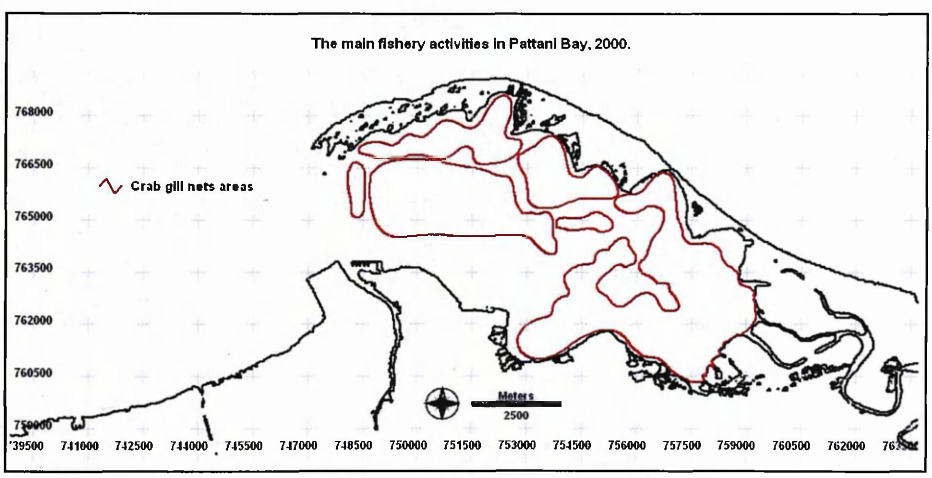


Fig. 2.16. Crab fishing areas of Pattani Bay, Thailand; 2000.
Source: Based on data provided by Sukansil (2000).

2.2.4.2 Cockle

The only two sites for cockle fishing are in front of Laem Nok village and near the shore between Da To and Talo Samilae villages (Fig. 2.17). The total area of these two sites is 1.73 km^2 and the main fishing method is hand dredging (without powered boat).

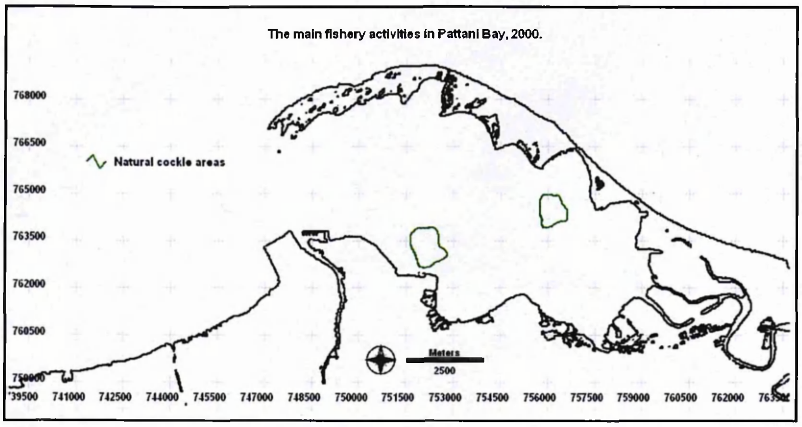


Fig. 2.17. Natural cockle fishing areas of Pattani Bay, Thailand; 2000.
Source: Based on data provided by Sukansil (2000).

2.2.4.3 Shrimp

The main area for shrimp fishing is surrounded by Laem Nok, Budee, Da To and Tanyong Lulo villages. Additional areas are near the shoreline of Yaring River mouth to Laem Nok, small area near shore at the southwest of Budee, 2 small areas at the middle of the bay opening and two small areas on the north coast between Yaring River mouth and Budee. Total area of shrimp fishing ground is around 19.46 km^2 (Fig. 2.18). The main fishing gear is shrimp trammel net, except at the two small areas at the middle of the bay opening, where the bamboo stake traps are operated.

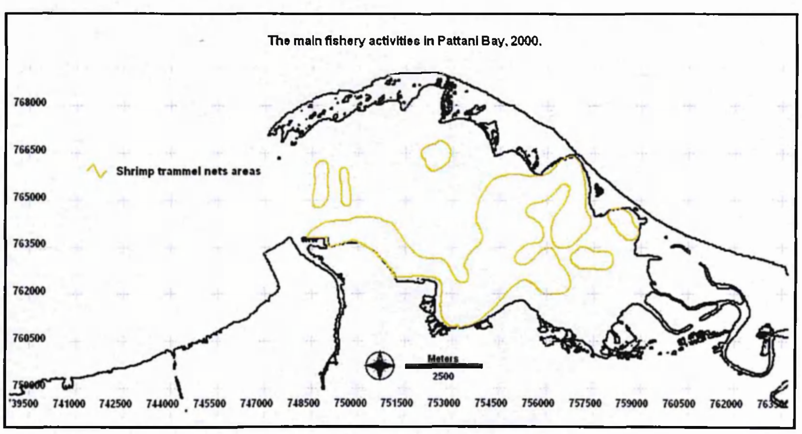


Fig. 2.18. Shrimp fishing areas of Pattani Bay in 2000.
Source: Based on data provided by Sukansil (2000).

2.2.4.4 Fish

The fish catching areas distribute along the bay coastline as shown in Fig. 2.19. It covers total area of 17.85 km^2. The main fishing gear is gill net.

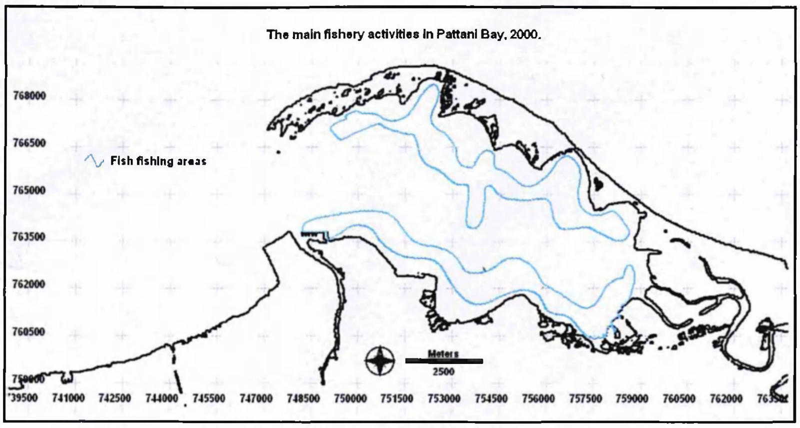


Fig. 2.19. Fish fishing areas of Pattani Bay in 2000.
Source: Based on data provided by Sukansil (2000).

2.2.5 Aquaculture activities

2.2.5.1 Mollusc culture

The main cultured species of mollusc in the bay area are cockle, mussel and oyster, although the bay is principally used for bottom farming of cockles (Sukansil, 2000), mussels and fish cage culture (Predalumpaburt & Chaiyakam, 1994). Sukansil (2000) found that the main culture areas were off the south coastline from Pattani River mouth to the area next to Bang Pu, as well as offshore of Talo Samilae and Budee (Fig. 2.20). The total area of cockle culture was 11.90 km^2.

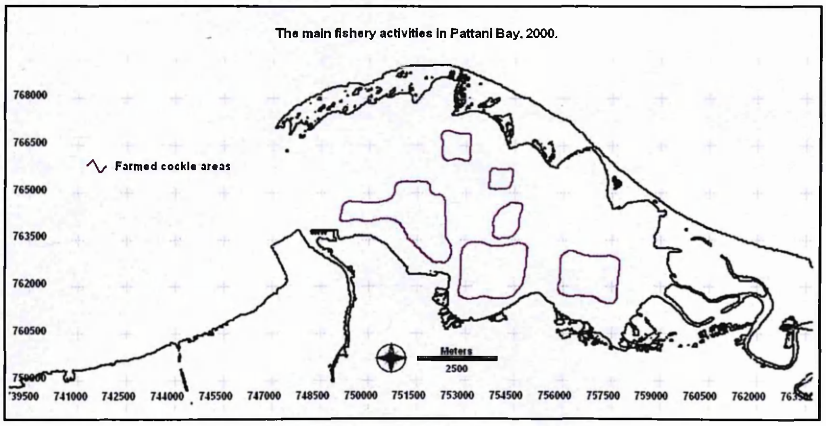


Fig. 2.20. Cockle farming areas of Pattani Bay in 2000.
Source: Based on data provided by Sukansil (2000).

Cockle was the first species to be cultured and reported and during 1978-1981, the production was 229, 105, 78 and 94 tons, respectively (Broom, 1985). During 2004-2007, cockle contributed >95% of total molluscs product and total cockle production of the last three years is almost stable at 1,986-2,190 tonnes, in a culture area of 633-658 ha (3,958-4,111 rai) (Table 2.4) (Fishery Statistics Division, 2007a; Fishery Statistics Division, 2007b). Almost all of this production is from Pattani Bay.

Table 2.4. Mollusc farm area and number by type of Pattani province; 1999-2007.

Items/Years	1999	2000	2001	2002	2003	2004	2005	2006	2007
Number of farm (farm)									
Total	1	2	1	1	1	2,232	60	71	73
Cockle	1	2	1	1	1	2,231	57	57	59
Mussel	-	-	-	-	-	-	1	11	11
Oyster	-	-	-	-	-	1	2	3	3
Culture area (rai.)									
Total	100	350	100	100	250	13	3,990	4,005	4,158
Cockle	100	350	100	100	250	-	3,958	3,958	4,111
Mussel	-	-	-	-	-	1	30	43	43
Oyster	-	-	-	-	-	-	2	4	4
Production (ton)									
Total	22	307	134	96	252	658	2,002	2,033	2,265
Cockle	22	307	60	27	252	652	1,986	1,986	2,190
Mussel	-	-	74	69	-	-	6	34	41
Oyster	-	-	-	-	-	6	10	13	34

Note: The number of farm in 2004 includes proposed culture households

Source: Fishery Statistics Division (2007b)

A general survey carried out as part of this study showed that, bottom culture is the only technique used for cockle farming whereas fixed raft and pole cultures are employed for both oyster and mussel (Fig. 2.21).

(a)

(b)

(c)

(a) Fixed raft mussel culture (b) fixed raft oyster culture (c) mussel pole culture

Fig. 2.21. Molluscs culture techniques in Pattani Bay, Thailand.

The other source of mussel production is obtained as a by-product from bamboo stake traps (Fig. 2.22), which are established at the bay opening areas. The culture sites of mussel and oyster are near to Laem Nok village. Seed of mussel and oyster are collected from the bay and nearby areas, but cockle seed is from other provinces and Malaysia. Although some cockle seeds are available from near shore of PSU in some years, the quantity does not meet farmers demand.

Fig. 2.22. Bamboo stake trap as an additional mussel source in Pattani Bay, Thailand.

The size of cockle farm area is varied. Medium and large scale farms occupy larger area depending on investment and farm operations ranging from site preparing, seed sowing, thinning, guarding and harvesting, are done by hired labour. Farm boundaries are indicated by big poles at each corner and a guard house is established nearby. Harvesting is done by powered boat dredging. Some farm owners are local cockle collectors and invest in grading machine as well as trucks for transportation (Fig. 2.23). Small scale farm or backyard farm size varies from <4.8 ha (30 rai) to very small area of 100-2,000 m^2 (Fig. 2.24). A summary of farm size and farm characteristics from the field survey is summarised in Table 2.5

Table 2.5. Summary of cockle farm size and characteristic in Pattani Bay.

Farm size	Farm area (ha)	No. of labour/ source	Harvesting method*
Small	<4.8	1-2 ind./ family labour	1 or 2
Medium	4.8-32	3-5 ind./ family+hired labour	2
Large	>32	5-12 ind./ hired labour	2

Note*: 1= hand dredging without powered boat; 2= hand dredging with powered boat.

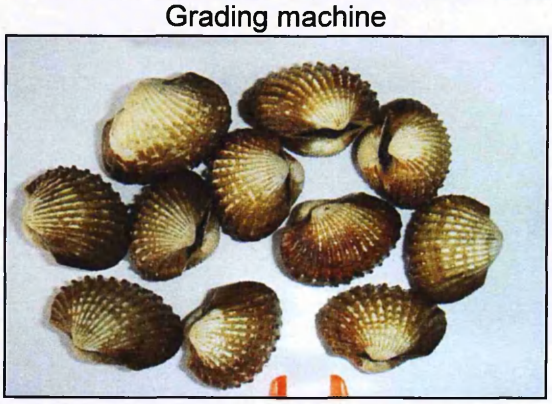
Source: Field survey (2009).

Dredge harvesting

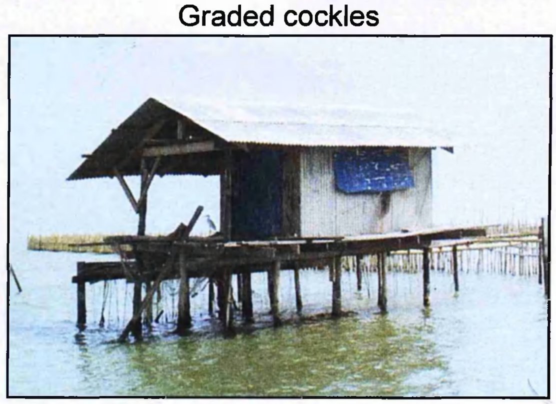
Harvested cockle and dead shell

Grading machine

Graded cockles



Farmed cockle



Guard house

Fig. 2.23. Medium and large cockle farms and farm operations in Pattani Bay, Thailand.

For green mussel, technical feasibility of rearing was started in 1979 using transplanted seeds (no wild seeds available at that period) and a pilot project was conducted for 2 years until 1981. Mature mussels were seeded into the bay in September 1979. Spat fall was found 3 months later and continued throughout the year (Brohmanonda *et al.*, 1988b).

Fig. 2.24. Small scale cockle farm in Pattani Bay, Thailand.

2.2.5.2 Other culture activities

Fish cage culture is mainly found near the Laem Nok area and occasionally found at Talo Samilae and Budee villages. Sea bass (*Lates calcarifer*) is the main culture species and, sometimes, grouper (*Epinephelus coioides, E. malabaricus*) is also included. Farmers use fixed cages to rear their fish as in Fig. 2.25. This is operated by members of the farmer's household.

Fig. 2.25. Fish cage culture in Pattani Bay, Thailand.

2.2.6 Existing molluscs production areas

The general survey for the present study showed that existing mollusc production areas in the bay are classified into 4 categories; mussels collected from bamboo stake traps (stationary gears), mussels farmed by pole and fixed raft, farmed cockle and natural mollusc dredging area (Fig. 2.26). The total areas of each production type are summarised in Table 2.6. The main production area is cockle farms (13.97 km^2) while mussel farm areas are very small (0.14 km^2). For natural molluscs, other than 2 hand dredging sites some molluscs are found seasonally, particularly near the North coastline area.

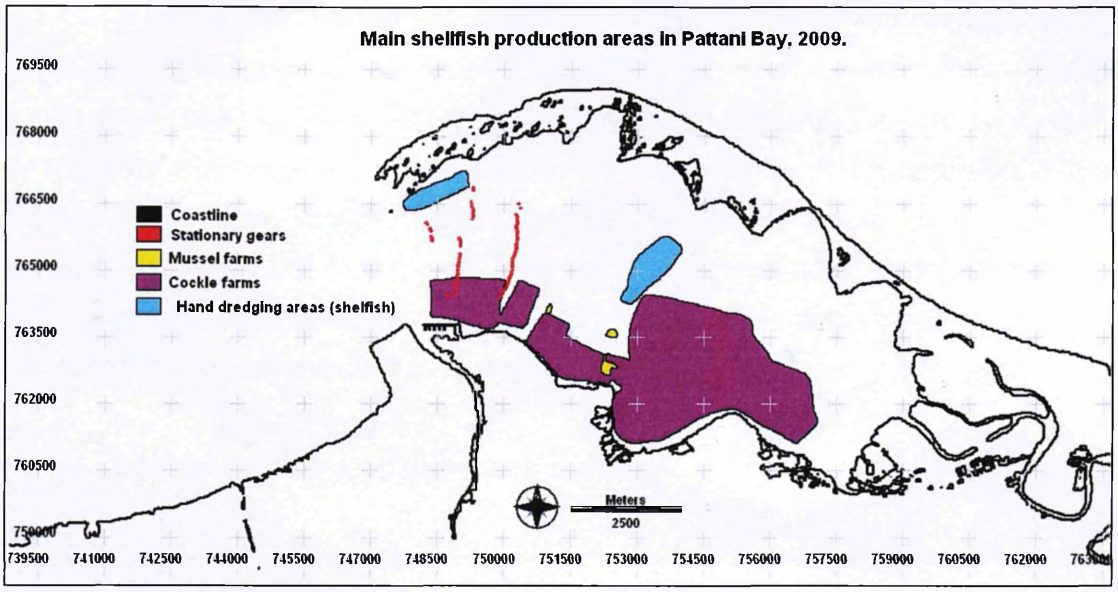


Fig. 2.26. Shellfish production areas in Pattani Bay, Thailand 2009.

Table 2.6.Total area of the main shellfish production in Pattani Bay, Thailand; 2009.

Activities	Area (m^2)	Area (km^2)	Note
Hand dredging areas	1,547,500.00	1.55	
Stationary gears	352,031.25	0.35	Include around trap wing area.
Mussel farms	137,343.75	0.14	
Cockle farms	13,972,343.75	13.97	

Source: Field survey (2009).

Chapter 3
Materials and Methods

3.1 Field experiments and data sampling

This chapter focuses on primary data collection, including sampling stations for ecological parameters, sample analysis, data manipulation and model formulation. The primary data is grouped into mussel growth, water quality, sediment quality and existing land use for mollusc fisheries in Pattani Bay, Thailand. General surveys and discussions with stakeholders were established before the sampling campaign started. For each sampling occasion the time and date of all electronic devices was synchronised. Data and field sampling records were based on sampling stations and corresponding coordinates. Field coordinates were identified using a handheld GPS, a Garmin eTrex vista and a Garmin GPSmap 60csx.

3.1.1 General survey and sampling stations

The general survey, during 10 -13 June 2009, was designed to covered the bay and nearby areas. From the general surveys, information about water quality, sediment type and existing water space utilisation was gathered for all sampling stations including those to be used for the mussel growth experiment. Information from the general survey was used in planning for the whole sampling campaign. The sampling stations and UTM coordinates of the general survey for water and sediment quality are shown in Fig. 3.1. Sampling stations were assigned using the SAMPLE module in IDRISI by the systematic sampling option. The vertical interval between sampling points was approximately 850 m while that of the horizontal interval was 1,700 m.

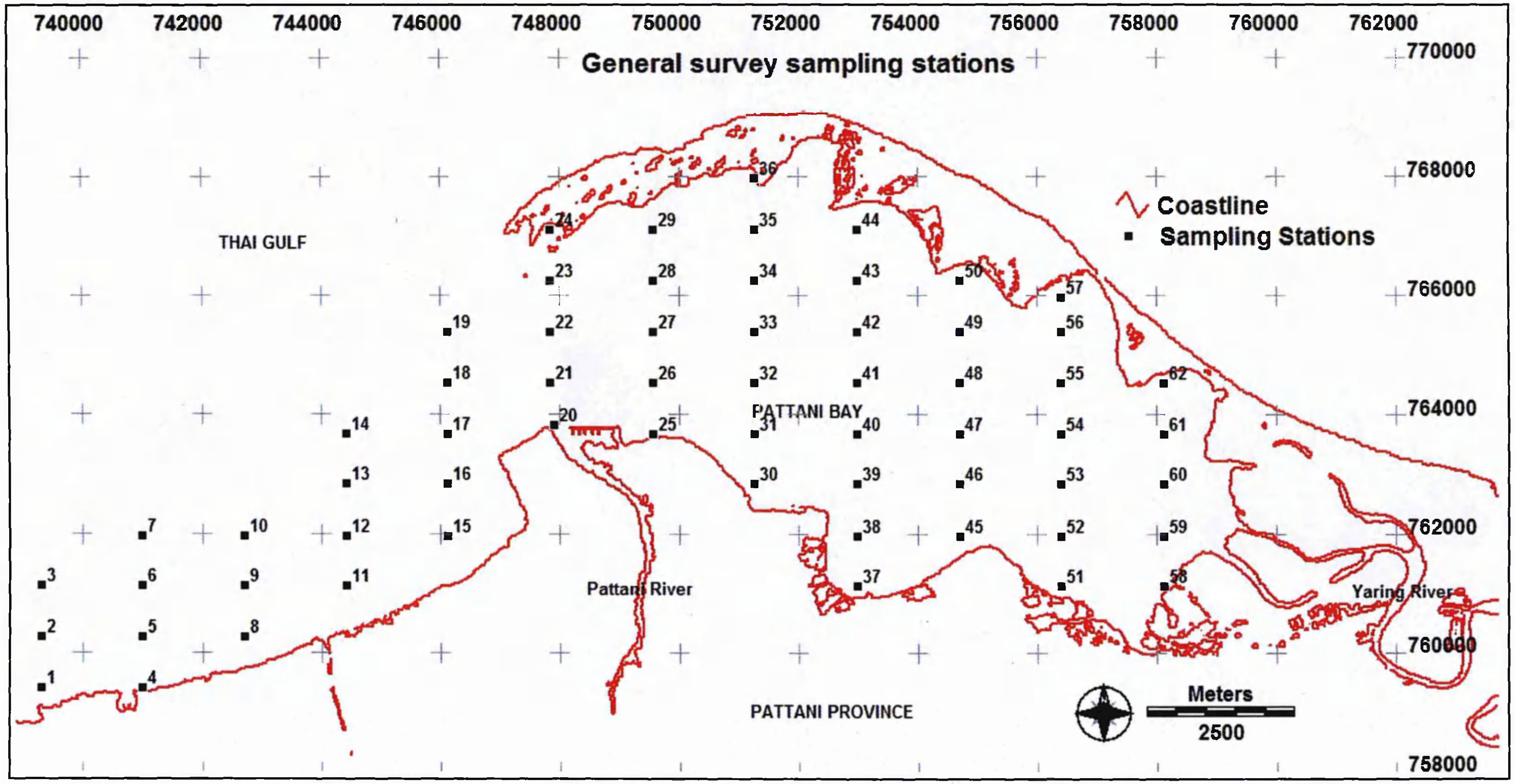


Fig. 3.1. Sampling stations used in the general surveys in Pattani Bay, Thailand.

3.1.2 Mussel growth experiment

3.1.2.1 Experimental station selections

There were several factors involved in the selection of mussel growth station locations; these were bottom sediment type, general water quality, and current fishing and farming activities. Data from the general survey was used along with information from group discussions with key personnel. The locations of the stations were in areas that were considered to be most representative of the bay space whilst also avoiding any conflict with the current fishing activities. Station 1 was affected by both brackish and sea water, whereas stations 2 and 6 situated near the river mouth were influenced by freshwater. Stations 3, 5 and 7 were in areas which may have been influenced by anthropogenic inputs, while stations 8 and 9 were within zones considered relatively free from pollution. Station 4 appeared to be in a transition zone between freshwater or seawater during tidal exchange. The location of the mussel growth trial stations are shown in Fig. 3.2. Station names and corresponding coordinates are shown in Table 3.1.

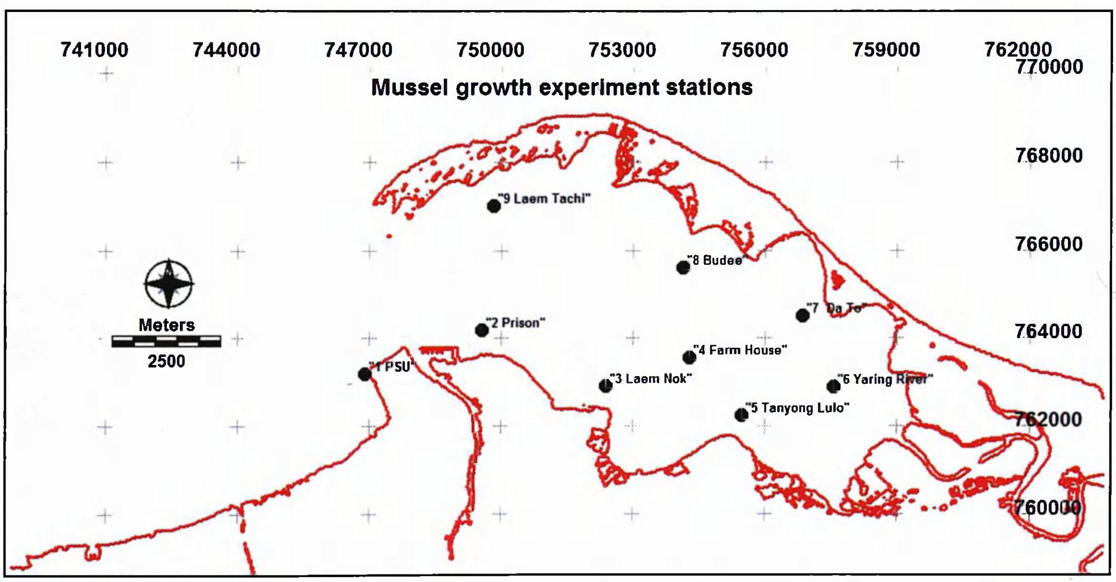


Fig. 3.2. Locations of the mussel growth experiment stations, Pattani Bay, Thailand.

Table 3.1. Station names and UTM location coordinates for mollusc growth experiment stations.

Station ID	Station names	X	Y
1	PSU	746927	763167
2	Prison	749567	764176
3	Laem Nok	752395	762912
4	Farm House	754298	763546
5	Tanyong Lulo	755470	762232
6	Yaring River	757568	762896
7	Da To	756851	764510
8	Budee	754144	765598
9	Laem Ta Chi	749871	767654

3.1.2.2 Mussel seeds and poles preparations

Small mussels were collected from a private pole culture farm. Mussels were removed from the original substrate by cutting their byssus using scissors. Thereafter, all bio-fouling and mud were cleaned thoroughly using seawater. Clean mussels were graded to obtain mussels of the same size for selection of the initial mussel seeds. During selection processes, mussels were placed in a flow of natural sea water. This study used seed mussel sizes of 1.69±0.36 g, 2.56±0.25 cm and 1.39±0.15 cm in weight, length and height, respectively.

The 50 mm mesh size net was cut, folded and sown to become a cylindrical bag of approximately 100 cm in length and 7-9 cm in diameter. To attach mussels to the pole, each pole was inserted into the cylindrical net and tied at the suitable point based on water depth of each station. Nylon rope was fastened to fix the lower end of net bag and 400 mussels were put in to the bag. Mussels were distributed along the 1 m length of the pole using another rope as a fastener. A total of 40 poles were used, with 4 poles being assigned to each station. In addition, a few poles were used for seed settlement monitoring before moving poles with firmly attached mussel to growth trial stations.

3.1.2.3 Mussels acclimatization and pole culture setting

After the mussel wrapping process, all poles were located at a private farm for acclimatization. After 4 days, mussels developed byssus and attached themselves to the bamboo poles. The net bags were then cut and poles with settled mussels were moved to the growth trial stations. Four poles were set up at each station and marked with a flag (Fig. 3.3) to prevent disturbance by local fishermen. The poles were driven at least 40 cm into the bottom to ensure firm anchorage. At each station the exposed parts of the poles were tied together "like a wig-wam" to prevent wind and wave actions.

Fig. 3.3. Some mussel growth experiment stations in Pattani Bay, Thailand.

3.1.2.4 Mussel growth measurement

After the poles were established at each experiment site, the net bags were cut longitudinally to extend the space for mussel growth. Thereafter, mussel growth observations were carried out monthly. Total length and height were measured onsite from 30 - 35 individual mussels selected from each station using Vernier callipers. Thirty mussels were brought back during each sampling occasion to measure length, weight and height to establish the length-weight relationship (Rajagopal, Venugopalan, Nair, van der Velde, Jenner, & den Hartog, 1998b). The length and height dimensions are illustrated in Fig. 3.4. The equation was then applied to find the weight of all onsite mussel samples (Waite, Grant, & Davison, 2005). Mussel weight was measured by electric balance (OHAUS PA 2102) to an accuracy of ±0.01g.

3.1.3 Water quality study

3.1.3.1 Sampling stations

The number of sampling stations for water quality analysis was decreased after the initial general surveys to enable sampling to be completed within the time frame of the project period. In addition, discussions with key personnel confirmed that the offshore area outside the bay (outside shaded area in Fig 3.5.) was unsuitable for carrying out the experiments due to the presence of active fishing grounds. As a result, some stations in each line transect were discarded, though the first and last stations (near shore stations) were maintained. The study area was limited to within the bay where the coordinates of selected sampling stations were identical to those of the general survey. The locations of water sampling stations are shown in Fig. 3.5. The sampling of water currents (Fig. 3.6) were measured separately at each position because of the time consuming nature of the task and water current meter availability. All station coordinates were similar to those of the general survey sampling points.

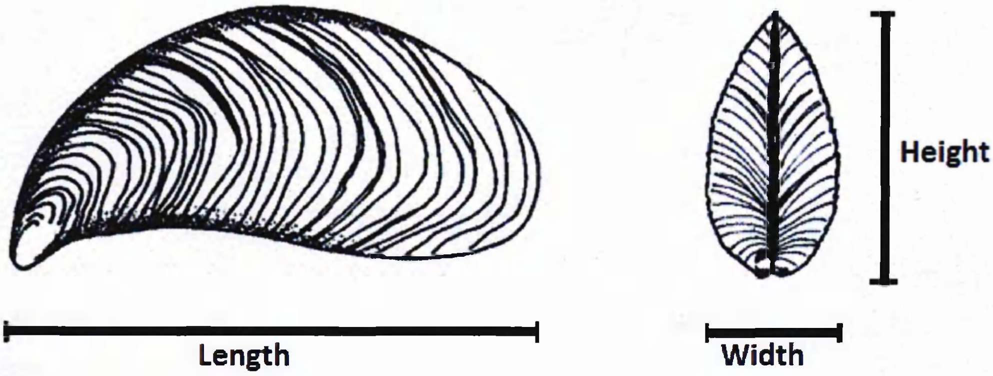


Fig. 3.4. Dimension definition for *P. viridis*
Source: Vakily (1989)

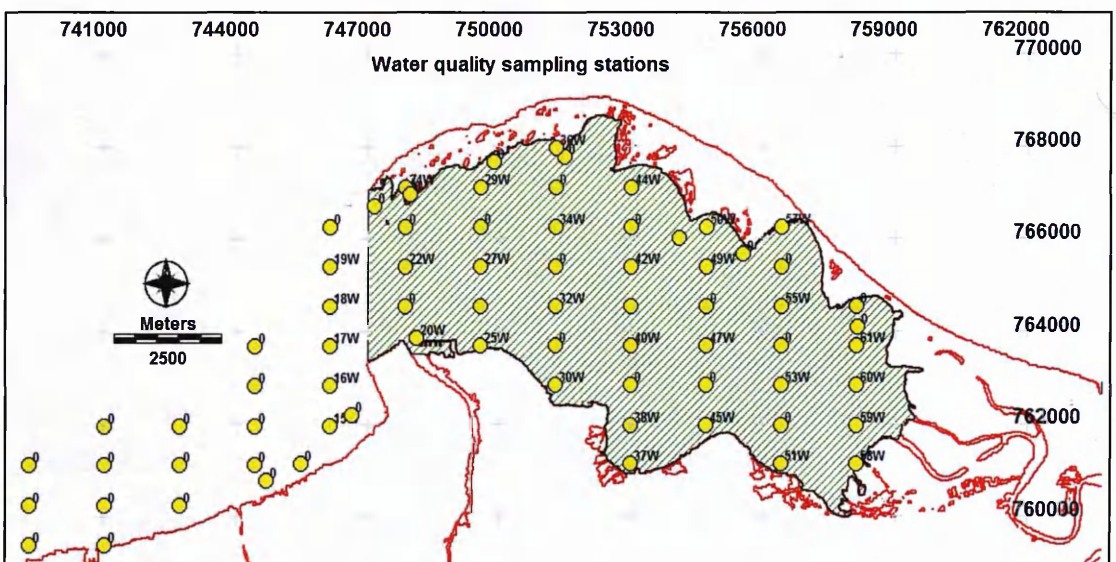


Fig. 3.5. Water sampling stations (W) in Pattani Bay, Thailand.

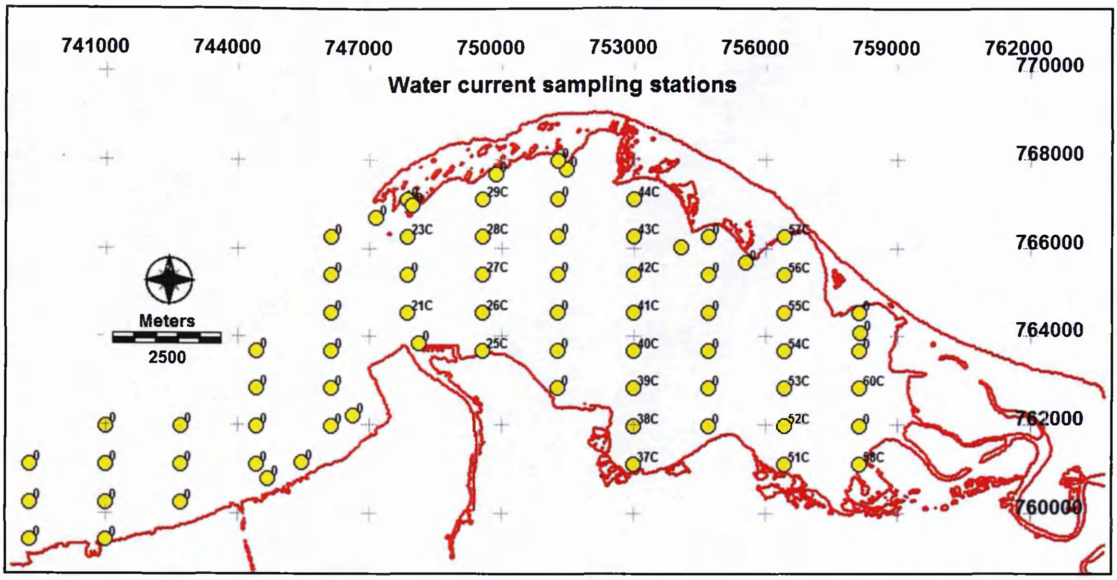


Fig. 3.6. Water current sampling stations (C) in Pattani Bay, Thailand.

3.1.3.2 Sampling parameters

Physical, chemical and biological water quality parameters were investigated. The physical parameters were water depth, transparency, temperature, total suspended solid (TSS), particulate organic matter (POM) and water current. The chemical parameters were dissolved oxygen, pH and salinity. The biological parameter investigated was chlorophyll-a as an indicator on biological productivity.

3.1.3.3 Sampling times

There were two sampling periods, the first during July-September 2009, and the second during December 2009 – February 2010. Over the first period, water quality was sampled 1-2 times per month. Some sampling dates were timed to coincide with the Landsat 7 ETM+ data acquiring schedule (Table 3.2) over the bay.

The water parameters during the first phase represented a time series and were used as inputs to a mussel growth determination model up to marketable size. The second sampling phase was conducted monthly. Both sampling periods covered the culture period of cockle, which takes more than 1 year to reach marketable size.

Sampling times and number of sampling stations for water quality varied depending on parameters, time and available resources, and are summarised in Table 3.3. Practical sampling opportunities also varied because of area accessibility and fishing activities.

As a result, some sampling stations were ignored. The total sampling station with observed data for each sampling time is given in Table 3.4 and 3.5.

Table 3.2. Water quality sampling times and dates.

Sampling phase/Month	Sampling date	Note
The 1st phase		
June 2009	13-06-2009*; 29-06-2009	With 3 days general
July 2009	15-07-2009; 31-07-2009	surveys
August 2009	16-08-2009	
September 2009	01-09-2009	
The 2nd phase		
December 2009	13-12-2009	
January 2010	20-01-2010	
February 2010	23-02-2009	

Note: *From a general survey.

Table 3.3. Sampling parameters, sampling stations and number of occasions for water quality sampling.

Parameters (units)	Sampling stations		Sampling times	
	Phase I*	Phase II	Phase I	Phase II
Depth (m.)	30 and 55**	32	5 and 1**	3
Current (m/s.)	24	-	1	-
Transparency (cm.)	32	32	5	2
Temperature (°C)	32	32	5	3
pH	32	32	4	3
DO (mg/l.)	32	32	5	2
Salinity (ppt.)	30 and 55*	32	5 and 1*	3
TSS (g/l.)	32	32	5	3
TDS (g/l.)	32	32	5	3
Chlorophyll-a (μg/l.)	32	32	5	3
POM (mg/l.)	32	32	3	3

Note: * 49 stations were sampled on 29-06-2009, thereafter this was reduced to 32 stations due to resource availability.

** sampled for the general survey on 13-06-2009

Table 3.4. Number of water quality sampling stations at each sampling time in the first sampling campaign.

Date/ Parameter	Jun. 09		Jul. 09		Aug. 09	Sep. 09
	13/06/09	29/06/09	15/07/09	31/07/09	16/08/09	01/09/09
Chlorophyll-a	-	49.0	29.0	32.0	29.0	29.0
DO	-	48.0	27.0	32.0	29.0	29.0
Depth	52.0	49.0	29.0	32.0	29.0	-
pH	-	-	27.0	32.0	29.0	29.0
POM	-	-	-	32.0	28.0	29.0
Salinity	52.0	48.0	27.0	32.0	29.0	29.0
TDS	-	48.0	27.0	32.0	29.0	29.0
Temperature	-	48.0	27.0	32.0	29.0	29.0
Transparency	-	49.0	29.0	32.0	29.0	29.0
TSS	-	49.0	29.0	30.0	28.0	29.0
Date				26/7/09		
Current (Flow)				20.0		
Current (Ebb)				18.0		

Table 3.5. Number of water quality sampling stations at each sampling time in the second sampling campaign.

Date/Parameters	December 2009	January 2010	February 2010
	13/12/2009	20/01/2010	23/02/2010
Chlorophyll-a	26	29	27
DO	26	29	26
Depth	-	29	26
pH	26	29	26
POM	26	29	27
Salinity	26	28	26
TDS	26	28	26
Temperature	26	29	26
Transparency	26	29	26
TSS	26	29	26

3.1.4 Bottom sediment quality

3.1.4.1 Sampling stations and sampling times

Sediment sampling was conducted twice. The first sampling was done during the general survey period (13/06/2009) using the same sampling stations (Fig. 3.1). Additional data from specific sampling stations from another study project (stations labelled S without a number in Fig. 3.7) were also included. For the second sampling time conducted January (20/02/2010), only 44 sampling stations were used. These were similar to stations 20 – 62 of the general survey because local shellfish producers confirmed that cockle farming was impossible to establish outside the bay due to social and legal limitations. Some sampling stations had to be ignored if fishing was being operated during field sampling.

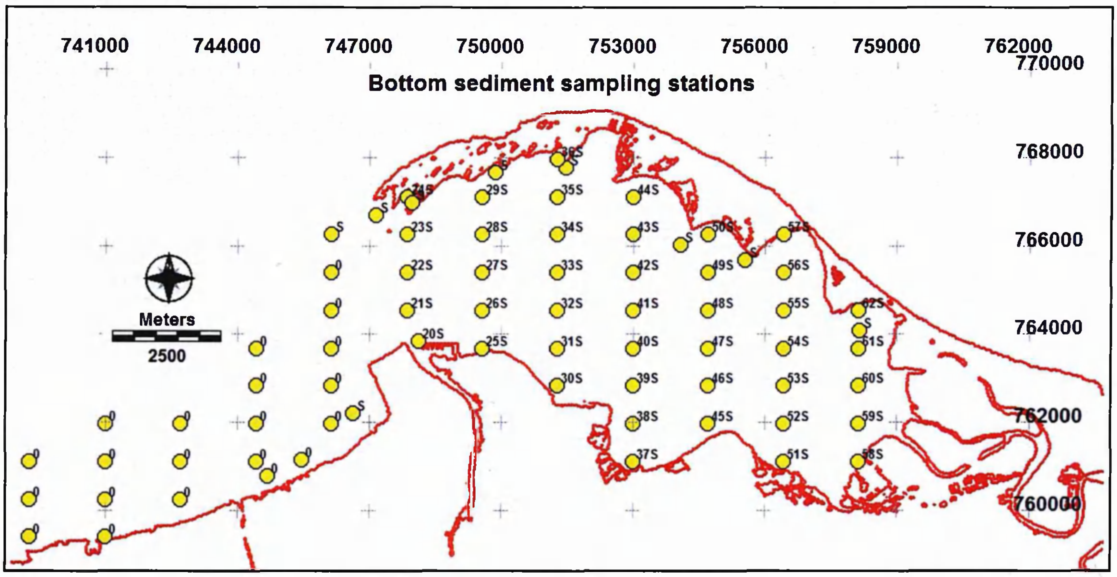


Fig. 3.7. Sediment (S) sampling stations.

3.1.4.2 Sampling parameters

Only bottom sediment up to 0.20 m depth from the surface was collected. Two replicate sediment samples were collected from each sampling station using a PVC tube in shallow water areas while an Ekman grab was applied in deep water areas at the middle of the bay opening. Sediment samples were then analysed in the laboratory to evaluate particle size distribution (%sand, %silt and % clay), organic matter, organic carbon and sediment pH. Bottom slope was calculated based on water depth data.

3.1.5 Existing land use of the bay

The existing use of the bay was focused on the water area. Initially, general area use activities were obtained from discussions with the local fishermen. Thereafter, a local fishing boat and handheld GPS were used to investigate the boundaries of the main activities related to mollusc culture and capture. Using the GPS route tracking function, the data of each water space use type was uploaded to a PC by the GARMIN Map Source™ software. Then, data was imported, mapped and analyzed using IDRISI™ software.

3.2 Samples analysis

3.2.1 Water quality analytical method

Table 3.6 summarises the water parameters monitored and related equipment. Water pH, DO, salinity and TDS were recorded by a multi-probe meter at 1-3 different depth levels depending on water depth. The multi-probe meter also recorded the corresponding date and time for each measured parameter in each sampling station. The remaining water quality parameters were analyzed in the laboratory.

Table 3.6. Water quality parameters, analytical methods and devices.

Parameters	Methods	Devices/Reference
Transparency (cm.)	Sechi-disk	-
Depth (m.)	Depth meter	Hondex echo sounder
Current (m/s.)	Current meter	Valeport BFM 008
Temperature (°C)	Portable meter	YSI 556 MPS Multi-probes
pH	Portable meter	YSI 556 MPS Multi-probes
DO (mg/l.)	Portable meter	YSI 556 MPS Multi-probes
Salinity (ppt.)	Portable meter	YSI 556 MPS Multi-probes
TDS (g/l.)	Portable meter	YSI 556 MPS Multi-probes
TSS (or TPM; g/l.)	Gravimetric method	Boyd & Tucker (1992)
Chlorophyll-a (µg/l.)	Spectrophotometric	Boyd & Tucker (1992)
POM (mg/l.)	Gravimetric method	Boyd & Tucker (1992) Wong (2000) Wong & Cheung (2001b)

Water samples from sampling stations were collected by cylindrical water sampler (WS-2000VS), poured into 1 litre cleaned and dried PE bottles, and stored in Styrofoam boxes. All water samples were kept cool by ice during transport to laboratory. On the same day as the water sampling, 50-100 ml of water sample from each station was filtered for 2 replicates. The residue on filter paper of each station was used for chlorophyll-a analysis. The remaining water samples from each station were stored at 4°C until analysed for TSS and POM.

TSS was obtained by filtered 100-200 ml of water sample using tared GF/C filter paper, rinsed filtered residual with 20 ml distilled water and dried at 104±1°C for 24 hrs. The measured weight was the TSS of the filtered water, which was converted to mg/l (Boyd & Tucker, 1992).

For POM, 200-300 ml of sample water was filtered by GF/C filter paper and washed the residue with 20 ml distilled water. The residue was dried in an oven at 110 °C for 24 hours and weighed. The particulate organic matter (POM) was determined by ignition the filtered residue in muffle furnace at 450 °C for 6 hours. The difference between pre-and post-ignition weights is the POM per filtered volume. This was converted to mg/l (Wong, 2000; Wong & Cheung, 2001b).

The relationship among total particulate matter (TPM), POM, particulate inorganic matter (PIM), and organic seston factor (*f*) can be summarised as Equation 3.1 and 3.3 (Wong, 2000; Wong & Cheung, 2001b). These equations are used for some secondary data conversion in this study.

$$TPM = PIM + POM \qquad \text{Equation 3.1}$$

$$f = POM/TPM \qquad \text{Equation 3.2}$$

Chlorophyll-a was analysed using a spectrophotometric method (Boyd & Tucker, 1992). Water samples were filtered by GF/C fibre filter. A 50-100 ml sample of water was filtered and the residue and filter mixed in 2 ml of 90% acetone using a tissue grinder. Then 8 ml of 90% acetone were added to the mixture and refrigerated overnight in the dark. The mixture was then centrifuged at 2,000-3,000 rpm and the supernatant transferred to a cuvette for absorbance measurement using spectrophotometer (SHIMADZU UV-160A) at 655 and 750 nm. Acetone (90%) was used as a blank. Chlorophyll-a was calculated using Equation 3.3.

$$\text{Chlorophyll-a } (\mu g\ l^{-1}) = 11.9*(A_{665} - A_{750}) *(V/L)*(1000/S) \qquad \text{Equation 3.3}$$

Where A_{665} = the absorbance at 655 nm.

A_{750} = the absorbance at 750 nm.

V = the acetone extract (ml.)

L = the length of light path in the spectrophotometer (cm.)

S = the sample filtered volume (ml.)

3.2.2 Soil sample preparation and analytical methods

A summary of sediment parameters is shown in Table 3.7.

Table 3.7. Bottom soil quality parameters and samples analytical methods.

Parameters	Method	Reference
Soil pH	pH-meter	Boyd (1995)
Organic matter	Walkley-Black method	Boyd & Tucker (1992) and Boyd (1995)
Organic carbon	Walkley-Black method	Boyd & Tucker (1992) and Boyd (1995)
Soil separates (% Sand, Silt,Clay)	Pipette method	van Reeuwijk (2002)
Bottom slope	SURFACE module	Calculate by IDRISI

After sediment samples were collected, they were transported to the laboratory where they were air dried. Each sample was spread as a very thin layer on a rigid plastic sheet and kept in a shaded area for drying. Dead shell and plant debris were removed during this process. Air drying took around 2-3 weeks, after which each dry sediment sample was crushed by rubber hammer into sediment particles. The sediment particles were then sifted using a Number 10 sieve, based on U.S. Standard Sieve Number 10 (Boyd, 1995), to exclude particle sizes of >2 mm.

The ground dry samples were used for sediment pH and particle size (%sand, %silt and %clay) analyses. Sediment pH determined by pH-meter (Boyd, 1995) while soil particle sizes was analysed by the pipette method (van Reeuwijk, 2002) to identify the relative percentage of sand, silt and clay particles in sediment. The relative particle sizes were used to classify sediment types using a soil triangle (Boyd, 1995) as shown in Fig. 3.8. Organic matter and organic carbon were determined by titration using the Walkley-Black method (Boyd & Tucker, 1992; Boyd, 1995). Here the ground, dried sample was passed through a Number 60 sieve (0.025 mm mesh size) prior to titration.

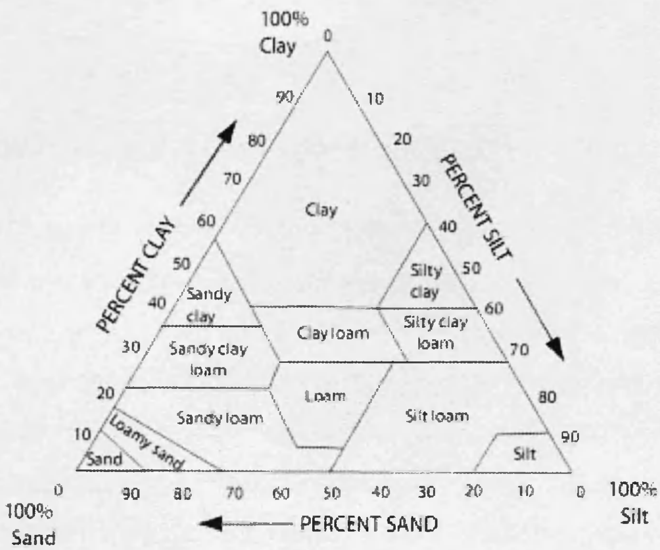


Fig. 3.8. Soil texture triangle and soil type

Source: Boyd, Wood, & Thunjai (2002).

3.3 Data processing

3.3.1 General data manipulation and analysis

3.3.1.1 Basic data manipulation and analysis

Microsoft Excel 2007 was used for initial data manipulation, particularly during data collection and laboratory analysis, as well as preparation of some graphs and calculation of functions, such as progressive growth functions of mussel. Thereafter, the data was organised and imported to other software depending on analytical techniques and study purposes.

3.3.1.2 Statistical analyses

Basic descriptive statistics (minimum, maximum, mean, standard deviation) and some multivariate analysis, such as Analysis of Variance (ANOVA), were performed by SPSS for Windows version 13. Duncan's New Multiple range test was applied as the *post-hoc* test to compare the mean values among groups/stations. The measurement of sample adequacy and identity matrix were performed using Kaiser-Meyer-Olkin (KMO) and Bartlett's tests, respectively. These two tests were applied to prove some basic requirements prior to do principal component analysis (PCA). A KMO value of >0.5 implies that the data is adequate for PCA analysis, while a Bartlett's test value must be significant at α = 0.05 in order to establish that there is autocorrelation and thus validate the use of PCA. All techniques mentioned previously were applied in Chapter 5.

3.3.2 Databases and data layers construction

All data prepared were imported to the IDRISI Database Workshop for database construction. From the database, point values of each parameter were exported to a vector file which was then interpolated and filtered to create a raster file (layer). All point data layers were transformed to raster layers by the similar method within the IDRISI Andes™ and IDRISI Taiga™ environments. These layers were used as input layers for the subsequent modelling processes. Raster layers in this study were classified into 4 main different groups, which were (1) mussel growth, (2) water quality layers, (3) sediment quality layer and (4) a Boolean layer of the study area. The detailed processing of data layers is described in Chapter 4.

3.4 Model formulations

Three main models were formulated in this study: a mussel growth determination model, a mussel harvesting model and an optimization model for suitable cockle culture.

3.4.1.1 Principal component analysis (PCA)

PCA was applied for data reduction. The PCA analysis in this study was performed within the IDRISI Taiga Environment and used raster layers as an input data. The numbers of extracted principal components (PCs) were equal to the total number of input water quality parameters. Main principal components (MPCs) of each PC set were defined by eigenvalue of >1.0 (Milstein, 1993; Çamdevýren, Demýr, Kanik, & Keskýn, 2005).

3.4.1.2 Mussel growth determination models

Mussel growth determination models were divided into 2 main groups. All groups were constructed based on a multiple regression approach. The first group, namely principal component regressions (PCR), applied the PCs or the MPCs as explanatory variables

(Equation 3.4 and 3.5). The second group was multiple linear regressions (MLR), which employed the highest loading water quality (WQs) of the MPCs as the explanatory variables (Equation 3.6). A simple regression equation was included in the second group in the case where only one WQs was applied. The coefficient of determination (R^2) was used as an indication of prediction success of each model. All model function forms and variables in this study are illustrated in the following equations:

$$Y = f(PC_1, PC_2, \ldots PC_n) = a_1PC_1 + a_2PC_2 + \ldots + a_nPC_n + c \quad \text{Equation 3.4}$$

$$Y = f(MPC_1, MPC_2, \ldots MPC_n) = a_1MPC_1 + a_2MPC_2 + \ldots + a_nMPC_n + c \quad \text{Equation 3.5}$$

$$Y = f(WQ_1, WQ_2, \ldots WQ_n) = a_1WQ_1 + a_2WQ_2 + \ldots + a_nWQ_n + c \quad \text{Equation 3.6}$$

Where Y = Average mussel growth rate (g/month)

c = Constance value

a_1-a_n = Coefficient values

PC_1-PC_n = All PCs

MPC_1- MPC_n = Main PCs

WQ_1-WQ_n = The highest loading water parameter of MPC_1- MPC_n

3.4.2 Mussel harvestable area model

The Mussel harvesting model comprised two main steps, (1) mussel empirical growth functions and (2) spatial growth model formulation. The final output of the model illustrated the harvestable area of mussels from the bay for every 10 days intervals.

The first step of the model was carried out within Microsoft Excel 2007 using point data. Empirical growth functions were formulated using the Julian day[1] as an explanatory variable to explain mussel length and weight (dependent variable).

[1] Julian day is used in Julian date (JD) system. It refers to day-of-year (ordinal date) ranging between 1 and 366 (starting on January 1st).

Function forms were simple linear regression and logarithmic functions. Coefficient of determination (R^2) indicated the prediction power of all explanatory variables. The empirical growth functions were done on a sampling station basis.
For the spatial growth model formulation, all input data were raster files. The raster files used in this model represented the average weight of seed mussels and the coefficients and constant values of all progressive growth functions for all mussel growth trial stations. The spatial growth model was mainly formulated by the Macro Modeler in the IDRISI Taiga™ environments. DynaLink was employed for repeated calculation processes.

3.4.3 Optimization model for cockle culture site

Suitable culture sites were determined based on 3 main parameter groups, water quality, sediment quality and constraint factors. Related raster layers of environmental parameters from field sampling were classified by a fuzzy technique, which transformed the original value of each parameter to suitability scores, ranging from 0-1 (Burrough, 1989; Eastman, 1999b). Fuzzy classification using sigmoidal function was done for every parameter of each sampling occasion. Suitability score layers were then used as an input for the sub-model formulation factors.

Three sub-models; water, sediment and constraint sub-models, were formulated by a Multiple Criteria Evaluation (MCE) technique based on each sampling occasion. Pairwise scoring between input factors was based on a 9 point continuous rating scale (Eastman, 1999b). The weighting for each factor used in the MCE process was calculated by the WEIGHT module in IDRISI. Acceptability of the weight of factors was indicated by a consistency ratio (CR) value of <0.10 (Saaty, 1977). Suitable culture sites of each sampling occasion were classified by a suitability score cut off value of >0.95. Overall suitability of areas was obtained using different overlaying options. Not only suitable areas were evaluated, but vulnerable factors for cockle culture were also illustrated by comparing field sampling data to the reported information.

Chapter 4
Database construction

The majority of the data used in this study was derived from original field work or was sourced from internet while some was obtained from relevant governing agencies. Most data was originally supplied in varying formats, projections and resolutions all of which needed some manipulation and conversion before incorporation into the database. All data sources were processed in IDRISI to conform to the UTM47N projection. Data used for spatial modelling was rasterised to 30m resolution to match baseline LANDSAT ETM+ imagery. The spatial data used in this study comprised 4 different groups; a) development of a Boolean image of the study area, b) water quality parameters, c) sediment parameters and d) mussel growth data. This chapter describes the data manipulation and database construction for the last three groups and spatial layer construction of all data groups.

4.1 The bay boundary identification

A Boolean image of the study area was developed from a January, 2005 LANDSAT 7 ETM^+ satellite image. The main scene is LE71280552005025EDC00, which was gap-filled using 2 scenes, LE71280552006060EDC00 and LE71280552002065SGS00 provided by NASA Landsat Program (2005). Firstly, the PANSHARPEN module was used with colour space transformation approach for resolution enhancement. The resolution of satellite image of band 3, 4 and 5 (Fig. 4.1) were enhanced using the panchromatic band (Band 8, Fig. 4.2) to become 15m x 15m pixel size.

A composite image (RGB: 4:5:3) was produced using the enhanced bands (Fig. 4.3). Dark blue areas in the composite image illustrated water bodies including sea and inland water surface.

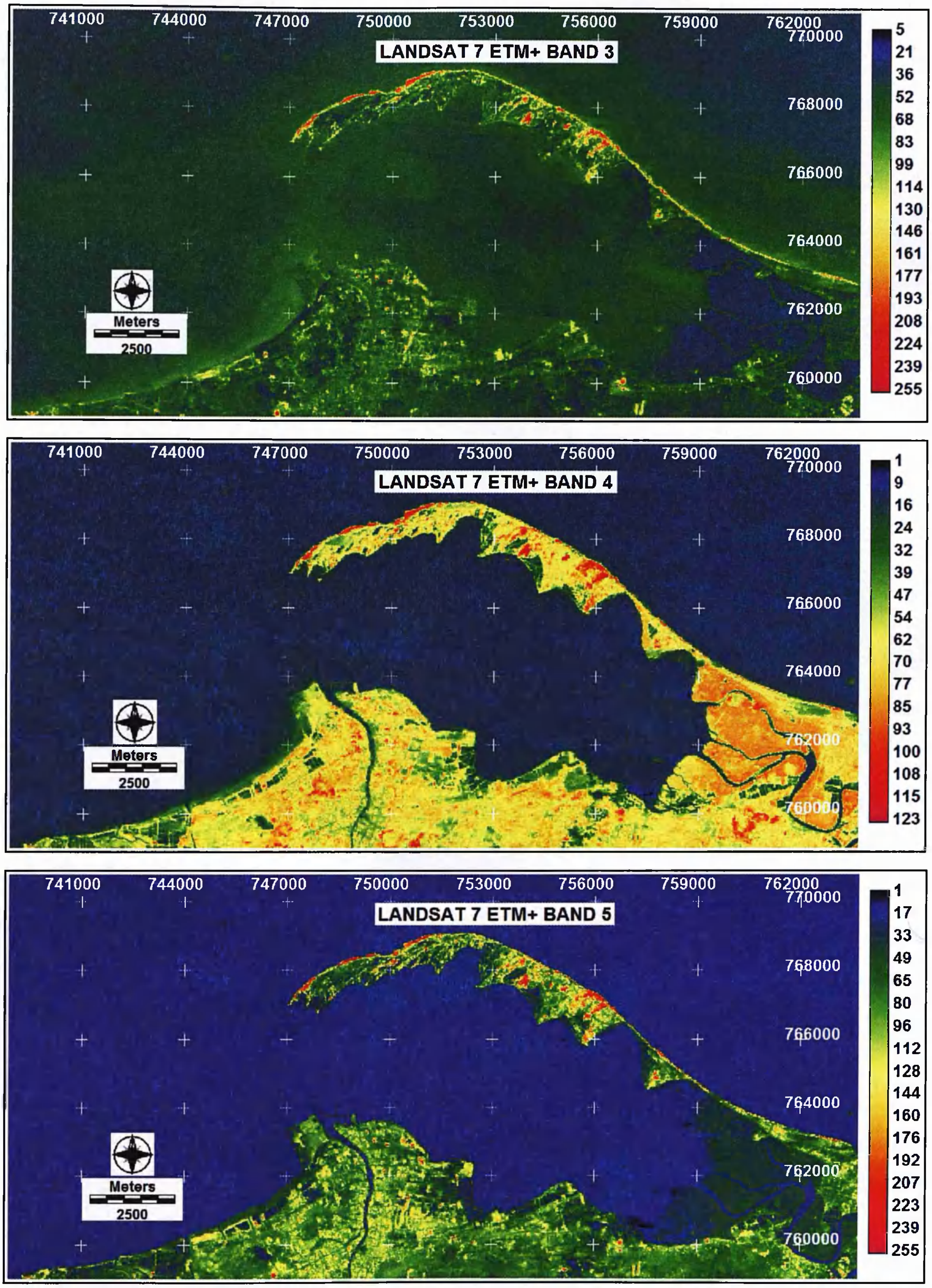


Fig. 4.1. LANDSAT 7 ETM+ images of band 3, 4 and 5 of Pattani Bay, Thailand.

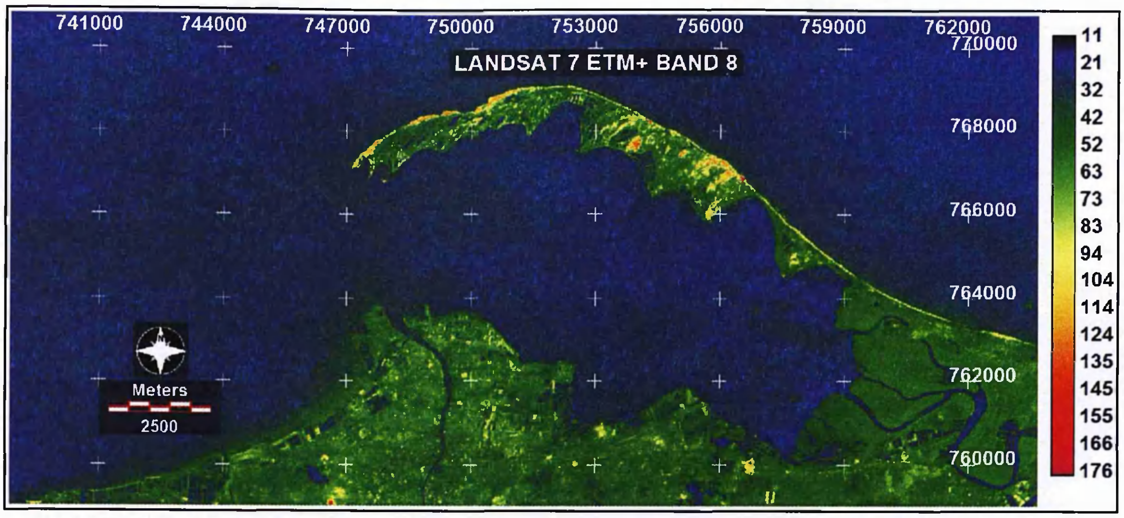


Fig. 4.2. LANDSAT7 ETM^{+} image band 8 of Pattani Bay, Thailand.

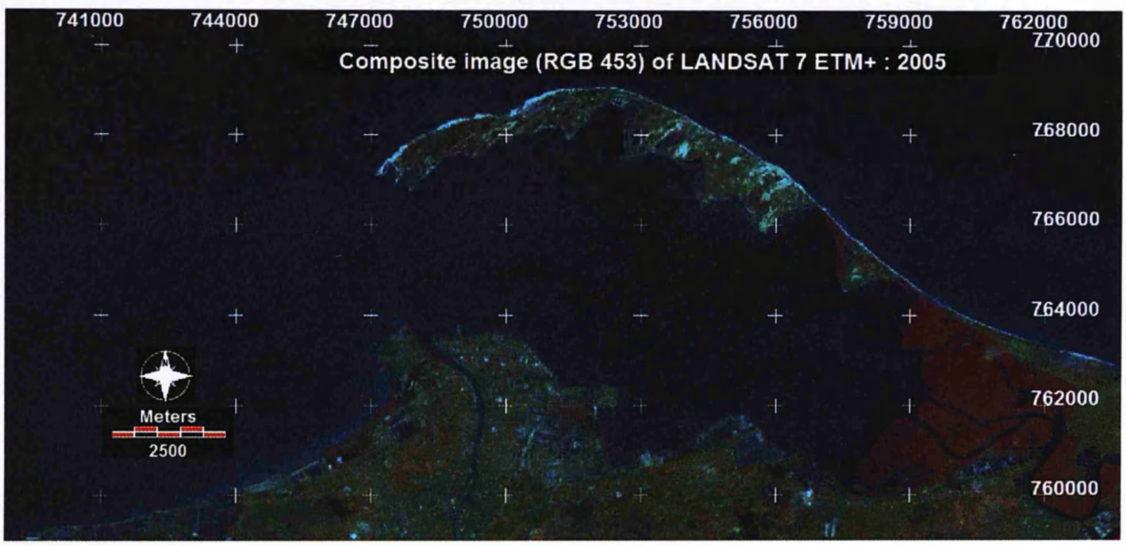


Fig. 4.3. Pansharpened composite image (RGB 4:5:3) of Pattani Bay, Thailand.

The enhanced bands were then analyzed using unsupervised classification in the CLUSTER module, specifying 4 different clusters as shown in Fig. 4.4. Cluster 1 represented the sea area and all inland water bodies. Cluster 3 reflected mangrove areas, especially the reserved mangrove area around Yaring River mouth and a small area just next to Da To village. Man-made mangrove areas near PSU Pattani and additional inland forest areas were also included. The remaining inland areas were occupied by clusters 2 and 4.

A Boolean image was constructed by reclassification. The summation of 3 clusters (2, 3 and 4) represented land area while the rest represented water bodies (Fig. 4.5). However, additional editing was necessary for some areas, where the land-water boundary was not clear as well as areas with cloud shadow. A combination of ground truthing and Google Earth were employed to identify the real coastline. Unclear boundaries were found at Land Fill, shrimp farms near Laem Nok, Tanyong Lu Lo and Budee villages. Some inland water bodies, except rivers, were filled by onscreen editing. Thereafter, the coastline was identified by rasterizing the land area polygon file. The actual study area used in study was limited to the bay water body, extending from the vertical line of UTM 747000 East or the vertical line from the tip of Leam Tachi to Land Fill (as detail mentioned in Fig. 3.5.).

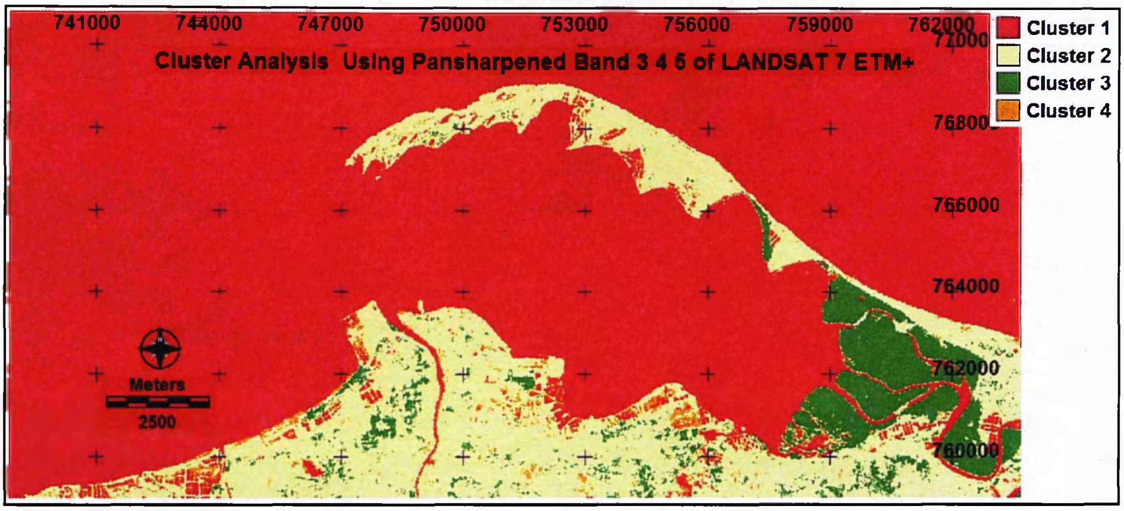


Fig. 4.4. Cluster analysis from pansharpended images (Bands 3:4:5) of Pattani Bay, Thailand.

Finally, the RECLASS module was used to produce a Boolean image which separated the water bodies from the land area.

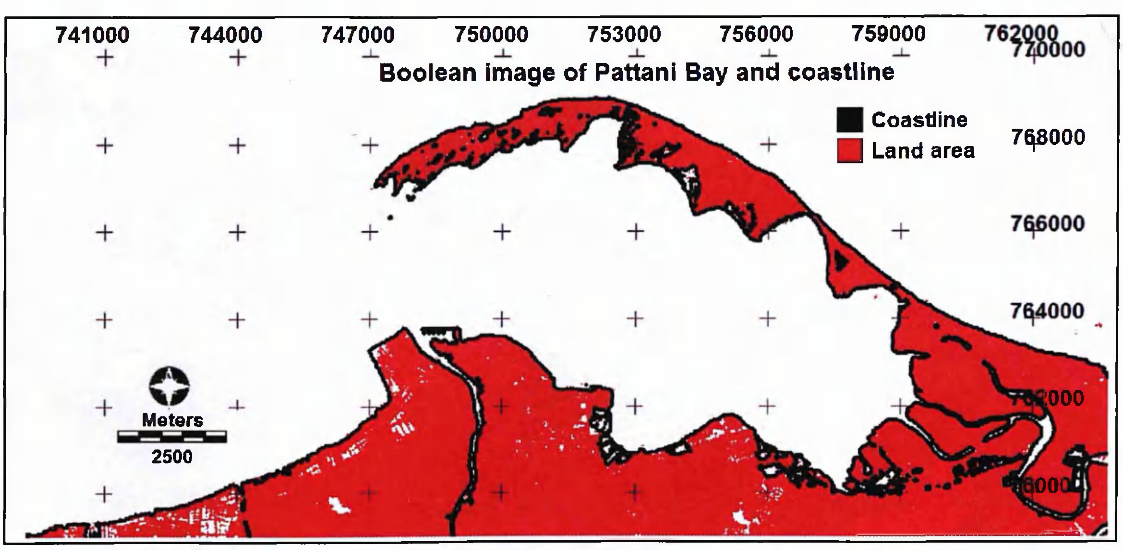


Fig. 4.5. Boolean image of the Land and water area of Pattani Bay, Thailand.

A flow chart summarising these processes is shown in Fig. 4.6.

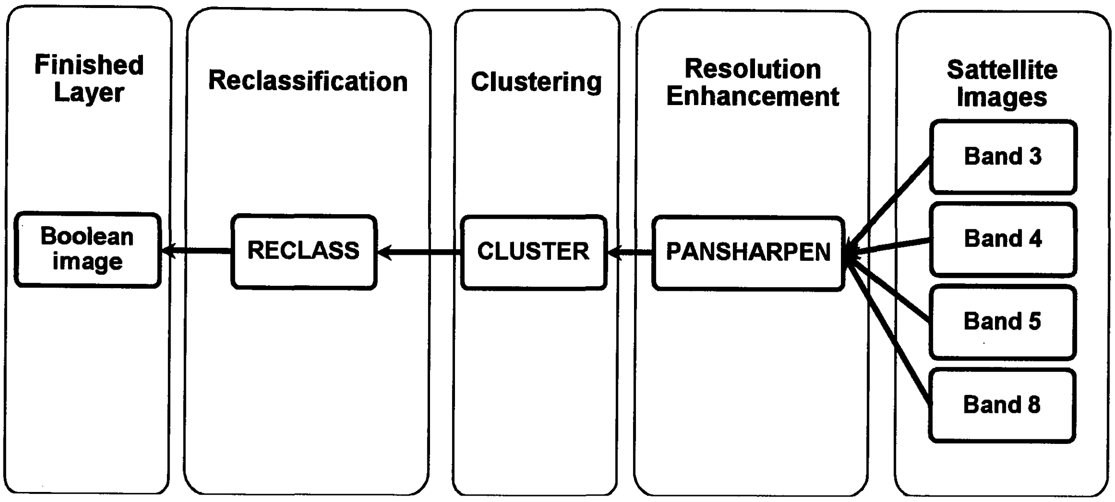


Fig. 4.6. Schematic diagram of the production of a Boolean image from the LANDSAT7 ETM+ satellite images.

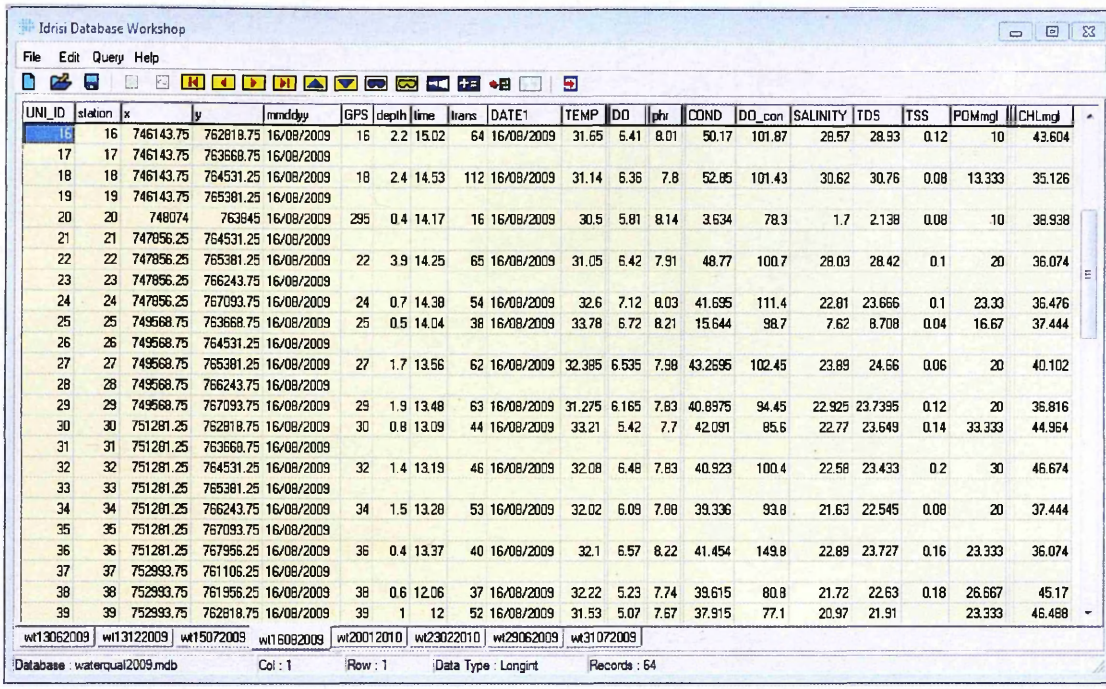
4.2 Database construction

The databases were divided into 3 main groups: water parameters, sediment parameters and mussel growth. The common structure of all databases was: record ID, sampling station, UTM coordinates of sampling station and observed value of parameters. Examples of the construction and structure of each database are illustrated below.

4.2.1 Water quality parameters

Water parameters from the first sampling phase were mainly used for principal component analysis (PCA) and mussel growth determination. Additionally, the information was used as a general water quality description to confirm that the bay area is suitable for mussel culture. Water quality parameters from all sampling phases were used to identify suitable cockle culture areas because the culture period of cockles extended for longer than that of mussels. A general discussion with farmers in the bay revealed that the cockle culture period varied depending on the size of the cockle seed and on average, it took around 1 year to attain marketable size.

The water quality database was formulated in the IDRISI Database Workshop, an example of which is shown in Fig. 4.7. Sampling stations in different rows were identified by different ID numbers. Station coordinates, sampling date, time and observed value of each water parameter were assigned to different columns. Because of the number of sampling stations and sampling parameters, and the differences between sampling occasions, separate databases were constructed for each sampling occasion.



UNI_ID	station	x	y	mmddyy	GPS	depth	time	trans	DATE1	TEMP	DO	phr	COND	DO_con	SALINITY	TDS	TSS	POMmgl	CHLmgl
16	16	746143.75	762818.75	16/08/2009	16	2.2	15.02	64	16/08/2009	31.65	6.41	8.01	50.17	101.87	28.57	28.93	0.12	10	43.604
17	17	746143.75	763668.75	16/08/2009															
18	18	746143.75	764531.25	16/08/2009	18	2.4	14.53	112	16/08/2009	31.14	6.36	7.8	52.85	101.43	30.62	30.76	0.08	13.333	35.126
19	19	746143.75	765381.25	16/08/2009															
20	20	748074	763845	16/08/2009	295	0.4	14.17	16	16/08/2009	30.5	5.81	8.14	3.634	78.3	1.7	2.138	0.08	10	38.938
21	21	747856.25	764531.25	16/08/2009															
22	22	747856.25	765381.25	16/08/2009	22	3.9	14.25	65	16/08/2009	31.05	6.42	7.91	48.77	100.7	28.03	28.42	0.1	20	36.074
23	23	747856.25	766243.75	16/08/2009															
24	24	747856.25	767093.75	16/08/2009	24	0.7	14.38	54	16/08/2009	32.6	7.12	8.03	41.695	111.4	22.81	23.666	0.1	23.33	36.476
25	25	749568.75	763668.75	16/08/2009	25	0.5	14.04	38	16/08/2009	33.78	6.72	8.21	15.644	98.7	7.62	8.708	0.04	16.67	37.444
26	26	749568.75	764531.25	16/08/2009															
27	27	749568.75	765381.25	16/08/2009	27	1.7	13.56	62	16/08/2009	32.385	6.535	7.98	43.2695	102.45	23.89	24.66	0.06	20	40.102
28	28	749568.75	766243.75	16/08/2009															
29	29	749568.75	767093.75	16/08/2009	29	1.9	13.48	63	16/08/2009	31.275	6.165	7.83	40.8975	94.45	22.925	23.7395	0.12	20	36.816
30	30	751281.25	762818.75	16/08/2009	30	0.8	13.09	44	16/08/2009	33.21	5.42	7.7	42.091	85.6	22.77	23.649	0.14	33.333	44.964
31	31	751281.25	763668.75	16/08/2009															
32	32	751281.25	764531.25	16/08/2009	32	1.4	13.19	46	16/08/2009	32.08	6.48	7.83	40.923	100.4	22.58	23.433	0.2	30	46.674
33	33	751281.25	765381.25	16/08/2009															
34	34	751281.25	766243.75	16/08/2009	34	1.5	13.28	53	16/08/2009	32.02	6.09	7.88	39.336	93.8	21.63	22.545	0.08	20	37.444
35	35	751281.25	767093.75	16/08/2009															
36	36	751281.25	767956.25	16/08/2009	36	0.4	13.37	40	16/08/2009	32.1	6.57	8.22	41.454	149.8	22.89	23.727	0.16	23.333	36.074
37	37	752993.75	761106.25	16/08/2009															
38	38	752993.75	761956.25	16/08/2009	38	0.6	12.06	37	16/08/2009	32.22	5.23	7.74	39.615	80.8	21.72	22.63	0.18	26.667	45.17
39	39	752993.75	762818.75	16/08/2009	39	1	12	52	16/08/2009	31.53	5.07	7.67	37.915	77.1	20.97	21.91		23.333	46.488

Fig. 4.7. An example of a water quality parameter database.

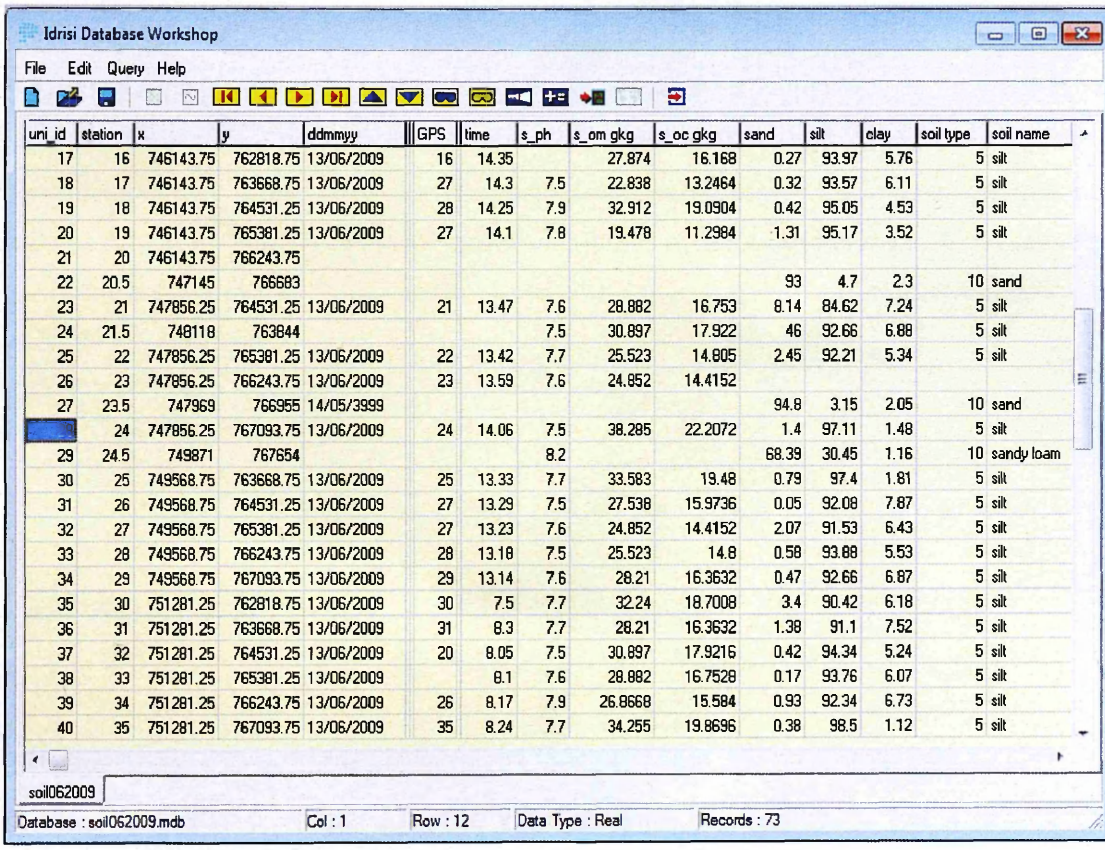
4.2.2 Sediment quality

Sediment data were obtained from 2 sampling periods as shown in Table 4.1. This data included the data from 32 sampling stations (see Chapter 3), some data from specific sampling sites and further data from another study project conducted in the same period. Sediment quality was mainly used for the cockle modelling because cockle is a bottom dweller and bottom culture is the only culture technique applied in the bay.

The sediment database (Fig. 4.8) was structured similarly to that for water quality but contained fewer observed parameters. From the different combination of ratios among sand, silt and clay particles, bottom soil types were classified. The main bottom sediment type was silt followed by silty loam, loamy sand, sand, sandy loam and clay loam. The last two types were each only found at one station while silt was found to be the main bottom sediment for approximately 76% of all sampling points. The remaining sediment types were found at 2-4 stations each.

Table 4.1. Sampling times and stations of sediment parameters.

Date/Parameters	June 09	February 10	Note
	13/06/2009	20/02/2010	
pH	50	35	Additional data in the 1st sampling time is obtained from other study project in the same period.
Organic matter (g/kg.)	47	35	
Organic carbon (g/kg.)	47	35	
Sand (%)	50	40	
Silt (%)	50	40	
Clay (%)	50	40	



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uni_id	station	x	y	ddmmyy	GPS	time	s_ph	s_om gkg	s_oc gkg	sand	silt	clay	soil type	soil name
17	16	746143.75	762818.75	13/06/2009	16	14.35		27.874	16.168	0.27	93.97	5.76	5	silt
18	17	746143.75	763668.75	13/06/2009	27	14.3	7.5	22.838	13.2464	0.32	93.57	6.11	5	silt
19	18	746143.75	764531.25	13/06/2009	28	14.25	7.9	32.912	19.0904	0.42	95.05	4.53	5	silt
20	19	746143.75	765381.25	13/06/2009	27	14.1	7.8	19.478	11.2984	1.31	95.17	3.52	5	silt
21	20	746143.75	766243.75											
22	20.5	747145	766683							93	4.7	2.3	10	sand
23	21	747856.25	764531.25	13/06/2009	21	13.47	7.6	28.882	16.753	8.14	84.62	7.24	5	silt
24	21.5	748118	763844				7.5	30.897	17.922	46	92.66	6.88	5	silt
25	22	747856.25	765381.25	13/06/2009	22	13.42	7.7	25.523	14.805	2.45	92.21	5.34	5	silt
26	23	747856.25	766243.75	13/06/2009	23	13.59	7.6	24.852	14.4152					
27	23.5	747969	766955	14/05/3999						94.8	3.15	2.05	10	sand
[illegible]	24	747856.25	767093.75	13/06/2009	24	14.06	7.5	38.285	22.2072	1.4	97.11	1.48	5	silt
29	24.5	749871	767654				8.2			68.39	30.45	1.16	10	sandy loam
30	25	749568.75	763668.75	13/06/2009	25	13.33	7.7	33.583	19.48	0.79	97.4	1.81	5	silt
31	26	749568.75	764531.25	13/06/2009	27	13.29	7.5	27.538	15.9736	0.05	92.08	7.87	5	silt
32	27	749568.75	765381.25	13/06/2009	27	13.23	7.6	24.852	14.4152	2.07	91.53	6.43	5	silt
33	28	749568.75	766243.75	13/06/2009	28	13.18	7.5	25.523	14.8	0.58	93.88	5.53	5	silt
34	29	749568.75	767093.75	13/06/2009	29	13.14	7.6	28.21	16.3632	0.47	92.66	6.87	5	silt
35	30	751281.25	762818.75	13/06/2009	30	7.5	7.7	32.24	18.7008	3.4	90.42	6.18	5	silt
36	31	751281.25	763668.75	13/06/2009	31	8.3	7.7	28.21	16.3632	1.38	91.1	7.52	5	silt
37	32	751281.25	764531.25	13/06/2009	20	8.05	7.5	30.897	17.9216	0.42	94.34	5.24	5	silt
38	33	751281.25	765381.25	13/06/2009		8.1	7.6	28.882	16.7528	0.17	93.76	6.07	5	silt
39	34	751281.25	766243.75	13/06/2009	26	8.17	7.9	26.8668	15.584	0.93	92.34	6.73	5	silt
40	35	751281.25	767093.75	13/06/2009	35	8.24	7.7	34.255	19.8696	0.38	98.5	1.12	5	silt

soil062009

Database : soil062009.mdb Col : 1 Row : 12 Data Type : Real Records : 73

Fig. 4.8. An example of a sediment parameter database.

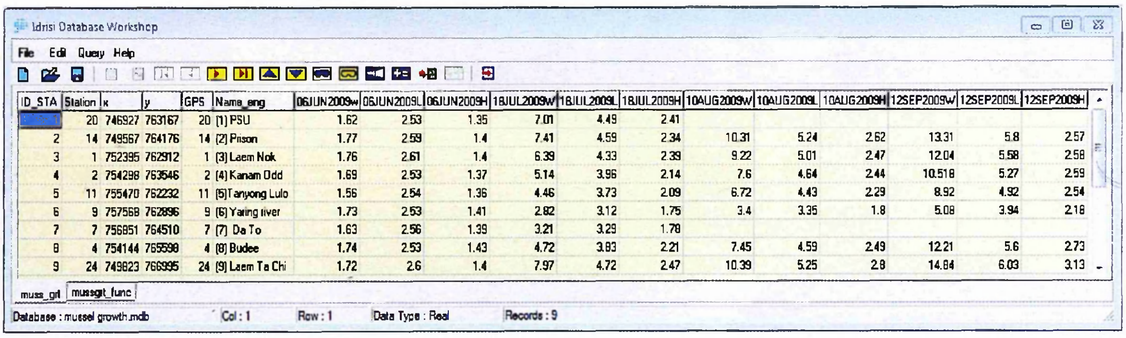
4.2.3 Mussel growth

The mussel growth experiment was carried out in the natural conditions of the bay during June-September 2009 until some mussels had reached marketable size of 6 cm in total length. Mussel size in terms of weight, height and length were monitored 4 times including an initial size measurement. The number of sampling times, stations and parameters are shown in Table 4.2.

Table 4.2. Sampling times and sampling stations of mussel growth parameters.

Date/Parameters	06 Jun. 2009	18 Jul. 2009	10 Aug. 2009	12 sept. 2009
Weight (g.)	9	9	7	7
Length (cm.)	9	9	7	7
Width (cm.)	9	9	7	7

The database structure of mussel growth is similar to that of the sediment and water qualities, but using different observed values (Fig. 4.9). Data on average monthly mussel growth is used as a dependent variable in Principal Component Regression (PCR), Multiple Linear Regression (MLR) and simple regression models. An additional database related to mussel growth was developed to illustrate values of progressive growth function's coefficients and independent parameters of the mussel progressive growth function. The progressive growth function at each station was formulated by using mussel length as the dependent variable (Y) and the Julian day as independent variable (X) (see Fig. 5.15).



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ID_STA	Station	x	y	GPS	Name_eng	06JUN2009w	06JUN2009L	06JUN2009H	18JUL2009W
1	20	746927	763167	20	[1] PSU	1.62	2.53	1.35	7.01
2	14	749567	764176	14	[2] Prison	1.77	2.59	1.4	7.41
3	1	752395	762912	1	[3] Laem Nok	1.76	2.61	1.4	6.39
4	2	754298	763546	2	[4] Kanam Odd	1.69	2.53	1.37	5.14
5	11	755470	762232	11	[5]Tanyong Lulo	1.56	2.54	1.36	4.46
6	9	757568	762896	9	[6] Yaring river	1.73	2.53	1.41	2.82
7	7	756851	764510	7	[7] Da To	1.63	2.56	1.39	3.21
8	4	754144	765598	4	[8] Budee	1.74	2.53	1.43	4.72
9	24	749823	766995	24	[9] Laem Ta Chi	1.72	2.6	1.4	7.97

ID_STA	18JUL2009L	18JUL2009H	10AUG2009W	10AUG2009L	10AUG2009H	12SEP2009W	12SEP2009L	12SEP2009H
1	4.49	2.41						
2	4.59	2.34	10.31	5.24	2.62	13.31	5.8	2.57
3	4.33	2.39	9.22	5.01	2.47	12.04	5.58	2.58
4	3.96	2.14	7.6	4.64	2.44	10.518	5.27	2.59
5	3.73	2.09	6.72	4.43	2.29	8.92	4.92	2.54
6	3.12	1.75	3.4	3.35	1.8	5.08	3.94	2.18
7	3.29	1.78						
8	3.83	2.21	7.45	4.59	2.49	12.21	5.6	2.73
9	4.72	2.47	10.39	5.25	2.8	14.84	6.03	3.13

muss_grl | mussgt_func

Database : mussel growth.mdb | Col : 1 | Row : 1 | Data Type : Real | Records : 9

Fig. 4.9. An example mussel growth database.

4.3 Data layer construction

The common features of water quality parameters, sediment quality parameters and mussel growth parameters are point data with corresponding UTM geographical positions. From databases formulated in the previous sections, vector point files of each parameter in each sampling occasion were constructed by exporting point data using Database Workshop. Thereafter, raster data layers were formulated by interpolation using a distance weight exponent of 2 and a six point search radius option. Thereafter, each interpolated layer was generalized by filtering using the mean value from a 7*7 pixel window. The generalized raster layer was then multiplied by the Boolean image of the study area to obtain finished raster layers of the study area. The series of processes is summarized in Fig. 4.10.

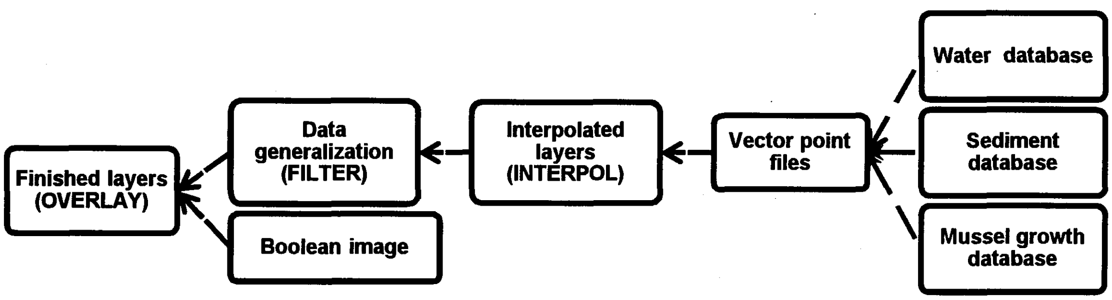


Fig. 4.10. Schematic diagram of databases and data layer construction.

Fig. 4.11 illustrates an example of data layer construction processes using chlorophyll-a values form 31st July 2009. A vector point file exported from the water quality database showed different values among sampling points (Fig. 4.11a). By interpolation, a primary raster data layer was developed showing a chlorophyll-a surface image (Fig. 4.11b). A filtering process was then applied in order to obtain a smoother raster surface as shown in Fig. 4.11c. Finally, the chlorophyll-a in the study area was obtained by multiplying the raster layer with the Boolean image of study area (Fig. 4.11d.). Raster layers of all parameters from each sampling occasions were constructed by similar processes.

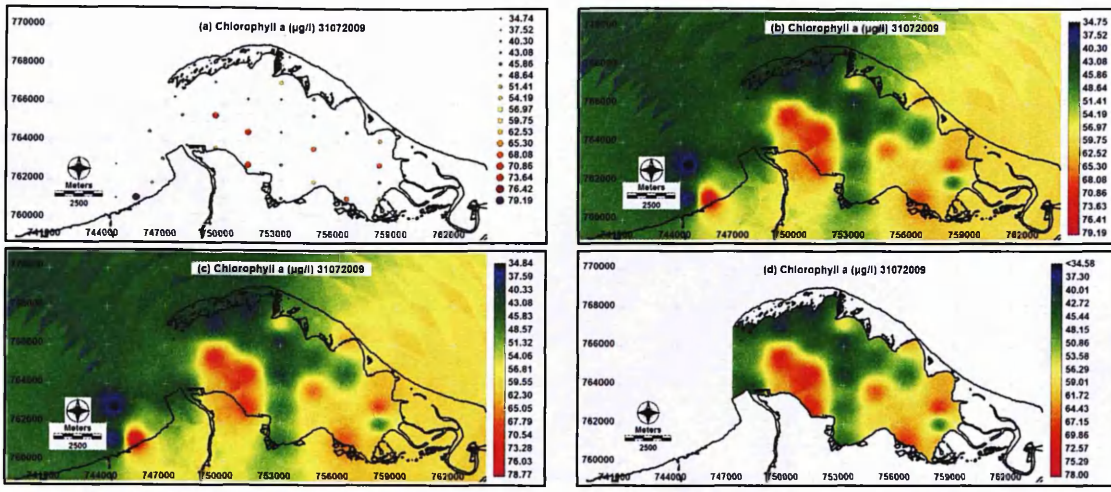


Fig. 4.11. An example of data layer construction using chlorophyll-a data.

4.4 Key data layers

This section describes the processing and derivation of the principal data layers necessary for the different models developed in the study. Almost all of the following layers are based upon average values calculated from 5-6 sampling occasions. In total, there are too many layers to illustrate here but the following selection give an indication of overall water and sediment qualities for both sampling periods.

4.4.1 Chlorophyll-a

The average value of chlorophyll-a was 46.33 µg/l. The maximum and minimum values were 37.43 and 53.74 µg/l, respectively. The high value were mainly found off shore near Industrial and Laem Nok areas followed by near shore areas of Lighthouse (Fig.4.12).

4.4.2 Dissolved Oxygen (DO)

The mean DO value was 6.68 mg/l while the minimum and maximum values were 4.92 and 7.35 mg/l, respectively. Spatial distribution of high DO value areas was similar to that of the chlorophyll-a. Relatively low DO levels were found near Pattani River mouth (Fig. 4.13).

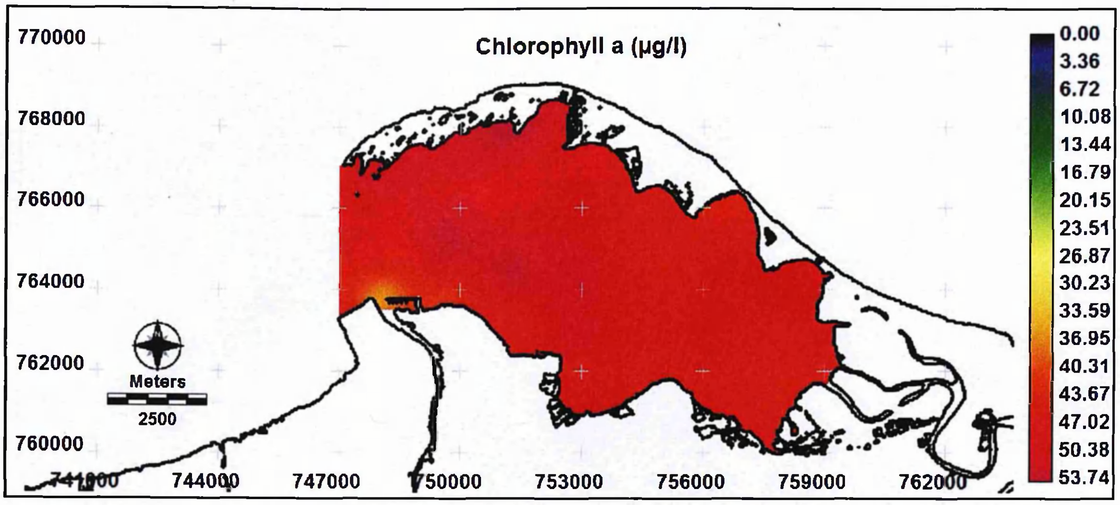


Fig. 4.12. Average chlorophyll-a (µg./l.) in Pattani Bay, Thailand; June-September 2009.

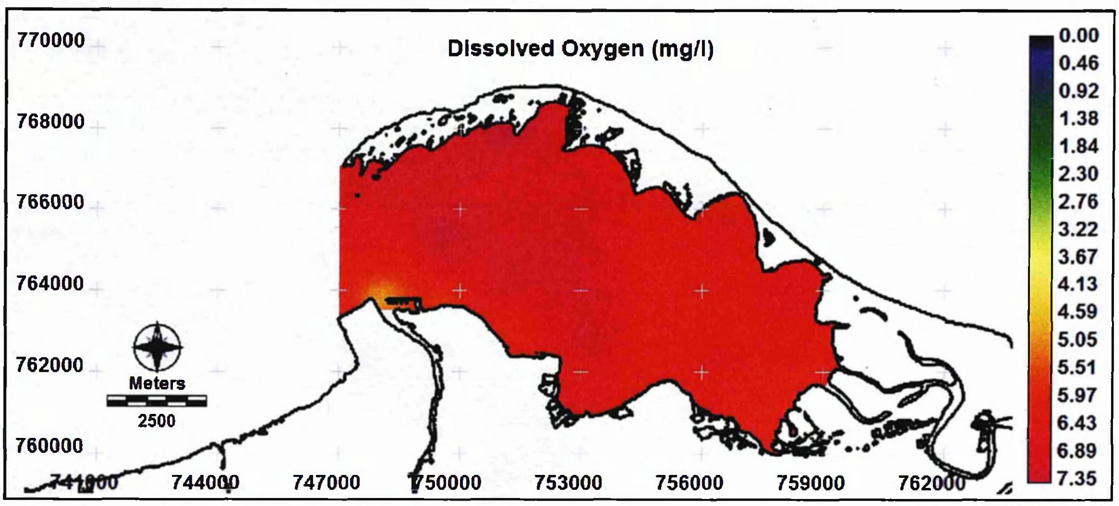


Fig. 4.13. Average dissolved oxygen (mg./l.) in Pattani Bay, Thailand; June-September 2009.

4.4.3 Water depth

Average water depth in the bay was 1.15 m with the minimum and maximum values of 0.10 and 4.25 m, respectively. The depth of the bay gradually increased from the East end of the bay (Yaring River mouth) toward the bay opening (Fig. 4.14).

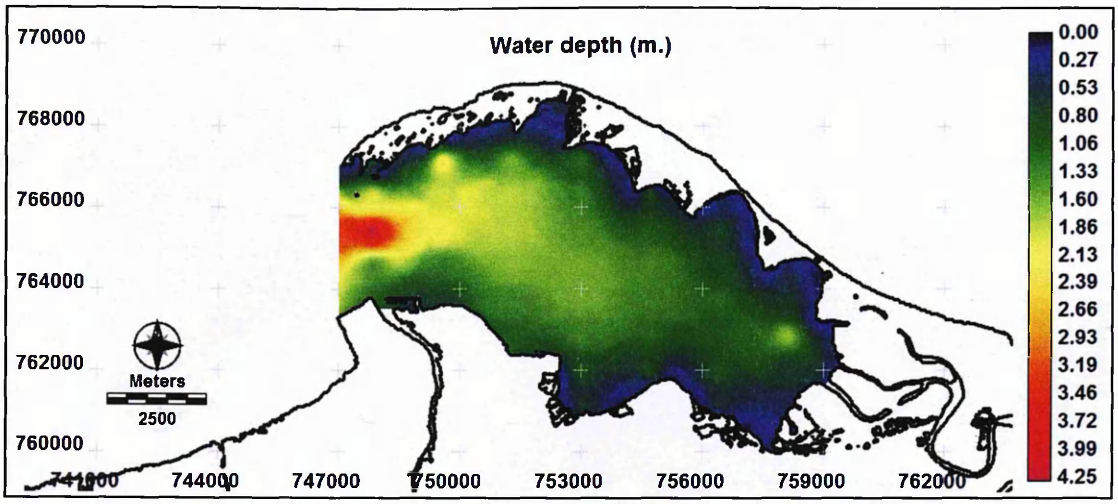


Fig. 4.14. Water depth (m.) in Pattani Bay, Thailand; June 2009.

4.4.4 Water pH

The water pH in the bay varied from 7.40-8.0 with an average of 7.69. Spatially, there was not much difference throughout the bay, but near shore at Industrial and Laem Nok had slightly lower pH values (Fig. 4.15).

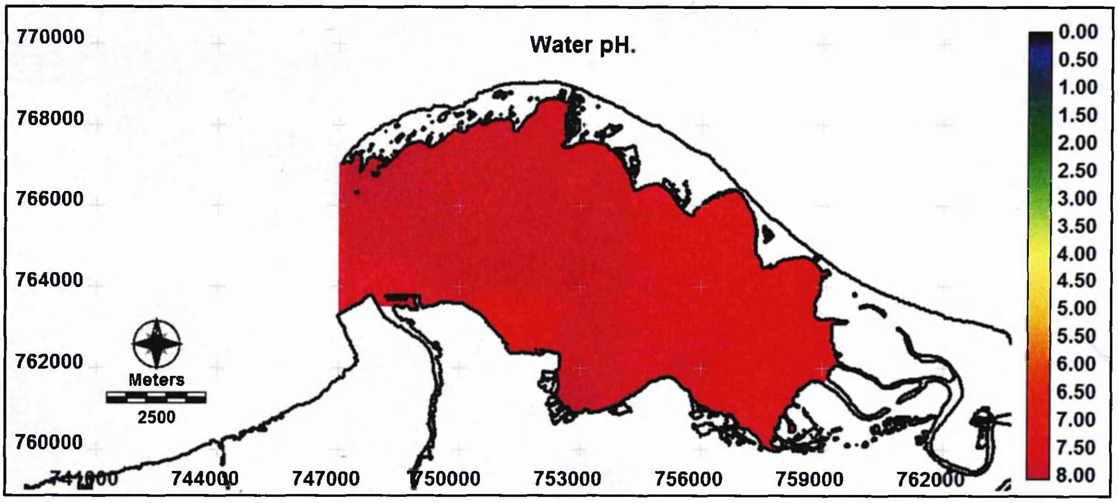


Fig. 4.15. Average water pH in Pattani Bay, Thailand; June-September 2009.

4.4.5 Particulate Organic Matter (POM)

The average POM value varied considerably from 15.64 -60.21 mg/l with an average value of 26.91 mg/l. The highest POM areas were found at the two river mouth areas while the central area of the bay and almost all areas around the northern coastline had relatively low POM levels (Fig. 4.16).

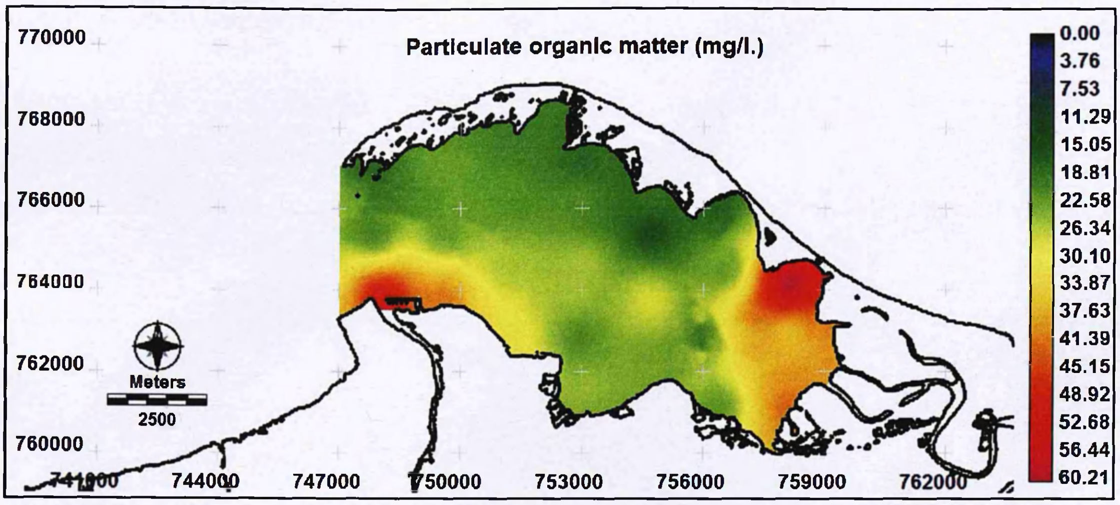


Fig. 4.16. Average POM (mg./l.) in Pattani Bay, Thailand; June-September 2009.

4.4.6 Salinity

Average salinity value was 19.76 ppt while the minimum and maximum levels were 7.31 and 27.41 ppt, respectively. Low salinity areas were also found at the two river mouths. The low salinity area at Yaring River occupied a larger space than that of the Pattani river. In general, the salinity gradually increased from the East end of the bay toward the bay opening (Fig. 4.17).

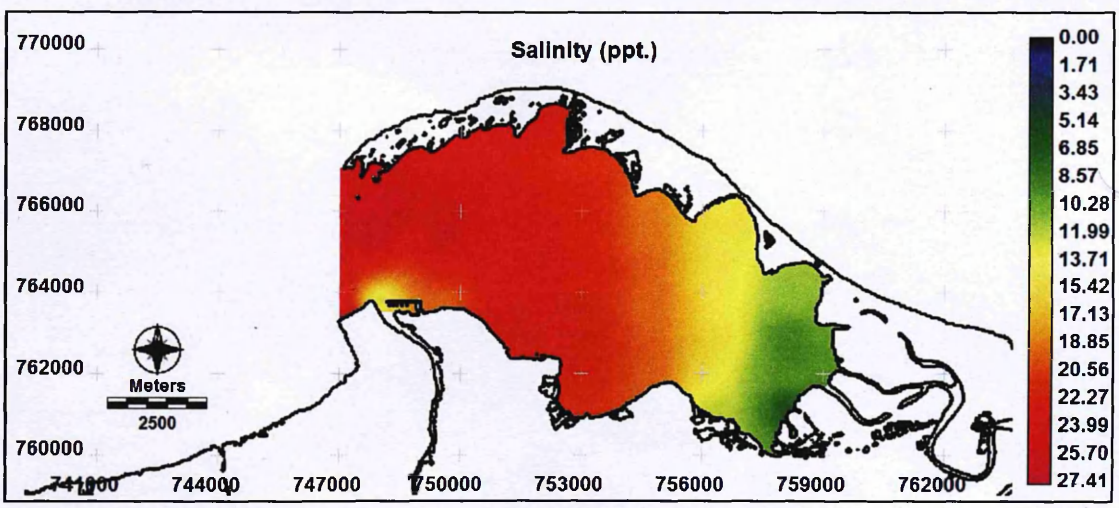


Fig. 4.17. Average salinity (ppt.) in Pattani Bay; June-September 2009.

4.4.7 Total Dissolved Solids (TDS)

Average TDS value was 20.86 g/l and the minimum and maximum values were 9.33 and 28.36 g/l, respectively. The spatial distribution of the TDS was similar to that of the salinity. It increased from the East end of the bay toward the bay opening (Fig. 4.18).

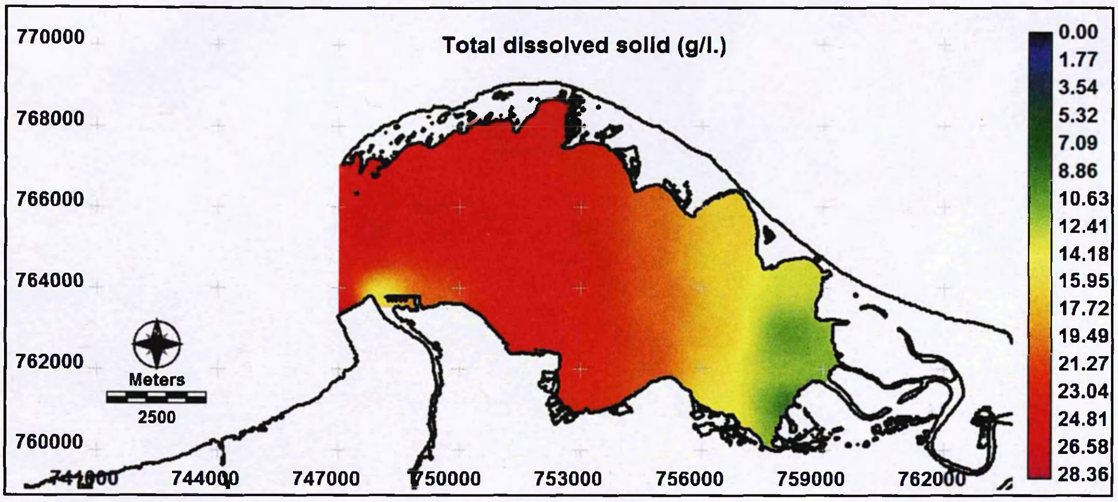


Fig. 4.18. Average TDS (g./l.) in Pattani Bay; June-September 2009.

4.4.8 Temperature

Water temperature varied from 29.29 to 32.53 °C, with a mean value of 30.56 °C. Relatively high temperature was found near shore from Industrial area to Laem Nok village (Fig. 4.19).

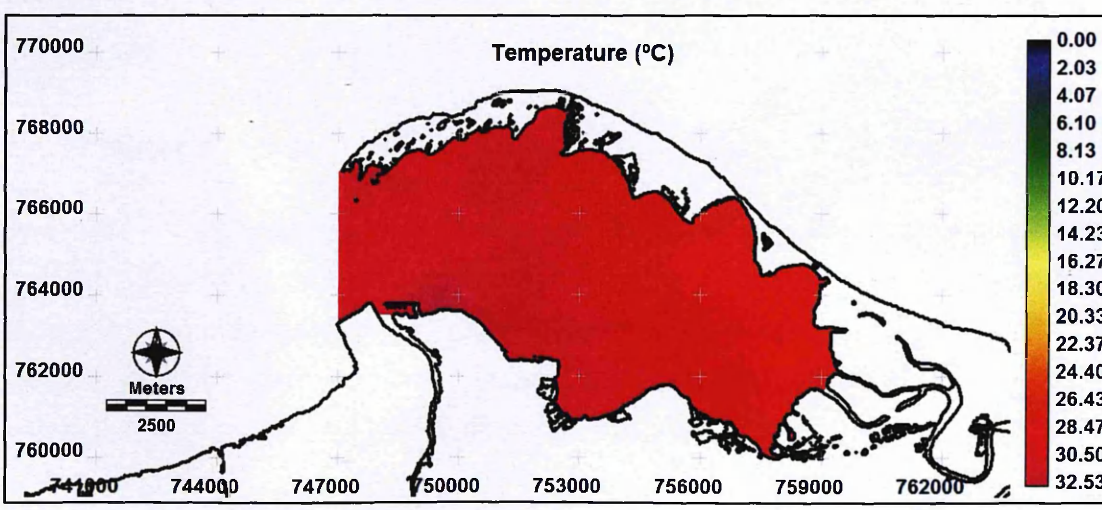


Fig. 4.19. Average temperature (°C) in Pattani Bay, Thailand; June-September 2009.

4.4.9 Transparency

Water transparency varied from 25.29 to 55.12 cm with a mean value of 38.37 cm. High transparency was found from the northern part of the bay opening to near shore of Lighthouse. The remaining area was less transparent, especially along the south shoreline form Pattani River to Yaring River, probably because the bottom sediment of the southern coastline is muddy and in shallow water (Fig. 4.20).

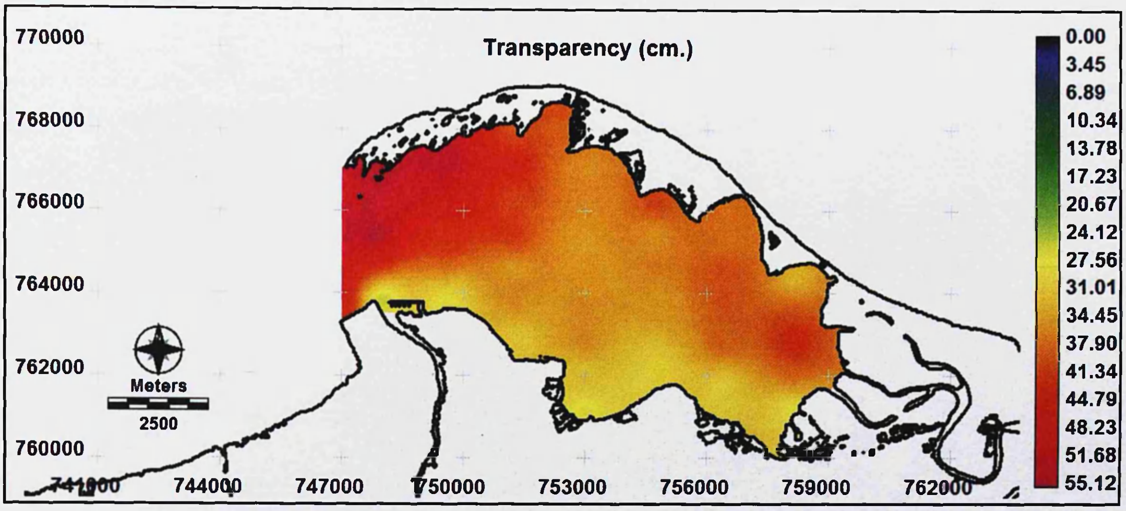


Fig. 4.20. Average transparency (cm.) in Pattani Bay, Thailand; June-September 2009.

4.4.10 Total Suspended Solid (TSS)

Average TSS varied from 0.12 to 0.21 g./l. with a mean value of 0.18 g/l. High TSS value was found in a small area next to Industrial site. Relatively low TSS was found at the bay opening and in small area near Yaring River mouth (Fig. 4.21).

4.4.11 Water currents

Water current was observed on both ebb and flood tides. The flood tide velocity varied from 0.07-0.24 m/s while that of the ebb tide was 0.07-0.60 m/s. High velocity currents were found from the bay opening to the offshore area between Laem Nok and Budee villages, especially near the north coastline. Generally, the velocity of the ebb current was higher than that of the flood current (Fig. 4.22 and 4.23).

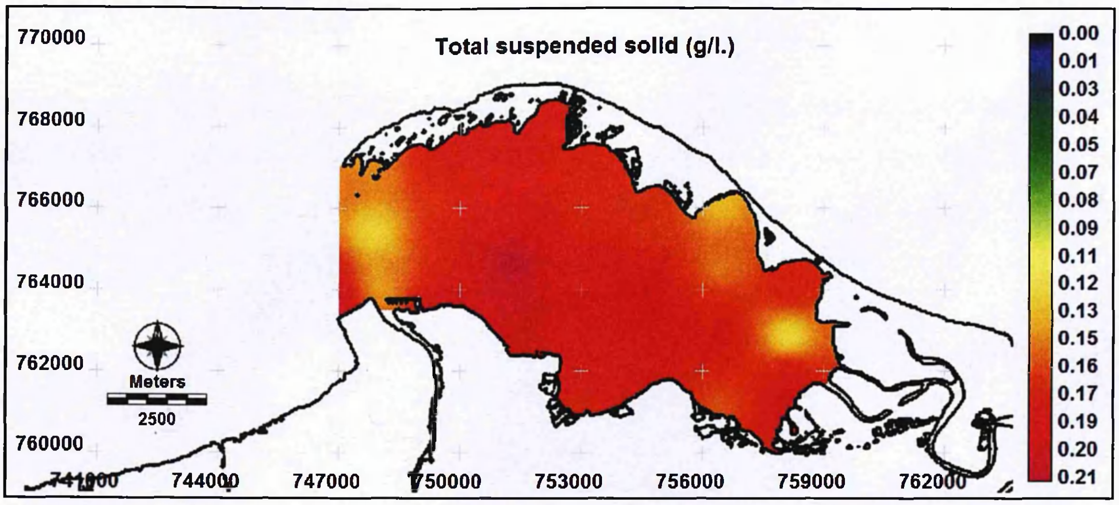


Fig. 4.21. Average TSS (g./l.) in Pattani Bay, Thailand; June-September 2009.

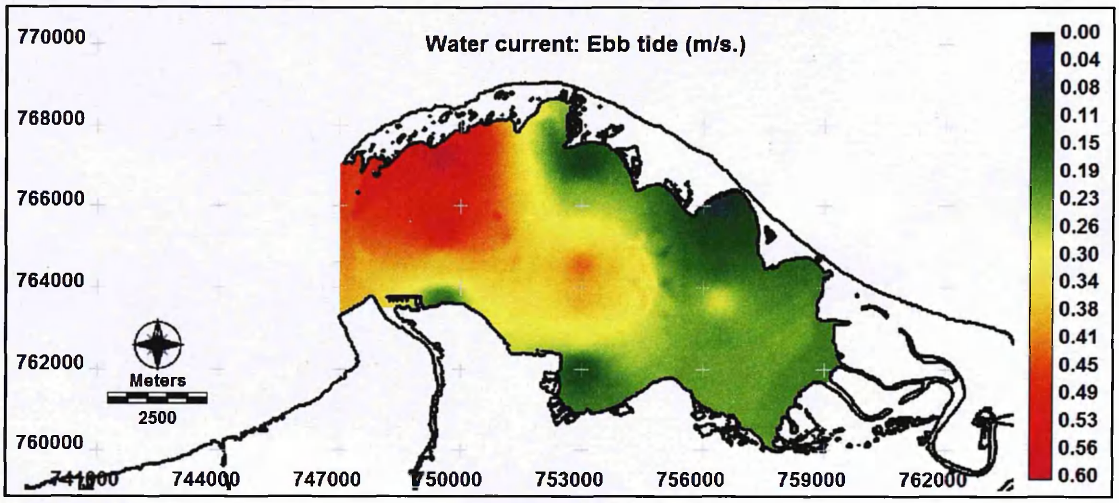


Fig. 4.22. Ebb current velocity (m/s) of Pattani Bay, Thailand; July 2009.

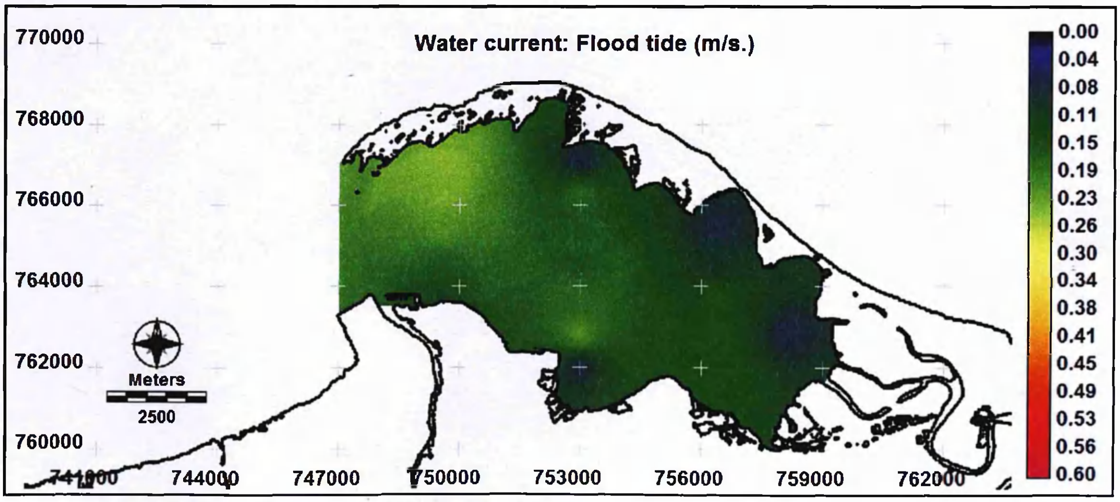


Fig. 4.23. Flood current velocity (m/s) of Pattani Bay, Thailand; July 2009.

4.4.12 Sediment organic matter

Bottom sediment organic matter varied from 6.48-41.39 g/kg with an average value of 28.01g/kg. High organic matter was found at sheltered area near Laem Nok, Bang Pu and Da To villages, where the water current was very low (Fig. 4.24). Low sediment organic matter was mainly found offshore at Budee and Lighthouse.

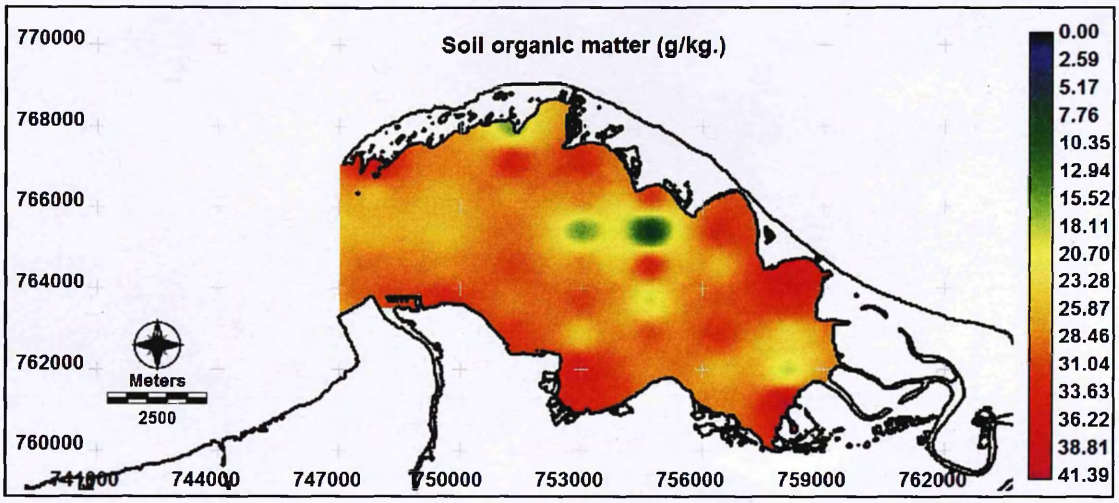


Fig. 4.24. Organic matter (g./kg.) in bottom soil in Pattani Bay, Thailand; June 2009.

4.4.13 Sediment organic carbon

Spatial distribution of sediment organic carbon was similar to that of sediment organic matter for both high and low sediment levels. The value ranged from 3.76-24.01 g/kg with a mean value of 16.25 g/kg (Fig. 4.25).

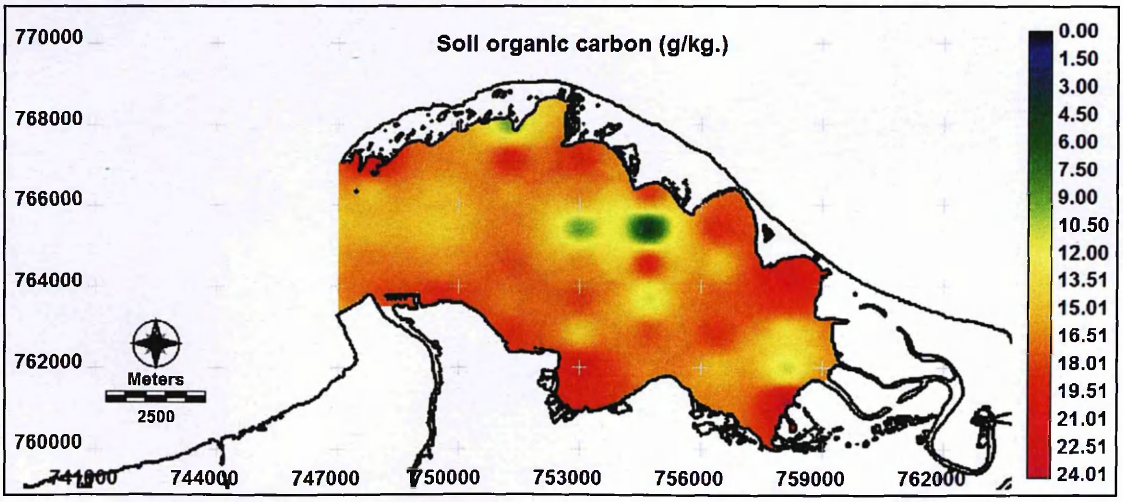


Fig. 4.25. Organic carbon (g./kg.) in bottom soil in Pattani Bay, Thailand; June 2009.

4.4.14 Sediment pH

Average sediment pH varied from 5.71-8.29 with a mean value of 7.36. Relatively low pH was found near Yaring River mouth. There was little variation in the remaining area except near shore at Lighthouse and a small area offshore of Laem Nok (Fig. 4.26).

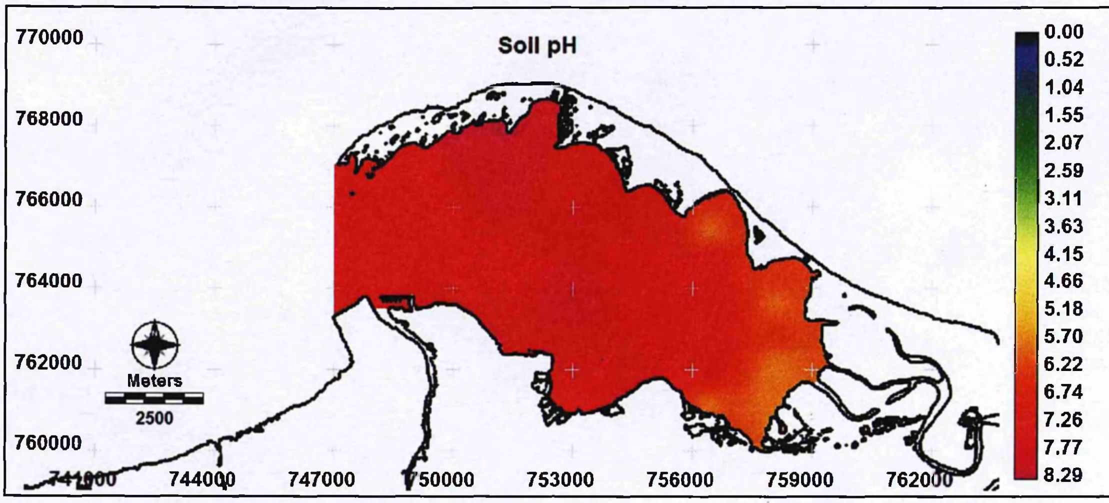


Fig. 4.26. Sediment pH of bottom soil in Pattani Bay, Thailand; June 2009.

4.4.15 Percent sand

The percentage of sand particles in the sediment varied from 0.05-95.61% with a mean value of 13.73% (Fig. 4.27). The percentage of sand was very high near the north coastline, from Laem Tachi to Lighthouse areas and also offshore of Budee village. The rest of the bay had low sand percentage, except a small site near the Pattani River mouth. Very low sand content was found at the end of the bay and offshore area of Industrial to Laem Nok village.

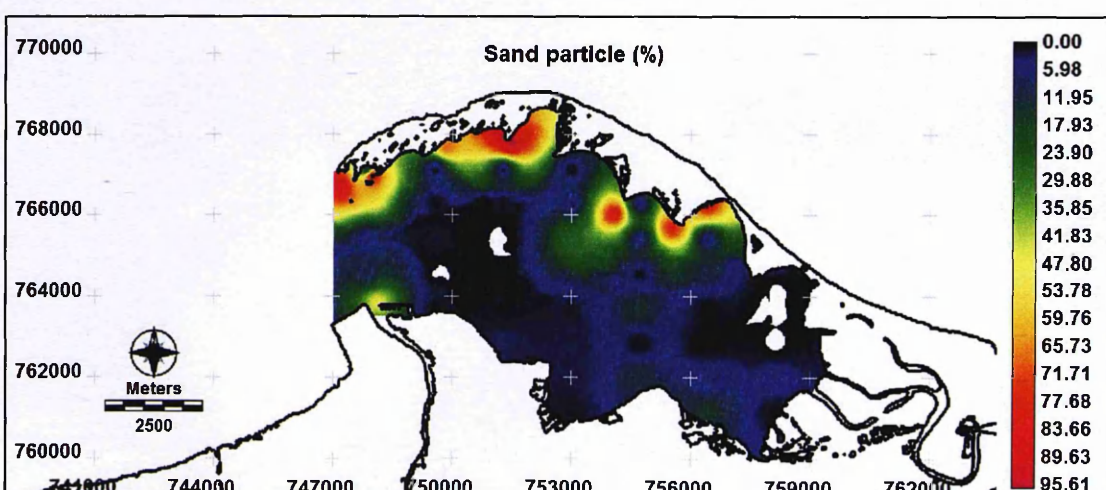


Fig. 4.27. Sand particle (%) in bottom soil in Pattani Bay, Thailand; June 2009.

4.4.16 Percent silt

The spatial distribution of silt in the bottom sediment was opposite to that of sand. Low silt content was found along the north coastline while the rest of the bay had a silt content of >40%. Relatively high percentage of silt was found in the sheltered areas of Laem Nok village and near Yaring River (Fig. 4.28).

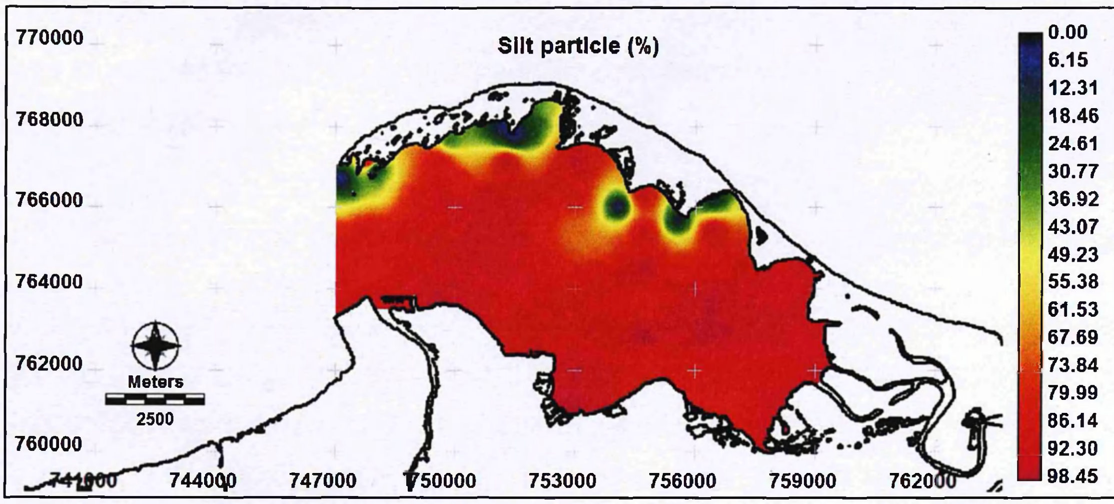


Fig. 4.28. Silt particle (%) in bottom soil in Pattani Bay, Thailand; June 2009.

4.4.17 Percent clay

The clay particle component in bottom sediment of the bay was <10%, varying from 0.85- 9.50 % with a mean value of 4.58%. Relatively low percentage of clay was found where there was a high percentage of sand area near Laem Tachi, Lighthouse, sheltered area at Laem Nok, and offshore area between Tanyong Lulo, Budee and Da To villages (Fig. 4.29).

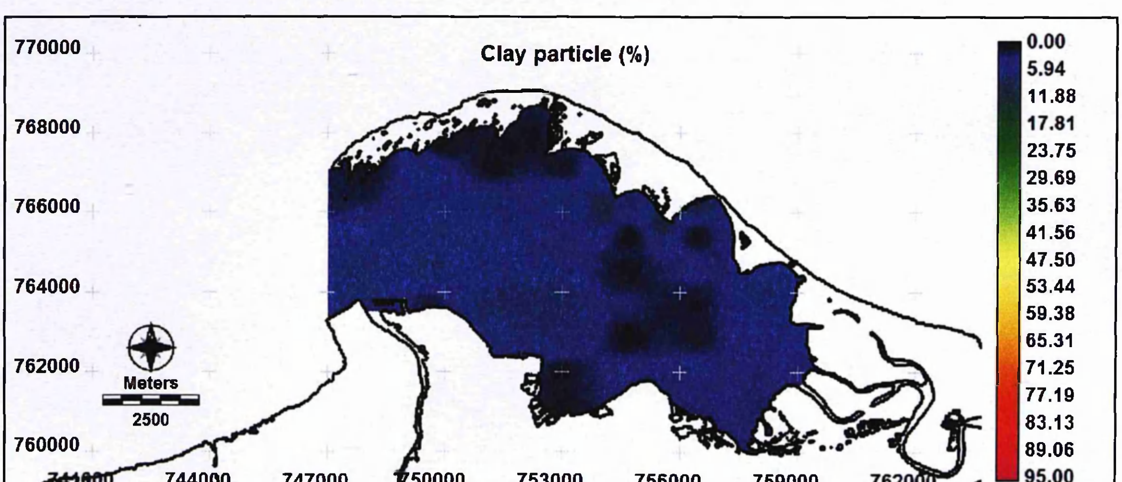


Fig. 4.29. Clay particle (%) in bottom soil in Pattani Bay, Thailand; June 2009.

4.4.18 Mussel growth

Mussel growth data was derived from the mussel growth experiment during June-September 2009. Average growth in terms of weight, height and length was 2.87 g/month, 0.38 cm/month and 0.85 cm/month, respectively. The ranges of these values were 1.03-4.01 g/month, 0.24-0.53 cm/month and 0.43-1.05 cm/month, respectively. High average growth rate was found at the near shore of Laem Tachi. High growth rate was found from the bay mouth and gradually decreased toward the East end of the bay at Yaring River mouth (Fig. 4.30).

4.5 Summary of parameters/layers for different study purposes

The data layers developed for this study were used for different modelling purposes. Firstly, mussel growth determination and determination of the harvestable area for mussels (Chapter 5) and, secondly, development of an optimization model for suitable cockle culture areas (Chapter 6). The summary details of input and outputs used in each chapter are illustrated in Table 4.3.

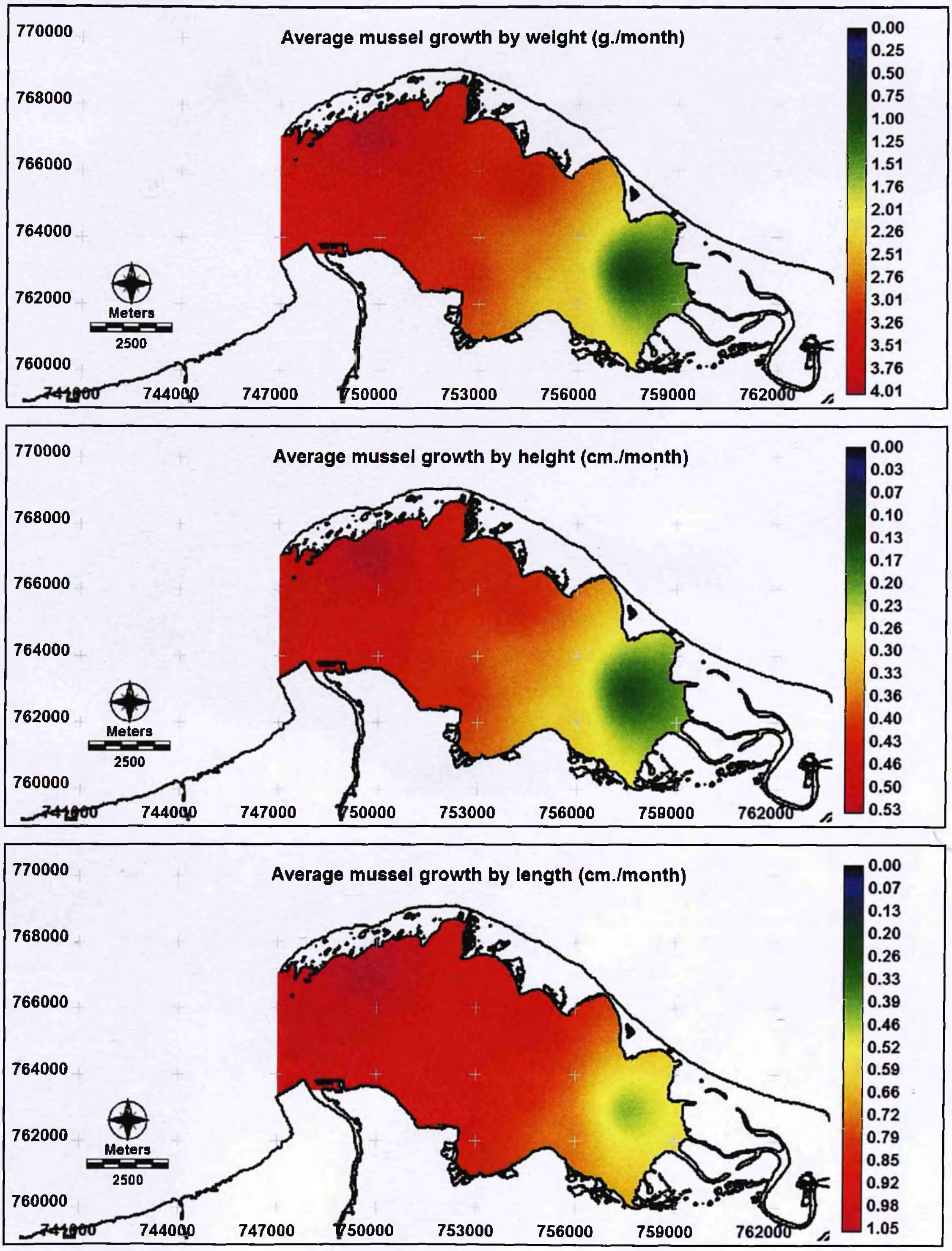


Fig. 4.30. Average monthly growth rate of mussel by weight, height and length recorded in Pattani Bay, Thailand.

Table 4.3. Summary details of the input data layers and outputs of each chapter.

Topics/Models	**Input layers**	**Outputs**
Principal component analysis (PCA)	• Average water quality parameters from the 1st sampling phase • Boolean image of study area	• Correlation matrix • PCs • MPCs • WQs
Mussel growth determination	• Average mussel growth per month • PCs, MPCs and WQs • Some water parameters from the 1st sampling phase. • Boolean image of study area	• PCRs • MLRs • Simple regression models • Mussel growth determinant
Mussel harvestable area	• Mussel progressive growth functions • Water depth • Water current • Boolean image of study area	• Mussel harvestable area
Cockle farm suitability area	• Water quality of all sampling phases • Sediment quality • Boolean image of study area	• Water suitable area • Sediment suitable area • Constraint factor suitable area • Vulnerable factors for existing cockle farm areas. • Overall suitable area for cockle culture

Chapter 5

Mussel growth and harvestable area models

This chapter comprises 4 main sections. The first section describes mussel culture in Thailand and nearby countries, suitable culture environments, and briefly reviews about the relationships between mussel growth and environmental parameters. The second section investigates empirical growth of mussels from field experiments in Pattani Bay, in terms of weight, length and height at each location. The third section investigates mussel growth determination using PCA and a multiple regression models within the GIS framework. The last section models the harvestable area of mussel pole culture within Pattani Bay, based on both secondary data and the progressive mussel growth functions from the field experiments within the bay.

5.1 Mussel culture and environmental conditions

5.5.1 Mussel culture in Thailand

The green mussel (*Perna viridis, L. 1758*) or "Malaeng Phu" is an economically exploited species from the family Mytilidae (Amornjaruchit, 1988; Sahavacharin *et al.*, 1988), and is an important commercially cultured species in Thailand (Vakily, 1989; Vakily, 1992). *Perna viridis* has many synonyms, though *Mytilus smaragdinus* and *Mytilus viridis*, are most commonly used (Vakily, 1989). Other synonyms are *M. opalus, Chloromya viridis* and *C. smaragdinus* (Rajagopal *et al.*, 2006b).

Initially, people in shoreline provinces collected these mussels from natural sources on rocks, stones and from natural beds. Over 60 years ago, they also began to collect these mussels from placed wooden stakes (Saraya, 1982; McCoy *et al.*, 1988). Over time, there has been a gradual shift from collection to culture due to deterioration of the natural supply (Saraya, 1982). Bamboo stake traps are also used as the main stationary culture method, each trap consisting of around 15,000 vertical 6.8 m stakes. Each trap is capable of harvesting about 50 tonnes of mussels 8 months after initial settlement (Phrommanont, 1969). Mussels are also harvested as a by-product from stationary fishing gear (Tookwinas, Mongkolomann, & Pongmaneerat, 1985b), and sometimes this is the main contributor to the trap operators. The right to collect mussels or to collect settled mussel spat for on-growing within a certain areas is, sometimes, leased or sold to other operators (McCoy *et al.*, 1988). Most production areas are situated near major rivers; Bang Pakong, Chao Praya, Mae Klong and Tha Chin (McCoy *et al.*, 1988) as well as in the brackish areas of Chachoengsao, Chonburi and Chumphon Provinces (Brohmanonda *et al.*, 1988b). Partly because of industrialisation and pollution, culture areas have been extended to Chumphon, Phangnga and Nakhon Sri Thammarat (McCoy *et al.*, 1988).

Mussel culture using transported and transplanted seeds has been used to extend the culture of these mussels to more sites. During 1979-1981, seed mussels from Sawi Bay, Chumphon Province, were transported and transplanted to Songkhla and Pattani Provinces for natural stock enhancement, where both growth rate and spat fall from the seeded mussels were found satisfactory (Brohmanonda *et al.*, 1988b). In 1983, mussel production from transplanted seed in Sawi Bay, Chumphon, was around 8,000 tonnes making it the 2nd largest mussel production site in Thailand at that time (McCoy *et al.*, 1988). In the Eastern region, seed collected from Chacheongsao Province are transported for rearing in Chonburi Province using raft and longline methods (Chaitanawisuti & Menasaveta, 1987).

Culture techniques for mussels are similar to those used for oysters; stick methods, hanging line methods (include rafts), and culture on hard bottoms or on rocky areas. Mussel culture is normally situated further from the river mouth than the two other cultured mollusc species, oysters and cockles (Tookwinas *et al.*, 1985b). In the past, it was reported that the profit from mussel pole culture varied from 31-266% of the total investment cost (Vakily, 1989 referred to in Kao-ian, 1988) .Although, sometimes, the profit is low, it's still enough incentive for local people (McCoy *et al.*, 1988).

5.1.2 Site selection

General considerations for the selection of mussel culture sites are normally based on technical aspects such as (Coastal Fishery Research and Development Bureau, 2004):

- Water body with available natural seed
- Brackish or salt water are found at least 7-9 months a year
- Sheltered area and safe form strong wave and wind current

- Far from industrial site, and away from polluted waters
- Near the coastline or where the water depth is around 3-10 metres
- Near markets, basic transport infrastructures (road and rail *etc.*)
- Areas safe from poaching.

Viewed holistically, there are primary and secondary factors that should be considered for suitable site for mussel culture. The primary factor involves physical, biological and ecological aspects while the secondary factor relates to risks and economic point of view, as detail in Fig. 5.1 (Lovatelli, 1988a). However, some factors can be ignored or solved, for example seed can be transplanted if lacking in a location because of no available natural seed sites (Chaitanawisuti & Menasaveta, 1987; Brohmanonda *et al.*, 1988b; Cheung, 1991). Investment cost of farm operation depends on the culture site, culture method and scale of production. As a result, economic evaluation should be taken into account when selecting sites (Sallih, 2005). The following sections will explain in more detail about the suitability of areas, especially for environmental and technical aspects of site selection.

PRIMARY FACTORS	SECONDARY FACTORS
• Area location	• Environmental pollution
• Substrate	• Resource competition
• Exposure	• Economic consideration
• Water movement	• Poaching
• Turbidity	
• Salinity	
• Temperature	
• Dissolve oxygen	
• Water pH	
• Food Availability	
• Source of seed	
• Predator potential	

Fig. 5.1. Primary and secondary factor for mussel culture site selection
Source: Lovatelli (1988a).

5.1.3 Seed collection and seed supply

Spat are obtained in several different ways because mussels attached themselves to various substrates (Saraya, 1982). Bamboo stakes are predominantly used for spat collection. The stakes of 2-3 m long are normally driven into the sediment to give about 2 m available for spat attachment. However, bamboo stakes of up to 13 m, giving 10 m for settlement have been used (Tuaycharoen, Valkily, Saelow, & McCoy, 1988), thus allowing spat collection at many depth levels in Thai waters.

Spawning and spat fall seasons are important for seed collection. Mussels always show two peak spawning seasons in a year, though the actual times can vary from place to place. In Trat Province spawning peaks in June to August and in November to February (Sahavacharin *et al.*, 1988), in Pattani Bay spawning peaks in June-August and October-January, and in both Petchaburi and Chachoengsao Provinces spawning peaks in June to August and in November to January (Tuaycharoen *et al.*, 1988). In Malaysia, on the other hand, peak spawning is earlier in March to April and in October to November (Sivalingam, 1977). In Pattani Bay, Niyomdecha (2009) found the highest spat fall in October at the average density of 7,973 spat/m^2 of substrate surface area (bamboo stake).

5.1.4 Culture technique

Culture techniques can be classified into 2 main types, bottom and off-bottom culture. The off-bottom is classified to fixed and suspended culture. Fixed culture comprises stake and pole, rope-web and rack methods while suspended culture comprises raft and longline methods. More detail about other culture techniques can be found in Vakily (1989).

5.1.5 Suitable environment factors for mussel culture

Although there are interrelationships between water quality parameters, mussel activities are also affected by water quality - such as clearance rate is dependent on water flow, temperature, and food availability (Denis, Alliot, & Grzebyk, 1999; Dolmer, 2000) - this section summarises the water quality requirements for each parameter. Secondary data from both field and laboratory studies are included to depict the suitable and tolerable ranges of mussels as follows:

5.1.5.1 Salinity

Suitable salinity for green mussel *P. viridis* has been published extensively. Culture sites in Thailand normally occur at a range of 15.0 - 32.0 ppt (Tookwinas *et al.*, 1985b). The highest salinity range in mussel culture site is 1-35 ppt (Dato-Cajegas & Lin, 1996; Nilkerd, 2001) while a laboratory study on effect of salinity on the mussel mortality indicates that salinities of between 5-15 ppt are fatal to mussel and a salinity range of 20 to 25 ppt gives 100% survival (Rawchai, 2003).

5.1.5.2 Temperature

In Thailand, reported temperature ranges are 24.0-31.0°C (Nilkerd, 2001), 26.0-33.0 °C (Dato-Cajegas & Lin, 1996) and 27.15-32.58°C (Intarachart & Rermdamri, 2005). Under controlled conditions, it is found that at 29°C the mussel larva settle more quickly than that of 31°C, 27°C and 24°C. However, regression equations of mussel growth, in terms of larva shell length, show fastest growth at 31°C (Manoj & Appukuttan, 2003).

5.1.5.3 Water pH

The lowest water pH reported in Thailand is 6.5-8.7 from the Upper Gulf of Thailand (Dato-Cajegas & Lin, 1996). This value almost covers all reported data of other culture sites in Thailand, including the pH range of 6.98 - 8.63 in Pattani Bay (Brohmanonda *et al.*, 1988b) ,7.90-8.38 at Sriracha, Chonburi (Intarachart & Rermdamri, 2005), and 7.10-8.83 at Ang Sila, Chonburi (Nilkerd, 2001)

5.1.5.4 Total Suspended Solid (TSS)

TSS range in natural water with cockle culture area is 19.83-127.71 mg/l (Nilkerd, 2001). Under the laboratory experiment on the effect of the TSS on mussel, at the TSS levels of 0-1,200 mg/l, gives 100% survival and at the TSS level of 0-600 mg/l is not effect on mussel oxygen consumption (Shin, Yau, Chow, Tai, & Cheung, 2002).

5.1.5.5 Chlorophyll-a

Organic carbon within phytoplankton plays an important role as diet of the mussel (Mazzola & Sarà, 2001). The productivity of phytoplankton represented by a chlorophyll- a value is reported from many areas in Central and South-East Asia (Table 5.1.)

Table 5.1. Chlorophyll-a values in Thailand and selected countries.

Country	Chlorophyll-a and sources	
Thailand	0.05-3.14 mg/m^3 (Nilkerd, 2001), 1.83-74.74 mg/m^3 (mean value of 6.50-25.18 mg/m^3) (Tookwinas *et al.*, 1985b)	
India	2-6 mg/m^3 (Rajagopal, Venugopalan, van der Velde, & Jenner, 2006a), 1.06-9.99 mg/m^3 (Rajagopal *et al.*, 1998a) and 0.7-17 mg/m^3(Rajagopal *et al.*, 1998b)	
Singapore	17-40 µg/l (Cheong, 1982)	
Australia	< 0.5 µg/l	Very poor growing conditions, very slow growth and loss of condition over the long term.
	0.5 – 1.0 µg/l	Poor growing condition, slow growth and may not lose condition. Slow recovery after spawning, takes a long time to reach marketable size.
	1.0 – 2.0 µg/l	Moderate growth. Mussels are in reasonable condition at the upper end of this range.
	2.0 – 4.0 µg/l	Good growth and reach marketable size by 10-12 months. Mussels in good condition and rapid recovery after spawning.
	4.0 – 8.0 µg/l	Ideal growing conditions with fast growth. Though this level is rarely found.
	> 8.0 µg/l	Unknown (Inglis *et al.*, 2000).

5.1.5.6 Dissolved Oxygen (DO)

In Thailand, the DO levels in coastal environments range from of 2.57-8.67 mg/l (1.57-7.47 mg/l and 3.90-8.67 mg/l at bottom and surface waters, respectively) (Nilkerd, 2001): This value covers all reported value in Pattani Bay, 4.95-7.96 mg/l (Brohmanonda *et al.*, 1988b).

5.1.5.7 Water currents

Water current plays an important role in food particle availability, feeding activity (Dolmer, 2000) and provision of dissolved oxygen (Sallih, 2005). Suitable ranges of current velocity for mussel culture sites is 0.1 - 0.3 m/s (Lovatelli, 1988a). Water current speeds in mussel culture sites in Singapore are between 0.17 - 0.25 m/s for flood tides and 0.25 - 0.35 m/s for ebb tides (Cheong, 1982). Within similar environment, the growth rate of mussels at lower current velocities is significantly lower than that of the higher current (the highest current ~3m/s) (Rajagopal *et al.*, 1998a). Mussel culture using vertical poles often requires strengthening by horizontal bars in strong currents, or are grouped like a "wig-wam" to resist strong current (Young & Sera, 1982)

5.1.5.8 Depth

Water depth for mussel culture depends on area and culture techniques. In Thailand, suitable depth for culture is from 1.0 - 4.0 m depth at mean sea level (Tookwinas *et al.*, 1985b) and extend to 10 m (Tuaycharoen *et al.*, 1988). Pole culture in Philippines, mainly using bamboo, takes place from < 2 - 10 m depths. This data is similar to the recommendation depth of >2 m, reported by Aypa (1990). Longline culture in New Zealand is conducted at a depth of 10 - 15 m (Ren, Ross, Hadfield, & Hayden, 2010) while a water depth of less than 1.5 m is considered suitable for bottom culture here.

5.1.5.9 Water transparency

Generally, for bivalve culture, the transparency of water should not be <0.15 m (Lovatelli, 1988a). The transparency at culture sties can vary, for example Pattani Bay has values of 0.31 - 0.92 m, (Brohmanonda *et al.*, 1988a; 1988b) whereas on the open shoreline areas have greater transparency of 0.50 - 3.33 m (Nilkerd, 2001) and 1.50 - 3.45 m (Intarachart & Rermdamri, 2005) in Chonburi.

5.1.5.10 Particulate Organic Matter (POM)

Some areas of Hong Kong, where *P. viridis* inhabit, has relatively low values of POM, such as 2.11 - 4.53 mg/l and 3.46 - 3.84 mg/l (calculated from TPM=POM+PIM) from Kat O and Ma Wan areas, respectively (Wong & Cheung, 2003). In Kat O Bay, Hong Kong, POM at natural mussel sites is from 0.60 - 7.44 mg/l (calculated from organic fraction of seston). However, at high seston levels, bivalve molluscs have selective processes to select preferred food and reject inorganic matter (Hawkins, Bayne, Bougrier, Héral, Iglesias, Navarro, Smith, & Urrutia, 1998) .

5.1.6 Relationship between mussel growth and environmental factors

Information in section 5.1.5 indicates that mussels have ability to grow in variety of environmental conditions. However, the interaction of environmental parameters within a particular location is complex and it is difficult to evaluate their effect on mussel growth (Parulekar, Dalal, Ansari, & Harkantra, 1982; Chatterji, Ansari, Ingole, & Parulekar, 1984) or mollusc stock decline because there is no single controlling factor (Dare, Bell, Walker, & Bannister, 2004) . Some selected parameters which may be applied to explain mussel growth and production are found as follows:

Intertidal mussel growth has a positive correlation with its body temperature (0.92; P<0.05), and a negative correlation with wave height (-0.83; P<0.01) and elevation (-0.84; P<0.01). For moored mussels, the growth shows a negative correlation with water temperature (-0.72; P<0.01) (Table 5.2.) (Blanchette, Helmuth, & Gaines, 2007) while the study of Rivonkar *et al.* (1993) found negative correlations between total weight of mussel and temperature, salinity and POC, but positively correlated with chlorophyll-a and suspended solid loading (Table 5.3.) The total length of raft mussel showed a negative correlation with temperature (-0.60), salinity(-0.25), dissolved oxygen (-0.43) and suspended solid loading (-0.22) (Parulekar *et al.*, 1982). The correlation matrix of various growth parameters for the mussel (*M. galloprovincialis*) and chosen water quality parameters is given in Table 5.4 .Moreover, meat yield of mussel correlates with POM (-0.69; P<0.05) (Karayücel, Celik, & Erik, 2010) and settlement positively relates to larva availability (0.85; P<0.05) (Rajagopal *et al.*, 1998b).

Table 5.2. Spearman's Rank correlation between average mussel growth and water quality over the culture period.

	Growth	Chlorophyll-a	Wave height	Elevation
Intertidal mussel				
Growth (mm/day)	1.00			
Body temperature (°C)	0.92*	1.00		
Wave height (m.)	-0.83**	-0.89**	1.00	
Elevation (m.+MLLW)	-0.84**	-0.93**	-0.96	1.00
Mooring mussel				
Growth (mm/day)	1.00			
Chlorophyll-a (µg/l)	-0.35	1.00		
Water temperature (°C)	0.29	-0.72**	-	1.00

Note: Values are Spearman's Rank Correlations (r_s) * = P<0.05; ** = P<0.01

Source: Blanchette *et al.* (2007).

Table 5.3. Correlations matrix between mussel weight and water quality parameters.

Parameters	Temp.	Salinity	POC	Chl-a	Sus_load	Total weight
Temperature(°C)	1.00	0.47^{+}	-0.21	-0.09	-0.31	-0.52^{+}
Salinity (ppt)		1.00	-0.71*	0.29	-0.22	-0.79**
POC (mg/l)			1.00	-0.08	0.04	-0.45**
Chlorophyll-a (µg/l)				1.00	0.14	0.46***
Suspended load (mg/l)					1.00	0.42**

Significant levels: ($^{+}$ P<0.10; ** P<0.05; *** P<0.01)

Source: Rivonkar, Sreepada, & Parulekar (1993).

Table 5.4. Correlations matrix of seston and growth parameters of *M. galloprovincialis*.

	Seston	POM	Chl-a	PIM	Temp	WMW	MY	DMW	SL
Seston									
POM	0.18								
	(0.56)								
Chl-a	0.47	0.57							
	(0.11)	(0.04)							
PIM	0.49	-0.77	-0.21						
	(0.08)	(0.00)	(0.50)						
Temp	0.49	-0.77	-0.33	0.09					
	(0.08)	(0.00)	(0.27)	(0.77)					
WMW	0.12	0.32	0.33	-0.20	-0.74				
	(0.70)	(0.29)	(0.28)	(0.51)	(0.00)				
MY	0.36	-0.69	-0.28	0.85	0.05	-0.24			
	(0.23)	(0.01)	(0.35)	(0.00)	(0.875)	(0.44)			
DMW	-0.01	-0.40	-0.04	0.35	0.18	0.13	0.34		
	(0.98)	(0.17)	(0.183)	(0.24)	(0.56)	(0.68)	(0.26)		
SL	-0.12	0.51	0.33	-0.52	-0.62	0.92	-0.55	0.01	
	(0.71)	(0.08)	(0.27)	(0.07)	(0.02)	(0.000)	(0.05)	(0.99)	
LW	-0.12	0.55	0.37	-0.57	-0.62	0.90	-0.58	-0.14	0.97
	(0.69)	(0.05)	(0.22)	(0.04)	(0.02)	(0.00)	(0.04)	(0.64)	(0.00)

Note: - Particulate Organic matter (POM, mg/l), Chlorophyll-a (Chl-a, µg/l), Particulate Inorganic Matter (PIM, mg/l), Temperature (Temp, °C), Mean Wet Meat Weight (WMW, g/month), Mean Meat Yield (MY g/month), Dry Meat Weight (MW, g/month), Mean Shell Length (SL, mm/month), Mean Live Weight (LW, g/month)

- Values are Pearson correlation with p-value in bracket.

Source: Karayücel *et al.* (2010).

The correlation is also applied for morphometric parameters (length, width, height and total weight) (Parulekar *et al.*, 1982), seed settlement and water quality correlation (Table 5.5.) (Nilkerd, 2001), and gonadosomatic (GSI) index and water quality correlation (Table 5.6.) (Lee, 1988).

Table 5.5. Correlations between mussel spat settlement and water parameters.

Parameters	Correlation coefficient
Velinger larva	0.143
Salinity	0.171
Temperature	-0.196
Water pH	-0.125
Dissolved oxygen	-0.176
Transparency	0.340
Total chlorophyll	-0.262
Suspended solid	-0.170

Source: Nilkerd (2001).

Table 5.6. Correlation between gonosomatic index of *P. viridis* and hydrographic parameter in Victoria Harbour.

G.S.I with	Spearman rank correlation	P-value
Salinity	-0.30	0.197
Temperature	0.64	0.022
Dissolved oxygen	-0.23	0.265
Turbidity	-0.24	0.249
Total coliform count	0.02	0.473
Faecal coliform count	0.17	0.319
pH	0.25	0.246
BOD	-0.17	0.317
Total suspended solid	0.09	0.401
Total nitrogen	0.31	0.192
Total phosphate	0.00	0.500
Chlorophyll-a	-0.27	0.226

Source: Lee (1988).

Linear and non-linear regressions are more complicated techniques, which have been used to illustrate the relationship between dependent and independent variables.

A series of multiple regressions functions between total length and abiotic factors (salinity, DO, temperature and suspended load) for raft mussel culture in Goa, India. All functions with different sets of exploratory variables show less prediction capability with R^2 <40% (P<0.05) (Parulekar *et al.*, 1982) (Table 5.7.).

Table 5.7. Multiple regressions functions for total length prediction using some abiotic factors of raft grown mussel (*P. viridis*).

Regression equations	R^2	F-value
L = -0.051T+0.112S+0.130DO+0.310SL	0.21	1.08
L = -0.385T-0.009S+0.111DO	0.18	1.29
L = -0.035S+0.238DO+0.300SL	0.22	1.57
L = -0.072T+0.185DO+0.328SL	0.20	1.39
L = -0.217T+0.570S	0.39	5.70*
L = -0.376S+0.141DO	0.19	2.12
L = -0.079DO+0.339SL	0.16	1.75
L = -0.206T+0.203DO	0.09	0.88
L = -0.148S+0.281SL	0.12	1.30

Note: L = Length, T = Temperature; S = Salinity; DO = Dissolved Oxygen; SL = Suspended Load; (*; P<0.05). Source: Parulekar *et al.* (1982).

T-test and ANOVA (with relevant *post-hoc* tests) are applied to compare differences in the means of temporal and spatial water quality, mussel growth and the effect of environment on mussel growth, such as spatial chlorophyll-a distribution differentiation between years (F-value =26.30; P<0.0001) in intertidal mussel culture sites while the chlorophyll-a distribution in deeper zones with mooring mussel shows significant difference between years (F-value 3.77; P<0.01), sites (F-value 7.02; P<0.01) and combined factors of year and site (F-value 2.07; P<0.01). Different growth rates of mussels between sites, seed sources and combined factor of sites*seed sources are significant difference (P<0.01). The growth of mussels from offshore mooring sites is significant higher than that of intertidal areas (Blanchette *et al.*, 2007). These techniques also compare growth and water quality parameters of mussel at different depths (Karayücel & Karayücel, 2000), clearance rate of mussel between sites (Navarro, Iglesias, Camacho, & Labarta, 1996), the different between gonad index (GI), density of settled seeds and growth rate of mussel between stations (Rajagopal *et al.*, 1998a)

Because of the existence of interactions among environmental parameters, principal component analysis (PCA) (or factor analysis) is applied for data simplification, parameter selection and grouping. The way to select valid regression parameters using linear and principal components is explained by Pires *et al.* (2008) who proved that PCA could be applied during data pre-processing to avoid co-linearity problems. A PCA of water quality on gonosomatic index (GSI) of *P. viridis* in Victoria Harbour, Hong Kong shows that 4 principal components (PC) are extracted from 12 water parameters over a 2 year study period. The 1st PC accounts for 30.60% of total variance. It shows high positive relation to the nutrients (total nitrogen and phosphate), chlorophyll-a and turbidity, but negatively relates to DO. The 2nd PC shares for 21.10% of total variance, indicates positive relation to pH, DO and total coliform, but negatively relates to turbidity and BOD. The last two PCs responsible for 17.2% and 11.10% of total variance (Table 5.8) (Lee, 1988).

Table 5.8. Extracted component and regression for GSI prediction with environment parameters.

Parameters	Components				Communality
	PC1	PC2	PC3	PC4	
Salinity	0.687			-0.567	0.878
Temperature	0.108		-0.342	0.879	0.906
DO.	-0.208	0.328	0.771	0.434	0.936
Turbidity	0.612	-0.534	0.369		0.809
Total coliform	0.273	0.614	0.556	0.324	0.981
Faecal coliform					0.834
pH		0.802	0.126	-0.271	0.988
B.O.D.	0.184	-0.949			0.994
Suspended solid	0.147	0.169	-0.854	0.229	0.977
Total nitrogen	0.797	-0.204		0.371	0.917
Phosphate	0.925		-0.213		0.924
Chlorophyll-a	0.693	-0.117	-0.133		0.565
Eigenvalue	3.67	2.53	2.07	1.33	
%Variance	30.60	21.10	17.20	11.10	
Cumulative%	30.60	51.60	68.90	80.80	

Source: Lee (1988).

They might be representative of winter and summer seasonal effects, respectively. Thereafter, the GSI is predicted by multiple regressions using 4 PCs as the equation 5.1 (Lee, 1988).

$$GSI = 0.01791 - 0.01672PC1 + 0.01032PC2 + 0.00842PC4 \qquad \text{Equation 5.1}$$

The PCA technique for the study of nutrients in relation to other physio-chemical variables has been applied in Cochin Estuary, India. The study shows 3 main PCs from component extraction. The 1st PC points out that nutrient concentrations are related to run-off water and thus related to potential blooms, the 2nd PC describes marine influx and the third reveals human activity. The first three PCs share 34.51%, 20.03% and 10.76% of total variance, respectively (Table 5.9). PC1 shows high loading on plant nutrients, such as inorganic phosphate, nitrite, nitrate, total phosphorus and total nitrogen. PC2 indicates high loading on pH and salinity while PC3 responsible for water temperature (Table 5.10). The study found that run-off water is major influencing source of the water variability in the bay. This is because of two rivers carry municipal, industrial and agriculture wastes to the bay (Joseph & Ouseph, 2010). Use of PCA in this case is relevant to conditions in Pattani Bay.

Table 5.9. Extracted component obtained from PCA in Cochin Estuary, India.

Components	Eigen values		
	Total	% of variance	Cumulative (%)
1*	3.45	34.51	34.51
2*	2.00	20.03	54.54
3*	1.08	10.76	65.30
4	0.96	9.60	74.90
5	0.86	8.59	83.50
6	0.63	6.26	89.76
7	0.38	3.75	93.50
8	0.30	3.00	96.51
9	0.20	1.97	98.48
10	0.15	1.52	100.0

Note: * Principal component extracted.

Source: Joseph & Ouseph (2010).

Table 5.10. Loadings of the main PCs in Cochin Estuary, India.

Parameters	Components		
	PC1	PC2	PC3
Temperature	0.24	0.36	0.76
pH	-0.30	0.81	-0.17
Salinity	-0.22	0.87	-0.26
DO	-0.34	-0.32	0.46
Inorganic phosphate	0.71	0.31	0.20
Nitrate	0.85	-0.15	-0.20
Nitrite	0.77	*	*
Ammonia	*	-0.33	-0.24
Total phosphorous	0.75	0.33	0.16
Total nitrogen	0.87	-0.17	-0.17

Note: * value <0.1 is omitted.

Source: Joseph & Ouseph (2010).

5.1.7 Mussel growth and production models

Mussel growth and production can be illustrated using many approaches. The normal techniques used is the plotting of a simple line graph of weight or size against time (see Rajagopal *et al.*, 1998b) and the progressive growth function (for individual and batch growth) based on time or rearing period. Mussel growth curve, in terms of mean shell length and live weight , shows a almost constant slope while the slope of growth by meat weight fluctuates over time (Karayücel *et al.*, 2010). The other mathematical models are summarised as the following sections and some of these reviewed models are included in this study modelling.

Simple regression function between rearing time (X; month) is used to predict mussel meat weight (Y; g) for a culture period of 240 days using rope technique and seed sizes of 3.0-8.0 mm. Because of a long culture period, bi-phase function is formulated for two periods of time; Y1 for 0-164 days and Y2 for 164-270 days (Equation 5.2 and 5.3) (Rivonkar, Sreepada, & Parulekar, 1993).

$$Y = 1.73 + 0.040X \quad (r = 0.53) \qquad \text{Equation 5.2}$$

$$Y = 2.71 + 0.017X \quad (r = 0.43) \qquad \text{Equation 5.3}$$

Similar to the previous case, the bi-phase regression function of mussel also found from around 1 year culture period. The culture period (X; days) is used to predict mussel total weight (Ytw) and meat weight (Ymw; g.). Subscript 1 and 2 represent the culture period of 0-180 days and >180 days, respectively (Equation 5.4-5.7) (Rajagopal *et al.*, 1998b).

$$Ytw_1 = -0.6227 + 0.085X \quad (R^2 = 0.99) \qquad \text{Equation 5.4}$$

$$Ytw_2 = 3.3309 + 0.043X \quad (R^2 = 0.98) \qquad \text{Equation 5.5}$$

$$Ymw_1 = 0.0147 + 0.040X \quad (R^2 = 0.98) \qquad \text{Equation 5.6}$$

$$Ymw_1 = 0.0029 + 0.026X \quad (R^2 = 0.94) \qquad \text{Equation 5.7}$$

In contrast, based on growth data of mussel from suspended bag culture (Sreenivasan, Thangavelu, & Poovannan, 1989) and the data from mussel growth using pole culture in Pattani Bay (Brohmanonda *et al.*, 1988b) for a 1 year rearing period, no bi-phase growth functions are found. Moreover, the R^2 obtained from regression and logarithm functions are very high and not much difference (Fig. 5.2-5.3).

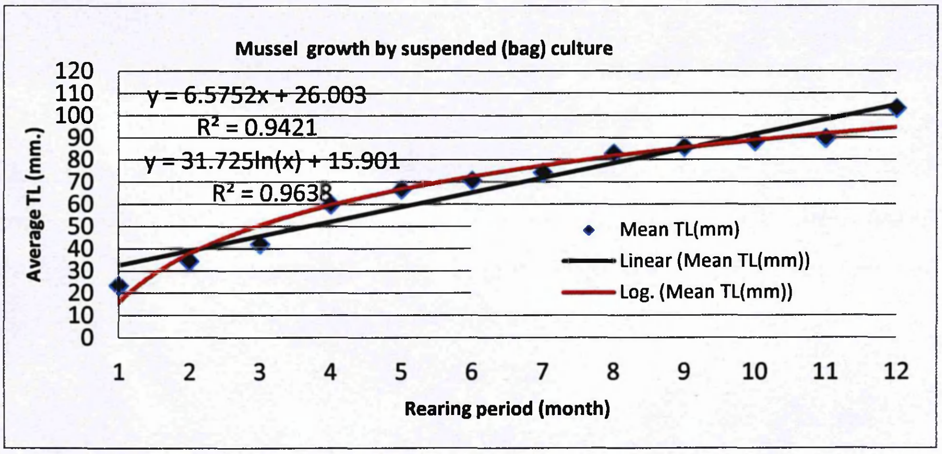


Fig. 5.2. Growth functions of mussel from suspended culture.
Source: Based on data provided by Sreenivasan *et al.* (1989).

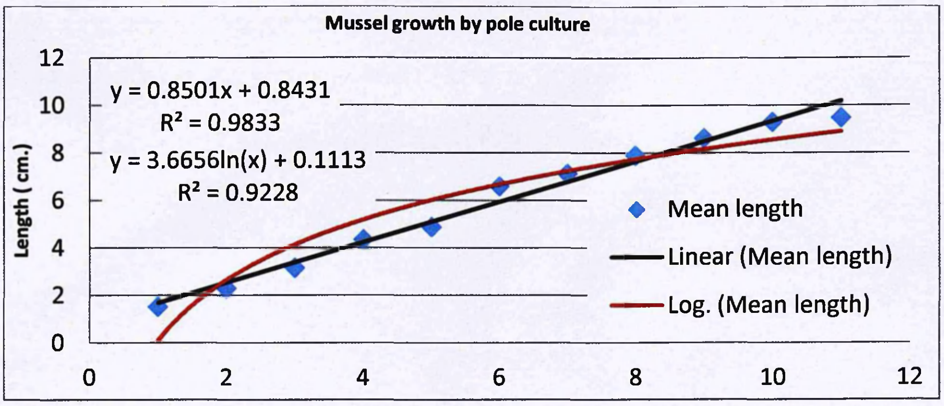


Fig. 5.3. Growth functions of mussel from pole culture.
Source: Based on data provided by Brohmanonda *et al.* (1988b).

Exponential function is also applied for mussel growth prediction. Mussel total length (Y1 = surface mussel, Y2 = bottom mussel ;mm) is explained bay rearing period (X;month) as follows (Equation 5.8-5.9) (Nilkerd, 2001):

$$Y1 = 1.1904X^{1.8797} \quad (R^2 = 0.97) \qquad \text{Equation 5.8}$$

$$Y2 = 1.0418X^{1.3579} \quad (R^2 = 0.99) \qquad \text{Equation 5.9}$$

In the present study, monthly mussel growth data was collected from 9 stations from field experiment in the bay (referred to Fig 3.2) together with a series of water quality parameters during a culture period from 27-52 stations (referred to Table 4.1). These field data were employed for mussel growth determination, progressive mussel growth functions and mussel harvestable area in the proposed suitable culture site. More details of these topics are described in the following sections:

5.2 Mussel growth from field experiment

5.2.1 Mussel size and size difference over the culture period

Nine experiment stations, namely PSU (1), Prison (2), Laem Nok (3), Farm House (4), Tanyong Lolu (5), Yaring River (6), Da To (7), Budee (8) and Laem Ta Chi (9) were established (Fig. 3.2.), but two stations, PSU and Dato, were lost by poaching. The mussel growth experiment (Section 3.1.2) was conducted during 06th June, 2009 - 12th September 2009 or during the 157th – 255th of the Julian calendar. Natural mussels (average size of 1.69±0.36 g., 2.56±0.25 cm. and 1.39±0.15 cm in weight, length and height, respectively) were used as initial seeds. Initial seed size of all stations was proved no significant difference (P>0.05). Mussel sizes by total weight, length and height from 7 stations are summarised (Table 5.11).

Table 5.11 Mussel sizes from field in Pattani Bay, Thailand.

MMDDYY	Station	N	Weight (g.) (Mean±SD)	Length (cm.) (Mean±SD)	Height (cm.) (Mean±SD)
06-06-2009	PSU	30	1.62±0.48	2.53±0.27	1.35±0.15
(157th Julian)	Prison	30	1.77±0.33	2.59±0.28	1.40±0.11
	Laem Nok	30	1.76±0.35	2.61±0.18	1.40±0.12
	Farm House	30	1.69±0.37	2.53±0.29	1.37±0.13
	Tanyoug Lulo	30	1.56±0.36	2.54±0.21	1.36±0.13
	Yaring River	30	1.73±0.33	2.53±0.33	1.41±0.18
	Da To	30	1.63±0.35	2.56±0.18	1.39±0.16
	Budee	30	1.74±0.32	2.53±0.33	1.43±0.17
	Laem Ta Chi	30	1.72±0.33	2.60±0.18	1.40±0.13
	Total	270	1.69±0.36	2.56±0.25	1.39±0.15
18-07-2009	PSU	40	7.01±1.37^{b}	4.49±0.35b^{c}	2.41±0.23^{a}
(199th Julian)	Prison	40	7.41±1.55^{ab}	4.59±0.39^{ab}	2.34±0.29^{a}
	Laem Nok	40	6.39±1.35^{c}	4.33±0.37^{c}	2.41±0.23^{a}
	Farm House	40	5.14±3.96^{d}	3.96±0.41^{d}	2.14±0.24^{b}
	Tanyoug Lulo	40	4.46±1.27^{e}	3.73±0.43^{e}	2.09±0.27^{b}
	Yaring River	40	2.82±0.70^{f}	3.12±0.30^{f}	1.75±0.24^{c}
	Da To	40	3.21±0.81^{f}	3.29±0.34^{f}	1.78±0.19^{c}
	Budee	40	4.72±1.08^{de}	3.83±0.36d^{e}	2.21±0.30^{b}
	Laem Ta Chi	40	7.97±1.76^{a}	4.72±0.44^{a}	2.47±0.35^{a}
	Total	360	5.46±2.15	4.01±0.66	2.18±0.37
10-08-2009	Prison	25	10.31±2.09^{a}	5.24±0.43^{a}	2.62±0.22^{b}
(222nd Julian)	Laem Nok	30	9.22±1.68^{b}	5.01±0.39^{b}	2.47±0.29^{c}
	Farm House	30	7.60±1.40^{c}	4.64±0.34^{c}	2.44±0.23^{c}
	Tanyoug Lulo	32	6.72±1.01^{c}	4.43±0.27^{d}	2.29±0.25^{d}
	Yaring River	31	3.40±0.99^{d}	3.35±0.40^{e}	1.80±0.18^{e}
	Budee	29	7.45±1.79^{c}	4.59±0.45^{cd}	2.49±0.19^{bc}
	Laem Ta Chi	30	10.39±2.36^{a}	5.25±0.47^{a}	2.81±0.33^{a}
	Total	207	7.78±2.80	4.62±0.72	2.41±0.38

Table 5.11. Mussel sizes from field in Pattani Bay, Thailand (cont.).

MMDDYY	Station	N	Weight (g.) (Mean±SD)	Length (cm.) (Mean±SD)	Height (cm.) (Mean±SD)
12-09-2009	Prison	30	13.31±2.15^{b}	5.80±0.38^{ab}	2.57±0.27^{bc}
(255th Julian)	Laem Nok	30	12.04±1.79^{b}	5.58±0.34^{b}	2.58±0.26^{bc}
	Farm House	30	10.52±2.32^{c}	5.27±0.46^{c}	2.59±0.23^{bc}
	Tanyoug Lulo	30	8.92±2.50^{d}	4.92±0.55^{d}	2.54±0.36^{c}
	Yaring River	30	5.08±1.33^{e}	3.94±0.40^{e}	2.18±0.22^{d}
	Budee	30	12.21±2.56^{b}	5.60±0.44^{b}	2.73±0.32^{b}
	Laem Ta Chi	30	14.84±3.83^{a}	6.03±0.62^{a}	3.13±0.50^{a}
	Total	210	10.99±3.85	5.31±0.80	2.62±0.41

Note: - The different alphabet in column shows significantly different at $\alpha < 0.01$

- Sig. value from ANOVA is <0.01 for all weight, length and height.

From the similar initial seed size at all locations throughout the bay, mussels showed significantly different between stations after >1 month of rearing period. Mussel form Laem Tachi station reached marketable size of 6.0 cm in total length.

5.2.2 Mussel growth function

In terms of length, mussel growth trends of most stations showed fast initial growth rate which decreased during the experimental period (Fig.5.4). Based on average weight, the mussel growth at almost all stations showed a constantly increasing and consistent rate (Fig.5.5.), except that from Budee, which showed a close fit to the exponential function (see Table 5.12). The mussel growth in terms of height expressed similar trend to those of length, except that mussels from the Yaring River station, which showed slightly fluctuation (Fig. 5.6.)

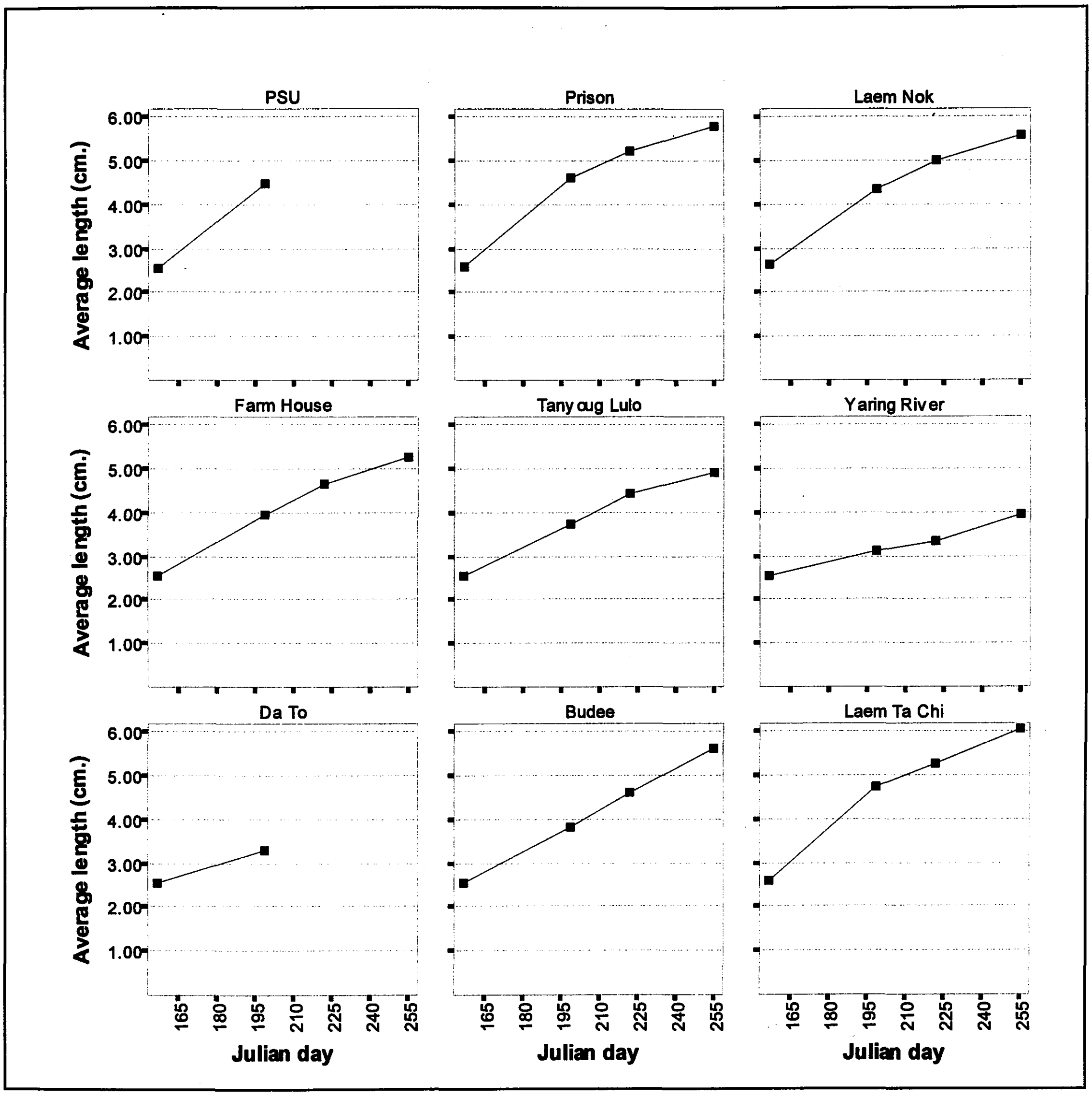


Fig. 5.4. Mean length of mussel of each station during Jun.-Sep., 2009.

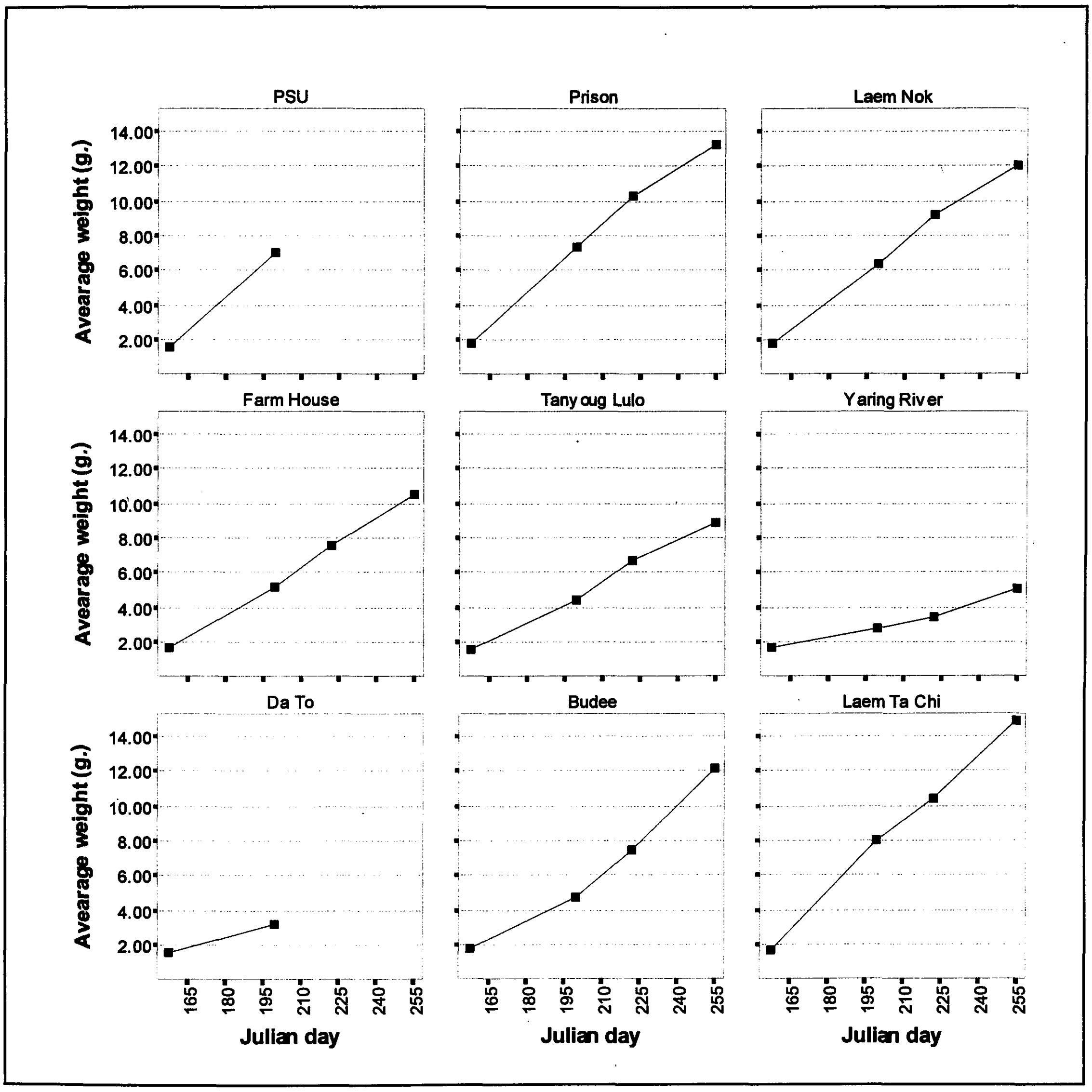


Fig. 5.5. Mean weight of mussel of each station during Jun.-Sep., 2009

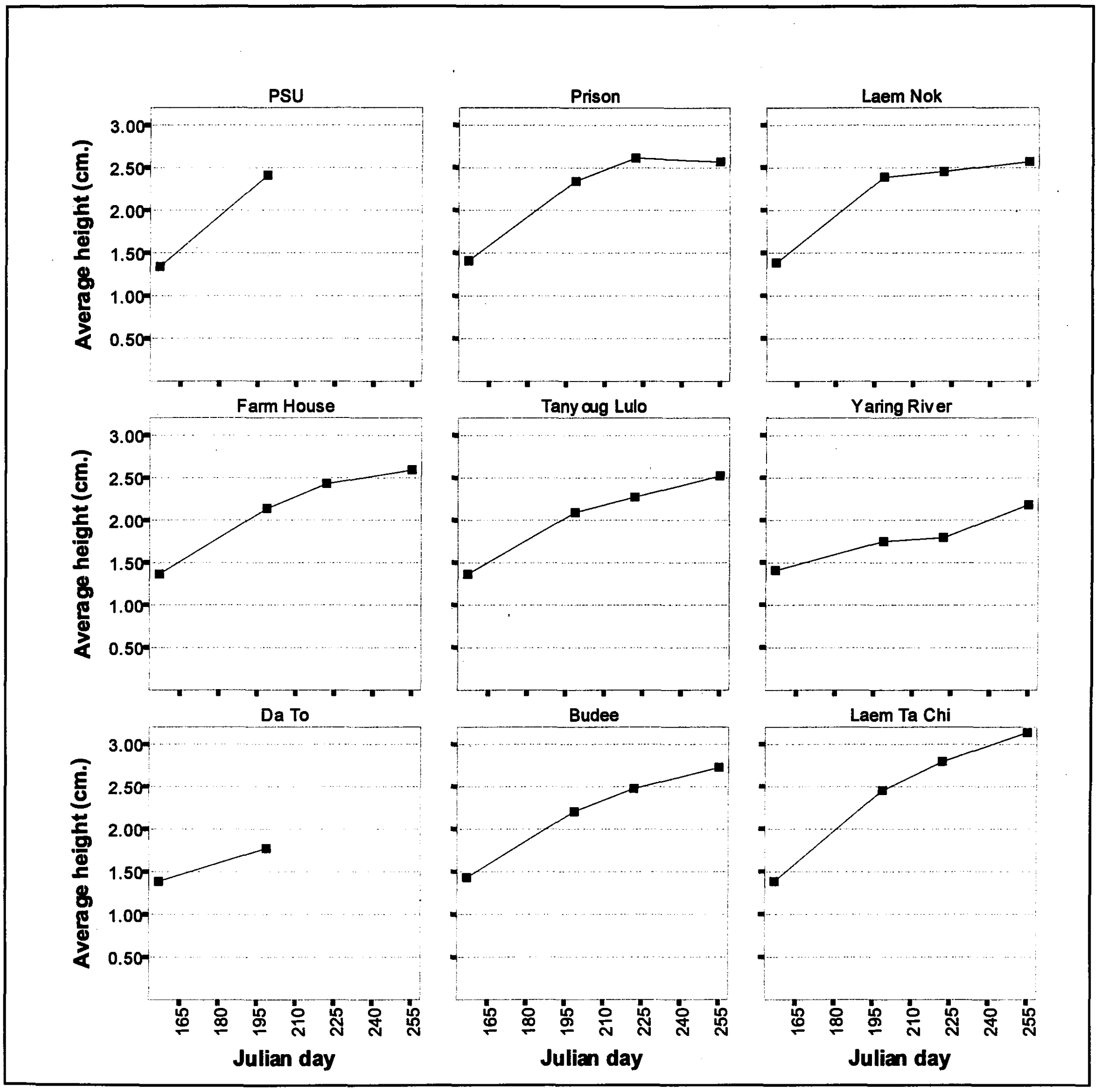


Fig. 5.6. Mean height of mussel of each station during Jun.-Sep., 2009.

From information found in the literature, the growth of mussels over time can be mainly described by two functions; logarithm and linear functions. These were tested for growth illustrated by all parameters at each location during the experimental period. Mussel size (Y; length (cm) and weight (g)) as dependent parameters were predicted by time (X; the Julian day calendar) were selected to apply in this study because obtained functions were considered high coefficient of determination (R^2), and mussel weight and length were used for mussel pricing and marketing purposes.

Based on mussel weight, logarithmic growth functions at all stations showed coefficient of determinations (R^2) of 93.05-99.91%. The lowest R^2 was from Yaring River station and the highest R^2 was from Prison station. Those for the linear growth functions varied from 96.24-99.78%. The lowest and the highest R^2 were from Yaring River and Farm House stations, respectively (Table 5.12.).

Base on mussel length, the R^2 of logarithm functions varied from 97.37-99.62%. The lowest and the highest R^2 were from Prison and Farm House stations, respectively. The R^2 for linear functions varied from 94.38-99.98%. The highest and the lowest R^2 were from Budee and Prison stations, respectively (Table 5.13.).

Table 5.12. Growth functions of mussel weight in Pattani bay, Jun.-Sep. 2009.

Station	Growth functions	Equations	R^2(%)
Prison	Logarithmic	y = 23.983ln(x) - 119.47	99.91
	Linear	y = 0.1189x - 16.561	99.11
Laem Nok	Logarithmic	y = 21.37ln(x) - 106.41	99.75
	Linear	y = 0.1063x -14.779	99.54
Farm House	Logarithmic	y = 18.166ln(x) - 90.468	98.80
	Linear	y = 0.0909x - 12.687	99.78
Tanyong Lu Lo	Logarithmic	y = 15.287ln(x) - 75.962	98.86
	Linear	y = 0.0764x - 10.485	99.54
Yaring River	Logarithmic	y = 6.5984ln(x) - 31.869	93.05
	Linear	y = 0.0334x - 3.6992	96.24
Budee	Logarithmic	y = 20.983ln(x) - 105.07	93.54
	Linear	y = 0.1062x -15.594	96.78
	Power	$y = 2E\text{-}09x^{4.0461}$	99.85
Laem Ta Chi	Logarithmic	y = 26.662ln(x) - 133.2	99.65
	Linear	y = 0.1327x - 18.909	99.67

Table 5.13. Growth functions of mussel length in Pattani bay, Jun.-Sep. 2009.

Station	Growth functions	Equations	R^2(%)
Prison	Logarithmic	y = 6.7482ln(x) - 31.369	97.37
	Linear	y = 0.0331x - 2.3322	94.38
Laem Nok	Logarithmic	y = 6.2283ln(x) - 28.773	98.55
	Linear	y = 0.0306x - 1.9951	96.18
Farm House	Logarithmic	y = 5.7245ln(x) - 26.371	99.62
	Linear	y = 0.0283x - 1.7889	98.20
Tanyong Lu Lo	Logarithmic	y = 5.0279ln(x) - 22.86	99.30
	Linear	y = 0.0249x - 1.2701	97.95
Yaring River	Logarithmic	y = 2.8262ln(x) - 11.809	97.76
	Linear	y = 0.0142x - 0.286	99.14
Budee	Logarithmic	y = 6.298ln(x) - 29.388	99.43
	Linear	y = 0.0314x - 2.4078	99.98
Laem Ta Chi	Logarithmic	y = 7.0871ln(x) - 33.076	97.98
	Linear	y = 0.0348x - 2.5986	95.42

5.3 Spatial mussel growth prediction by PCR and MLR models

5.3.1 Related environmental parameters

The mussel growth parameters measured at the locations within Pattani Bay can be related, as average growth, to average value of environmental parameters within the Bay. The average growth was applied as dependent variables in both PCR and MLR models while extracted PCs and some environmental parameters were selected as independent variables through the PCA. The analyses are summarised as follows:

5.3.1.1 Water quality parameters

Water quality parameters used in this chapter were collected during the first sampling phase (Table 3.4). Water depth and salinity of the general survey were included because they were collected from 52 sampling points, the highest number of sampling stations in the first sampling period. All water quality layers construction was explain in Chapter 4. Layer names, abbreviations and number of original layer are shown in Table 5.14.

Table 5.14. All water quality parameters including in PCR and MLR modelling.

Variables	Abbreviation	Unit	Layer name	No. of layers*
Chlorophyll-a	CHL	µg./l.	chl all5	5
Dissolved oxygen	DO	mg./l.	do all5	5
Depth	-	m.	m_depth06	2
pH	-	-	ph all5e6	5
Particulate organic matter	POM	mg./l.	pom all5e67	5
Salinity	SAL	ppt.	sal all6	6
Total dissolved solid	TDS	g./l.	tds all5	5
Temperature	TEMP	°C	temp all5	5
Transparency	TRAN	cm.	trans all5	5
Total suspended solid	TSS	g./l.	tss all5	5
Ebb & Flood currents	Ebb/Flood	m/s.	curr ebb/flood	2

Note: An asterisk (*) indicates total layers before mean value is calculated.

Descriptive point data of the water quality from field sampling based on each sampling occasion and of all sampling period is illustrated in Table 5.15.

For water currents, the summary of ebb and flood currents are given in Table 5.16. Mean water current of ebb tide (0.29 m/s) is higher than that of flood tide (0.14 m/s). This may be because of the added effect of river flow from the Yaring River.

Table 5.15. Descriptive data of water parameters during the first sampling phase.

Time	STAT	DEPT	TRAN	TEMP	DO	pH	SAL	TDS	TSS	POM	CHL
Jun1	Mean	1.40					19.79				
	N	52.00					52.00				
	SD	0.79					6.79				
	MIN	0.50					2.00				
	MAX	4.40					28.00				
	Range	3.90					26.00				
Jun2	Mean	1.37	43.73	31.58	7.82		25.04	25.62	0.17		39.76
	N	49.00	49.00	48.00	48.00		48.00	48.00	49.00		49.00
	SD	0.66	15.75	1.04	1.02		6.08	5.72	0.04		4.53
	MIN	0.30	6.00	29.19	4.95		10.54	11.67	0.09		33.36
	MAX	4.20	80.00	33.81	9.56		31.34	31.45	0.26		49.20
	Range	3.90	74.00	4.63	4.61		20.80	19.78	0.17		15.84
Jul1	Mean	1.19	46.40	30.89	6.69	7.57	22.09	22.85	0.18		48.19
	N	29.00	29.00	27.00	27.00	27.00	27.00	27.00	29.00		29.00
	SD	0.77	12.83	0.92	0.69	0.22	5.88	5.62	0.06		5.92
	MIN	0.40	28.50	29.71	5.38	7.04	8.33	9.40	0.08		35.54
	MAX	4.30	80.00	32.70	7.74	8.05	29.78	30.05	0.32		59.60
	Range	3.90	51.50	2.99	2.36	1.01	21.45	20.65	0.24		24.06
Jul2	Mean	1.08	31.84	31.83	6.61	7.65	20.19	20.99	0.28	54.65	53.02
	N	32	32.00	32.00	32.00	32.00	32.00	32.00	30.00	32.00	32.00
	SD	0.79	30.37	0.68	0.70	0.14	7.52	7.33	0.10	38.44	12.38
	MIN	0.40	10.00	30.53	3.63	7.17	1.44	1.83	0.09	20.00	34.75
	MAX	4.00	172.0	33.09	7.78	8.05	30.33	30.49	0.56	150.0	79.19
	Rang	3.60	162.0	2.56	4.15	0.89	28.89	28.67	0.47	130.0	44.45
Aug	Mean	1.04	51.03	31.22	5.70	7.83	18.31	19.20	0.11	16.94	38.99
	N	29.00	29.00	29.00	29.00	29.00	29.00	29.00	28.00	28.00	29.00
	SD	0.78	16.35	1.09	0.78	0.19	7.11	6.94	0.04	8.56	4.04
	MIN	0.40	16.00	29.08	4.09	7.51	1.70	2.14	0.04	3.33	32.97
	MAX	3.90	112.0	33.78	7.12	8.22	30.62	30.76	0.20	33.33	46.67
	Range	3.50	96.00	4.70	3.03	0.71	28.92	28.62	0.16	30.00	13.70
Sep	Mean		28.79	28.73	6.28	7.86	18.65	19.57	0.15	17.02	49.46
	N		29.00	29.00	29.00	29.00	29.00	29.00	29.00	29.00	29.00
	SD		11.11	0.52	1.16	0.21	4.77	4.58	0.06	6.62	7.00
	MIN		17.00	27.60	3.82	7.40	9.77	10.87	0.06	5.00	37.23
	MAX		60.00	29.73	7.87	8.10	28.70	28.99	0.32	30.00	66.05
	Range		43.00	2.13	4.05	0.70	18.93	18.12	0.26	25.00	28.82
Total	Mean	1.25	40.61	30.95	6.76	7.73	20.95	22.08	0.18	30.53	45.28
	N	191.00	168.0	165.0	165.0	117.0	217.0	165.0	165.0	89.00	168.0
	SD	0.76	20.05	1.39	1.17	0.22	6.83	6.55	0.08	29.79	9.11
	MIN	0.30	6.00	27.60	3.63	7.04	1.44	1.83	0.04	3.33	32.97
	MAX	4.40	172.0	33.81	9.56	8.22	31.34	31.45	0.56	150.0	79.19
	Range	4.10	166.0	6.21	5.93	1.18	29.90	29.63	0.52	146.7	46.22

Table 5.16. Descriptive of water currents (m/s) of ebb and flood tides in Pattani Bay.

Month	Stat	Flood current (m/s)	Ebb current (m/s)
July 2009	Mean	0.14	0.29
	n	20	18
	SD	0.06	0.16
	MIN	0.02	0.07
	MAX	0.24	0.60
	Range	0.22	0.53

5.3.1.2 Average mussel growth rate

Mussel growth rates during 16 June – 12 September 2009 (3.27 month) for each station is summarised in Table 5.17. In terms of weight, the highest average growth rate was at Laem Tachi (4.02 g/month) and the lowest was at Yaring River (1.03 g/month). The growth rates by length and height showed similar trends to the weight. By length, the growth rates varied from 0.43-1.05 cm/month and that in term of height were 0.23-0.53 cm/ month. The average growth by weight, length and height of the whole bay was 2.85 g., 0.84 cm. and 0.38 cm, respectively. The length-weight relationship of 353 mussels collected from tested and wild sources showed a coefficient of determination (R^2) of 95.93% (Fig. 5.7).

Table 5.17. Monthly average growth rate of mussels in Pattani Bay for the three parameters measured.

Stations	Weight (g./month)	Length(cm./month)	Height(cm./month)
PSU	na	na	na
Prison	3.53	0.98	0.36
Laem Nok	3.15	0.91	0.36
Farm House	2.70	0.84	0.37
Tanyoug Lulo	2.25	0.73	0.36
Yaring River	1.03	0.43	0.23
Da To	na	na	na
Budee	3.20	0.94	0.40
Laem Tachi	4.02	1.05	0.53
Total	2.85	0.84	0.38

Note: na is not available because of mussel lost.

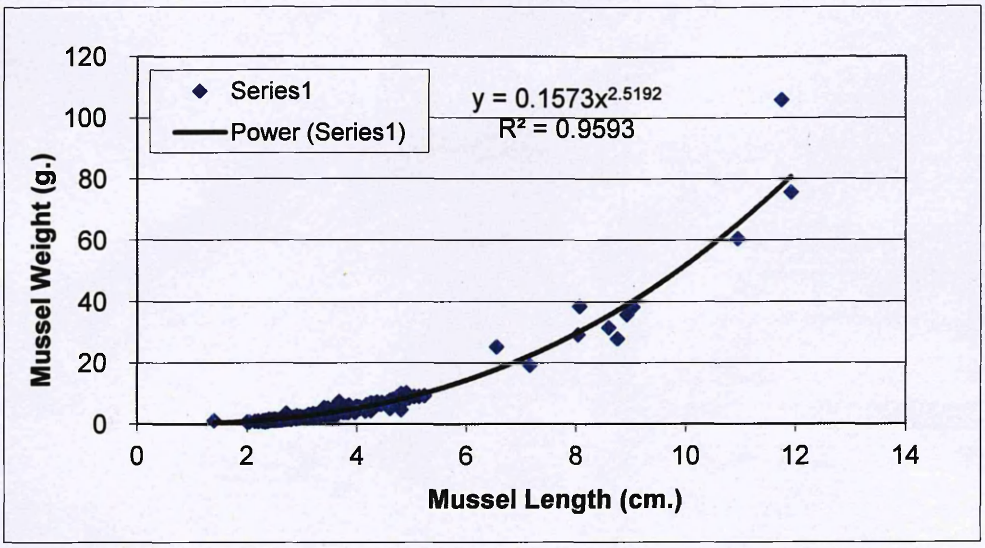


Fig. 5.7. Length-Weight relationship of mussel in Pattani bay, 2009 (n = 353).

5.3.2 Model conceptual framework

The conceptual framework of spatial model for mussel growth of this study is outlined in Fig. 5.8. Field experiment of mussel growth and water quality data were obtained from field experiment as point data. Satellite images of the LANDSAT7 ETM$^+$ were also included. Thereafter, vector point data of water quality and mussel growth were transformed into raster data layers by interpolation (more detail is given in section 4.3). The Boolean image (see Fig. 4.5.), created using satellite images, was used as a mask file to indicate water boundary. Principal Component Analysis (PCA) was employed for principle components (PCs) extraction. The PCs were then used as independent variables of the mussel growth models. Finally, the mussel growth modelling was done by multiple linear regressions approach by MULTIREG module in the IDRISI GIS program. In this step, the raster layer of monthly mussel average growth was employed as a dependent variable. Independent variables were classified into 3 different groups:

- All extracted PCs (PCs): Total PCs are equivalent to the total number of input parameters, which were created by the PCA process.
- Main PC(s) (MPCs): The MPCs are classified by the eigenvalue of each PC. Generally, the PC with eigenvalue ≥1.0 is considered as the MPC.
- The highest loading water quality parameters (WQs): This was selected by choosing the highest loading variable from each of the main PC. The number of the WQs equals the number of the MPCs.

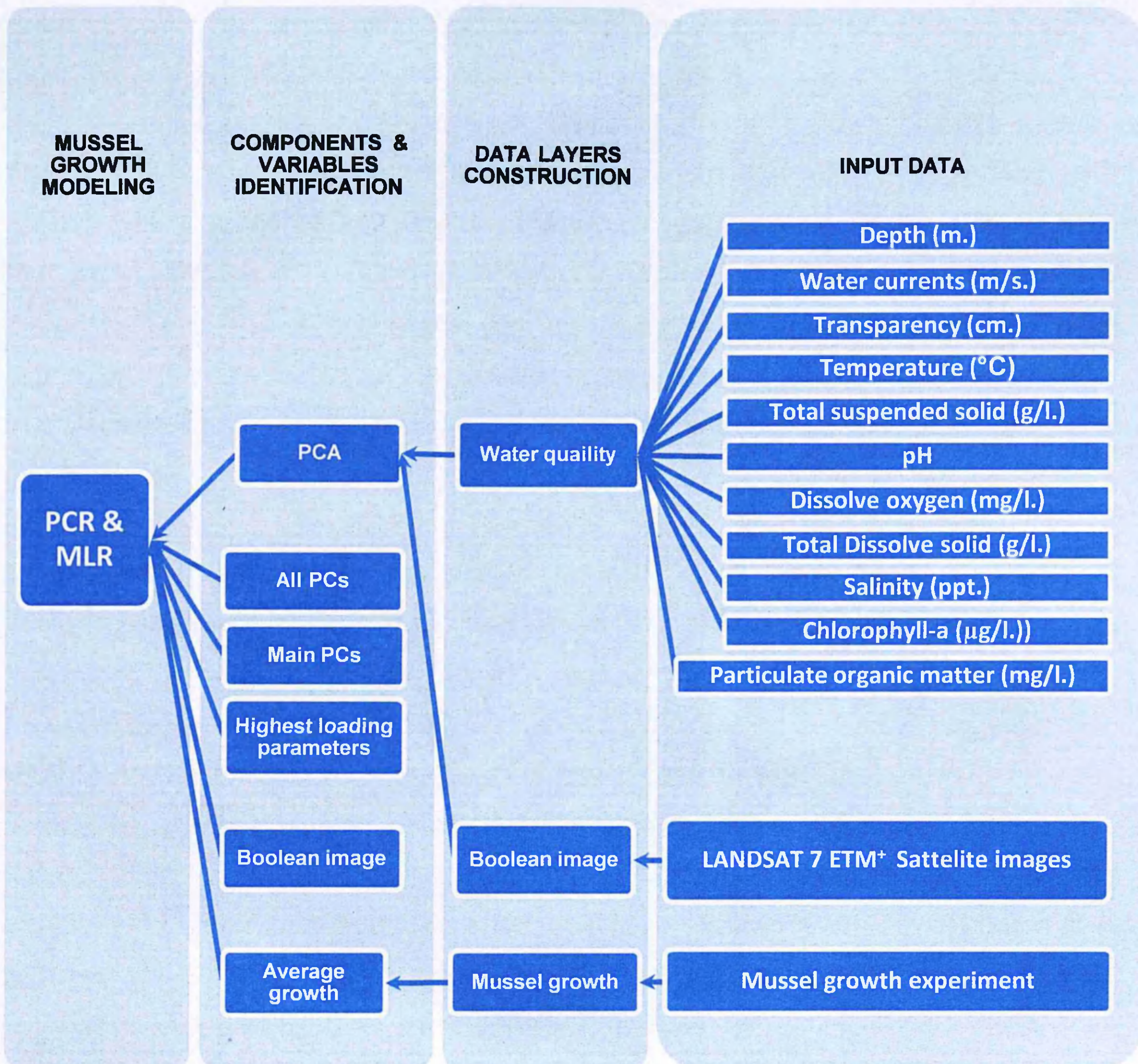


Fig. 5.8. Conceptual framework of using PCA and MLR for mussel growth model.

Here, regression models generated by using PCs or MPCs as an independent variables are named "principal component regression (PCR models)" and the model formulated by WQs are called "multiple linear regression; MLR models" (or simple regression model in case the model comprises single independent variable).

5.3.3 Principal component (PCs) extraction by PCA

Input data for the PCA module in this study were raster files (or raster group files). Each file represents mean value of each water parameter (Table 5.14) of the first phase of sampling. The PCA outputs are a new set of PCs with less autocorrelation and explain progressively less variance of the water parameters. In this study, PCs were formulated by forward process, which calculates covariance directly from the whole image. The "use standardized variables" was selected because the unit of the input images is difference (Çamdevýren *et al.*, 2005). Using these options, new component image extraction is performed on the correlation matrix in order to treats all variables with equal importance (DelValls, Forja, González-Mazo, Gómez-Parra, & Blasco, 1998). Moreover, standardizing the data set also reduces an effect of outlier on PCs extraction (Baxter, 1995; Cao, Williams, & Williams, 1999). Data pre-treatment is a necessary step that should be considered because outliers and skewed have significant influence the output and lead to misinterpretation (Reid & Spencer, 2009b). The Boolean image was used as a mask file to eliminate background value for all input components.

Conventionally, PCA using point data have to meet some basic requirements; sampling adequacy, inter-relation among data set and normalized input data. The KMO Test is applied to fulfil the first requirement while the Bartlett's test of sphericity fulfils the second one. A KMO test value of >0.5 indicates the data set is suitable to use PCA while the Chi-square form the Bartlett's should be significant at $\alpha<0.05$, which means the data set is not an identity matrix (the correlation matrix with all 0 correlation values). If the data set shows identity matrix, there is no relationship among any parameters of input parameters (correlation value = 0), thus a PCA is not necessary. Although this study uses raster data, some point values are extracted from every data layer used for the KMO and Bartlett's tests. The total number of extracted points is 44 points, which is equal to the maximum sampling stations for water salinity during the general sampling survey. The KMO Test gives a value of 0.70. The Chi-square (X^2) from the Bartlett's test was 623.42 and showed a significance level of $\alpha<0.001$ as in Table 5.18. Normal distribution of point data set was tested by the Kolmogorov-Smirnov, and Stem and Leaf tests and found that POM, TRAN and TSS hold some outliers while CHL, DO, DEPTH, pH, TEMP and Flood were proved normal distributed. The remaining water parameters were confirmed normal distributed by the Stem and Leaf tests (Table 5.19).

Table 5.18. KMO Test and Bartlett's Test of point data water quality.

Tests		Values
Kaiser-Meyer-Olkin Measurement of Sampling Adequacy		0.70
Bartlett's Test of Sphericity	Approx. Chi-square	623.424
	df	78
	Sig.	<0.001

Table 5.19. The normality test of the point water quality data.

Parameters	Statistic	d.f.	Sig.	Stem and Leaf
CHL	0.082	43	0.200*	
DO	0.102	43	0.200*	
DEPTH	0.108	43	0.200*	
pH	0.086	43	0.200*	
POM	0.233	43	<0.001	4 outliers
SAL	0.171	43	0.002	normal
TDS	0.172	43	0.002	normal
TEMP	0.103	43	0.200*	
TRAN	0.116	43	0.158	4 outliers
TSS	0.143	43	0.024	3 outliers
Ebb	0.123	43	0.094	normal
Flood	0.080	43	0.200*	

Note: The double asterisk (**) indicates fairly normal distribution.
The asterisk (* sig ≥0.20) indicates normal distribution.
The names of parameters are defined in Table 5.14.

Input data to IDRISI, in this study, were raster layers comprising a large number of pixels. High correlations among water parameters (see more detail in the following section) ensured that the data set was not an identity matrix. The normality of the distribution of water parameters was evaluated by HISTO module. The result found that some parameters showed a normal distribution, such as CHL, pH, TEMP, TRAN, TSS, TDS, DO, Ebb and Flood. In addition, POM, DEPTH revealed a positive skew (elongate tail at the right) whereas the SAL showed a slight negative skew. To standardise the distribution of the data to conform to normality the "use standardized variables approach" function of the PCA module was used, which is comparable to data-pre-treatment step of the conventional factor analysis, to reduce the influence of skewed data and outliers.

The outputs of the PCA, in this study, were raster images of PCs and a set of statistical tables. The maximum number of the PCs was equal to the number of input water parameter files. Other than autocorrelation elimination, the PCA can be used for data compression. As a result, some PCs (or MPCs) can be the representative for all input water parameters and the remaining PCs, which explains less than a certain percent of total variance of input parameters, can be ignored (Eastman, 1999b). PCs with eigenvalue >1 are considered MPCs based on the Kaiser Principle (Milstein, 1993; Çamdevýren *et al.*, 2005; Reid & Spencer, 2009a).

The statistical outputs of PCA module comprised 4 tables; (1) variance/covariance matrix, (2) correlation matrix, (3) eigenvalues and eigenvectors, and (4) loadings table. Of all tables, only the correlation matrix and the loadings are shown in this report. The loadings are coefficients that show the correlation between the water quality parameters and the PCs.

In summary, the PCA process extracts a set of PCs and provides a series of correlation values and loadings, which indicate how the water quality parameters contribute (or relate) to each PC. The PCs are, then, used as statistically validated independent parameters in the PCR models. However, PCs are only a proxy variable representing a set of the water quality parameters. Therefore, this study selected the WQs as independent parameters in MLR models to construct simple and practical models.

5.3.3.1 Correlation matrix between mussel growth and ecological parameters

The correlation matrix between water quality parameters and average mussel growth showed a high relationship between many parameters (Table 5.20.). The average mussel growth was found to positively correlate with many parameters, such as pH (0.73), salinity (0.91), TDS (0.91), temperature (0.79) ebb current (0.70) and flood current (0.74), but showed lower correlation with TSS (0.18) and chlorophyll-a (-0.14). Water currents (flood tide) also showed a high positive correlation with water depth (0.71), pH (0.70), salinity (0.76), TDS (0.75) and ebb tide current (0.94). Temperature revealed a high positive correlation with pH (0.71), salinity (0.80) and TDS (0.78). High salinity was correlated with high TDS (0.99). Other than those previously mentioned, the bold values also show high correlations. High negative correlation was seldom found, chlorophyll-a and transparency (-0.61), and POM and TDS (-0.62). The correlation matrix illustrated some auto correlation between water parameters for example, the high current flow area showed high TDS, salinity and also consistence with high mussel growth rate. This shows the reason why PCA, PCR and MLR were used to create simplified models of mussel growth prediction.

Table 5.20. The correlation matrix of water quality variables and average mussel growth (g./month).

COR MATRIX	CHL	DO	Depth06	pH	POM	SAL	TDS	TEMP	TRANS	TSS	Ebb	Flood	Muss growth
CHL	1.00												
DO	-0.07	1.00											
Depth06	0.03	0.27	1.00										
pH	-0.20	0.48	0.41	1.00									
POM	0.21	-0.42	-0.21	-0.42	1.00								
SAL	-0.02	0.55	0.56	**0.77**	-0.61	1.00							
TDS	-0.02	0.56	0.54	**0.76**	-0.62	**0.99**	1.00						
TEMP	0.22	0.26	0.39	**0.71**	-0.22	**0.79**	0.78	1.00					
TRANS	-0.61	0.45	0.48	0.50	-0.30	0.44	0.42	0.15	1.00				
TSS	0.45	0.31	-0.02	0.04	-0.09	0.30	0.32	0.36	-0.41	1.00			
Ebb	-0.18	0.51	0.62	**0.70**	-0.22	0.69	0.68	0.61	0.70	0.07	1.00		
Flow	-0.12	0.48	0.60	**0.71**	-0.34	**0.76**	**0.75**	0.65	0.58	0.19	0.94	1.00	
Muss growth	-0.14	0.34	0.46	**0.73**	**-0.54**	**0.91**	**0.91**	**0.79**	0.45	0.18	**0.70**	**0.74**	1.00

Note: The names of parameters are defined in Table 5.14.; Some high correlation values show by bold number.

5.3.3.2 PCs extracted from 12 water parameters

Of the PCs representing the 12 water parameters, only 3 MPCs were found (Table 5.21.). These PCs explained 78.52% of the total variance of all water parameters. MPC_1-MPC_3 accounted for 51.24%, 17.74% and 9.54% of total variance, respectively. The remaining of 21.48% was explained by the other 9 PCs.

Table 5.21. Total PCs and loading values of 12 water parameters.

LOADINGS	C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9	C 10	C 11	C 12
%variance	**51.24**	**17.74**	**9.54**	**6.60**	**5.70**	**3.49**	**2.29**	**1.72**	**0.74**	**0.64**	**0.29**	**0.01**
eigenvalue	**6.15**	**2.13**	**1.15**	**0.79**	**0.68**	**0.42**	**0.28**	**0.21**	**0.09**	**0.08**	**0.04**	**0.00**
CHL	.14	**.82**	.27	-.05	-.28	-.29	.23	.05	-.06	-.07	.00	.00
DO	**-.64**	.03	-.37	-.59	.00	-.31	-.07	.00	.06	.08	.02	-.00
DEPTH	**-.65**	-.09	.42	-.05	-.58	.07	-.22	-.13	-.01	.04	.01	.00
pH	**-.85**	-.06	-.00	.21	.27	-.25	-.06	-.29	-.05	-.09	-.00	.00
POM	.54	.05	**.69**	-.25	.32	-.08	-.20	.07	.07	-.07	.02	.00
SAL	**-.94**	.19	-.12	.17	-.05	.01	-.08	.14	.09	-.08	-.02	-.02
TDS	**-.93**	.20	-.15	.16	-.05	.02	-.08	.14	.09	-.08	-.01	.02
TEMP	**-.75**	.42	.23	.30	.24	-.07	-.08	.12	-.08	.17	.03	.00
TRAN	**-.63**	**-.71**	.05	-.17	-.03	-.03	.01	.19	-.18	-.08	.04	.00
TSS	-.20	**.81**	-.19	-.33	.13	.33	-.11	-.06	-.11	-.05	-.00	.00
Ebb	**-.87**	-.16	.32	-.20	.12	.09	.18	-.01	.01	.03	-.14	.00
Flood	**-.90**	-.03	.22	-.11	.09	.20	.25	-.07	.09	.00	.11	-.00

Note: The value in bold is the one with loading ≥ 0.60.

The names of parameters are defined in Table 5.14.

The MPC_1 component revealed negative loading on DO (-0.64), water depth (-0.65), pH, salinity (-0.94), TDS (-0.93), temperature (-0.75), transparent (-0.62) and water currents (-0.87% and -0.90% for ebb and flood tides, respectively). The highest loading variable of this was the salinity. It could be concluded that all physio-chemical water parameters, except TSS, were included in this component. Negative loading inferred that MPC_1 value increased if the previous parameters decrease.

The MPC_2 component accounted for 17.74% of total variance. It showed positive loading on chlorophyll-a (0.82) and TSS (0.81), and had negative relation to the transparency (-0.71). The chlorophyll-a was the highest loading parameter. This component could be named bio-physical because it comprised mainly on chlorophyll-a and the other 2 physical parameters.

The MPC_3 component occupied 9.54% of total variance and expressed positive loading distinctively on POM, at 0.69. This component could be named as the main contributor, the POM.

5.3.3.3 PCs extracted from 9 water parameters

POM, TRAN and TSS were discarded because the POM hold outstanding loading value in the third MPC of the 12 PCs extraction while the last 2 parameters showed relatively low loading on the first two MPCs of the same extraction. The result from 9 parameters extraction showed that only 2 PCs were considered as the MPCs. The both MPCs accounted for 74.14% of the total variance of 9 water parameters (Table 5.22.).

The MPC_1 accounted for 61.0% of total variance and showed a negative correlation with a series of physical variables, which were DO (-0.61), water depth (-0.65), pH (-0.85), salinity (-0.94), TDS (-0.93), temperature (-0.80) and water currents of both ebb (-0.88) and flow (-0.90) tides. The salinity was the highest loading parameter (0.94). The MPC2 component, representing 13.14% of total variance, had the highest loading on chlorophyll-a at the value of 0.95.

Table 5.22. Total component and loading value derived from 9 variables.

LOADING	C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9
%VAR	61.00	13.14	8.59	7.82	4.75	2.82	1.37	0.51	0.01
Eigenvalue	5.49	1.18	0.77	0.70	0.43	0.25	0.12	0.05	0.00
CHL	0.07	**0.95**	-0.02	-0.25	0.15	-0.06	-0.10	-0.02	0.00
DO	**-0.61**	-0.20	-0.45	**-0.62**	0.03	-0.06	0.09	0.03	-0.00
DEPTH	**-0.65**	0.08	**0.62**	-0.27	-0.28	-0.14	0.05	0.02	0.00
pH	**-0.85**	-0.13	-0.17	0.24	0.03	-0.39	-0.12	-0.00	0.00
SAL	**-0.94**	0.10	-0.15	0.07	-0.24	0.15	-0.07	-0.04	-0.02
TDS	**-0.93**	0.10	-0.17	0.05	-0.24	0.17	-0.07	-0.02	0.02
TEMP	**-0.80**	0.40	-0.10	0.37	0.07	-0.02	0.25	0.04	0.00
Ebb	**-0.88**	-0.19	0.24	-0.07	0.33	0.05	0.05	-0.15	0.00
Flood	**-0.90**	-0.10	0.20	-0.01	0.29	0.15	-0.12	0.14	-0.00

Note: The value in bold is the one with loading ≥ 0.60.

The names of parameters are defined in Table 5.14.

The remaining variance, 26.86%, was occupied by the other 7 PCs. The loadings of the 7 minor PCs on original variables were very low, except for the PC_3 and PC_4, which had relatively high loading on the water depth (0.62) and DO (0.62). However, eigenvalues of the two PCs were <1, which was the threshold value for being MPC.

5.3.3.4 PCs extracted from 7 water parameters

When compared to the 9 parameter extraction, Ebb and Flood tides were additionally excluded because these data were obtained from a single sampling occasion. Two MPCs were found out of total of 7 PCs. The 2 MPCs carried 74.33% of the total variance (Table 5.23). The MPC_1 accounted for 57.97% of the total variance and revealed negative loadings by the physio-chemical variables, which were DO (-0.61), water depth (-0.62), pH (-0.86), salinity (-0.97), TDS (-0.96) and temperature (0.83). The salinity was the highest loading parameter of the MPC_1. The MPC_2 component represented 16.36% of the total variance and showed the highest positive loading only on the chlorophyll-a of 0.95.

The remaining variance (25.67%) was represented by the rest 5 PCs. Although the PC_3 revealed high negative loading on the DO, its eigenvalue was not large enough to be considered as the MPC.

Table 5.23. Total component and loading value derived from 7 variables.

LOADINGS	C 1	C 2	C 3	C 4	C 5	C 6	C 7
%VAR	57.97	16.36	10.19	9.38	3.87	1.77	0.01
Eigenvalue	4.06	1.15	0.71	0.69	0.27	0.12	0.00
CHL	0.02	**0.95**	-0.28	-0.04	-0.08	-0.10	0.00
DO	**-0.61**	-0.28	**-0.71**	-0.17	-0.07	0.10	-0.00
DEPTH	**-0.62**	0.11	0.30	**-0.71**	-0.09	0.04	0.00
pH	**-0.86**	-0.20	0.11	0.22	-0.38	-0.15	0.00
SAL	**-0.97**	0.01	0.02	0.04	0.23	-0.09	-0.02
TDS	**-0.96**	0.01	-0.01	0.05	0.24	-0.09	0.02
TEMP	**-0.83**	0.33	0.18	0.32	-0.04	0.26	0.00

Note: The value in bold is the one with loading ≥ 60%.
The names of parameters are defined in Table 5.14.

5.3.4 Principle component and multiple linear regressions models

After the PC extraction was achieved by PCA, the variables which were not co-linear were then employed as independent variables of the multiple linear regressions as the same means to Pires *et al.* (2008). In this study, the MULTIREG module within IDRISI Andes™ software was employed to formulate the relation between average mussel growth (g/month.) and different groups of independent variables, which were PCs, MPCs and WQs. The MULTIREG module's outputs were raster files, text files of the linear regressions, ANOVA regressions table, and the T-test value of the corresponding coefficients and constant values. F-value from the ANOVA regression table was used for proving that at least one coefficient value was >0 (or the regression relation is existed). The significance of the coefficient for each independent variable was proved using a T-test. The coefficients of determination (R^2) were used to illustrate the predictive success of the all models. The aims of the PCR and MLR modelling were not only for formulation of models based on statistically validated independent variables from the PCA, but also to develop a simplified the function of using the WQs for mussel growth prediction. Because the length-weight function of mussel had the R^2 of 95.93% (Fig. 5.7). This study used mussel weight as a dependent variable and assumed that the output models did not different considerably from use of length.

5.3.4.1 Principal component regressions (PCR) models

5.3.4.1.1 The 12 components PCR

The MLR model found that 92.23% of average mussel growth throughout the bay was explained by all 12 PCs. There were 5 PCs, PC1, PC3, PC7, PC10 and PC11, which showed a negative relationship to mussel growth while the other 7 PCs, namely PC2, PC4, PC5, PC6, PC8, PC9 and PC12 had a positive relationship to mussel growth (Equation 5.10). T-test of all coefficient and constant values are shown in Table 5.24. All values were significant at $\alpha < 0.001$.

If only the main 3 MPCs were employed, the coefficient of determination (R^2) of the model decreased from 92.23% to 75.90%, meaning that the prediction capability of the model was around 76% of total variation of the mussel growth. The mussel growth would be expected to decreases if MPC_1 and MPC_3 increase and it would be increased if MPC_2 increases (Equation 5.11). The T-test coefficients ($\alpha < 0.001$) are shown in Table 5.25.

$$Y = 2.8740 - 0.2568*PC1 + 0.0383*PC2 - 0.0268*PC3 + 0.2557*PC4 + .0724*PC5 + 0.1465*PC6 - 0.0078*PC7 + 0.2885*PC8 + 0.1142*PC9 - 0.0929*PC10 - 0.334PC11 + 1.033PC12$$

Adjusted- R^2 = 92.23%

F-test (12, 93,406) = 92,459.8 Equation 5.10

Table 5.24. The 12 PCs regression coefficients and related statistical tests.

Parameters	Coefficient	T-test	R^2
Intercept	2.874	4,291.26	92.23%
PC1	-0.2568	-950.87	
PC2	0.0383	83.52	
PC3	-0.0268	-42.88	
PC4	0.2557	339.87	
PC5	0.0724	89.44	
PC6	0.1465	141.53	
PC7	-0.0078	-6.13	
PC8	0.2885	195.96	
PC9	0.1142	50.83	
PC10	-0.0929	-38.58	
PC11	-0.3395	-94.78	
PC12	1.033	39.19	

Note: All coefficient values are significant at $\alpha < 0.001$.

$$Y = 2.8740 - 0.2568*MPC1 + 0.0383*MPC2 - 0.0268*MPC3$$

Adjusted- R^2 = 75.89%

F-test (3, 93,415) = 98,046.13 Equation 5.11

Table 5.25. The 3MPCs of 12 PCs regression coefficients and related statistical tests.

Parameters	Coefficients	T-test	R^2
Intercept	-0.2568	-539.72	75.89%
MPC1	0.0383	47.40	
MPC2	-0.0268	-24.33	
MPC3	-0.2568	-539.72	

Note: All coefficient values are significant at $\alpha < 0.001$.

The model outputs of the two PCR approaches from 12 parameters data set showed slightly spatial differences in the growth rate of mussel. The maximum growth rate of the 12 PCs and 3 MPCs were 4.17 and 3.94 g./month, respectively (Fig. 5.9).

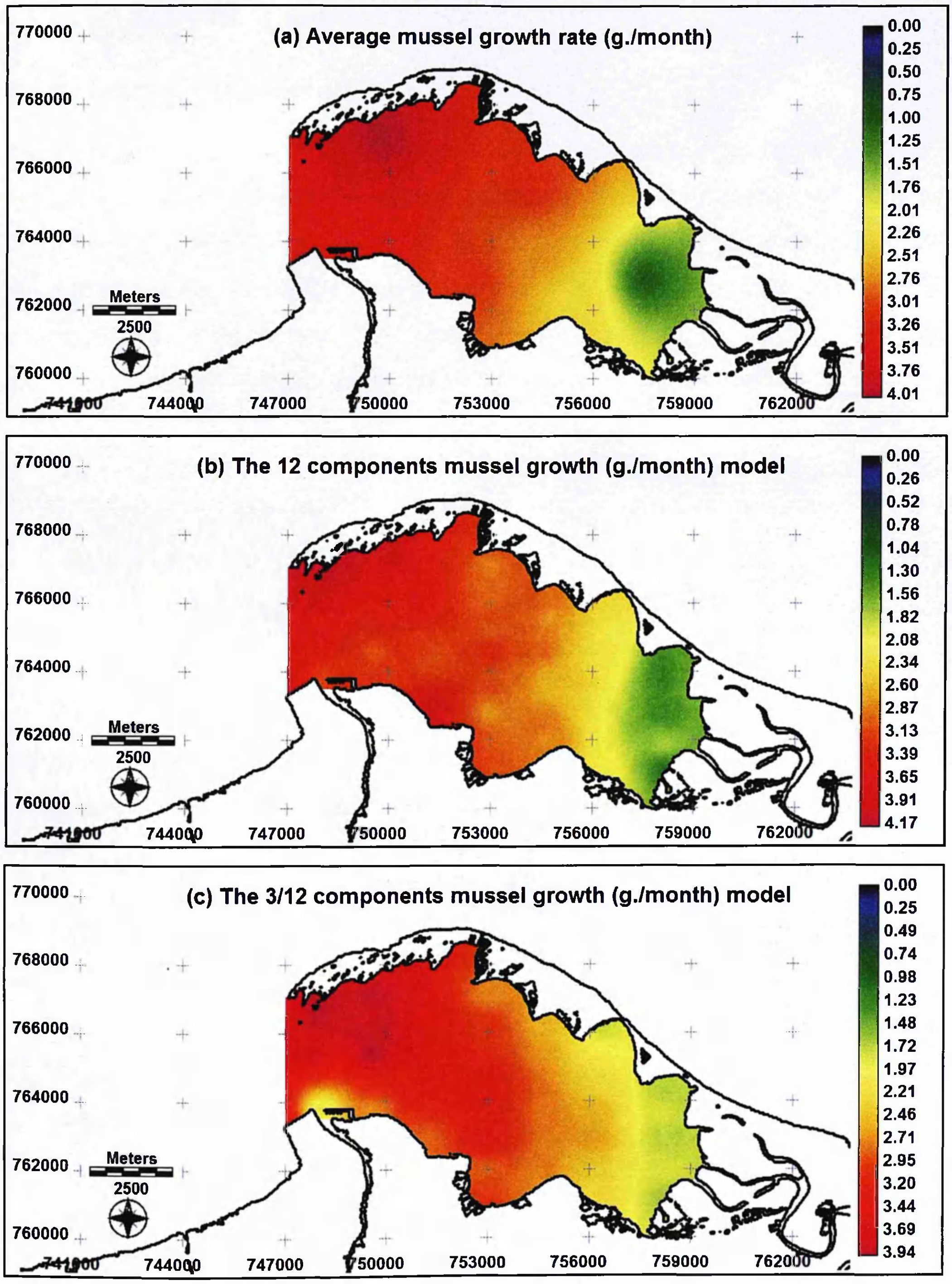


Fig. 5.9. Average mussel growth from (a) sampling data, (b) 12 PCs, and (c) 3/12 MPCs models.

High mussel growth rate areas from the 12 PCs model were mainly found from the mouth of the bay to the Lighthouse, especially near the northern coastline, as well as some small areas near Laem Nok and the Industrial zone. The 3 MPCs model showed high mussel growth area from the mouth of the bay to offshore of Laem Nok, but some areas at the mouth of the Pattani River and small area near the shore of the Industrial zone to Laem Nok were excluded.

5.3.4.1.2 The 9 components PCR

By the 9 components, the PCR indicated that all PCs accounted for 91.99% of the mussel growth variation. The PCs, which positively related to mussel growth rate, were PC2, PC4, PC6 and PC9. An increase in these components resulted in the higher growth rate of mussel. While the second group of PCs (PC1, PC3, PC5, PC7 and PC8) increasing would be decreased the mussel growth rate (Equation 5.12). T-test of all coefficients are shown in Table 5.26 and all showed significant at α <0.001.

$$Y = 2.8740 - 0.2716*PC1 + 0.0162*PC2 - 0.0513*PC3 + 0.2571*PC4 - 0.1582*PC5 + 0.3110*PC6 - 0.0565*PC7 - 0.3594*PC8 + 1.1930*PC9$$

Adjusted- R^2 = 92.00%

F-test (2, 93,416) = 140,918.39 Equation 5.12

Table 5.26.The 9 PCs regression coefficients and related statistical test.

Parameters	Coefficient	T-test	R^2
Intercept	2.8740	4,227.21	92.00
PC1	-0.2716	-935.97	
PC2	0.0162	25.84	
PC3	-0.0513	-66.41	
PC4	0.2571	317.32	
PC5	-0.1582	-152.06	
PC6	0.3110	230.57	
PC7	-0.0565	-29.13	
PC8	-0.3594	-112.74	
PC9	1.1930	47.4671	

Note: All coefficient values are significant at α <0.001.

If only 2 MPCs were applied in the MLR model, the predictive success of the model on the mussel growth rate was only 75.11%. The MPC1 showed negative impact on the mussel growth rate while the MPC2 expressed positive relationship (Equation 5.13). All T-test values are shown in Table 5.27 and were significant at α <0.001.

$$Y = 2.8740 - 0.2716*MPC1 + 0.0162*MPC2$$

Adjusted- R^2 = 75.11%

F-test (2, 93,416) = 140,918.39 Equation 5.13

Table 5.27. The 2 MPCs of 9 PCs regression coefficients and related statistical test.

Parameters	Coefficient	T-test	R^2
Intercept	2.8740	2,396.78	75.11
MPC1	-0.2716	-530.68	
MPC2	0.0162	14.65	

Note: All coefficient values are significant at α <0.001.

The maximum predicted growth rate of mussel for the 9 PCs and 2MPCs models were 4.39 and 3.80 g./month, respectively (Fig. 5.10). Spatial distribution of high growth rate areas for the 9PCs were found very similar to that of the 12 PCs model, but the maximum growth rate of the 9 PCs model was higher. High growth rate areas of the 2 MPCs model was also identical to that of the 3 MPCs in the previous section, but the maximum growth rate of the 2 MPCs was less than that of the 3 MPCs model and the relatively low growth rate area covering larger space, especially from Pattani River mouth to Laem Nok.

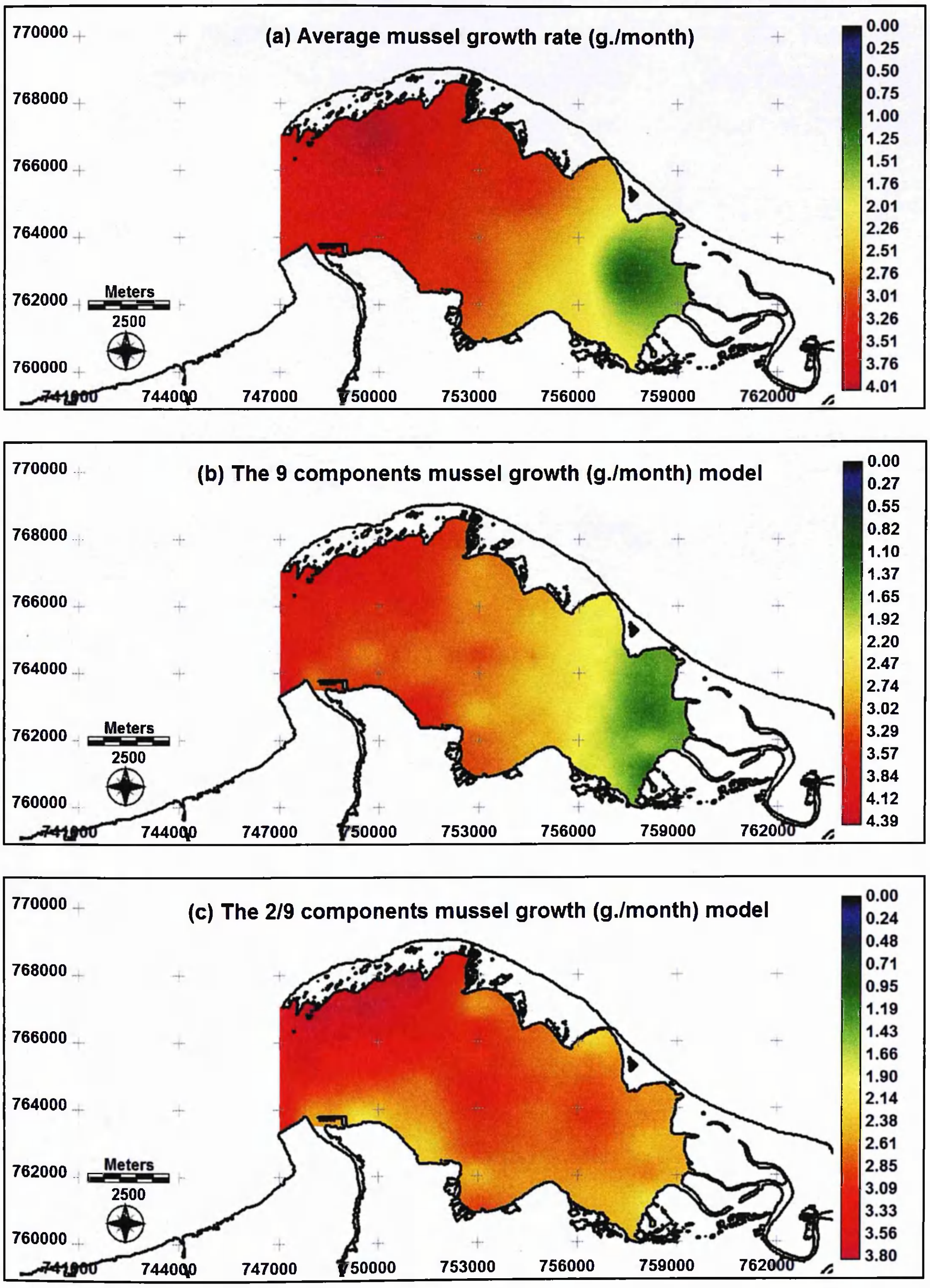


Fig. 5.10. Average mollusc growth of (a) sampling data, (b) 9 PCs, and (c) the 2/9 MPCs models.

5.3.4.1.1 The 7 components PCR

The MLR model using 7 PCs found that the mussel growth rate was positively related to PC3, PC4 and PC5 components, while the other PCs (PC1, PC2, PC6 and PC7) showed a negative relationship to the mussel growth (Equation 5.14). The predictive ability of all components on the mussel growth rate was 90.12% and T-test values of all parameters are found as in Table 5.28. All coefficients were significant at $\alpha < 0.001$.

$$Y = 2.8740 - 0.3184*PC1 - 0.0295*PC2 + 0.1904*PC3 + 0.1543*PC4 + 0.3404*PC5 - 0.0556*PC6 - 0.1611*PC7$$

Adjusted- R^2 = 90.12%

F-test (7, 93,411) = 121,732.28 Equation 5.14

Table 5.28. The 7 components regression coefficients and related statistical test.

Parameters	Coefficient	T-test	R^2
Intercept	2.8740	3,804.5669	90.12%
PC1	-0.3183	-848.9092	
PC2	-0.0295	-41.7712	
PC3	0.1903	212.8245	
PC4	0.1543	169.3960	
PC5	0.3403	234.5916	
PC6	-0.0556	-25.9138	
PC7	-0.1611	-6.5855	

Note: All coefficient values are significant at $\alpha < 0.001$.

When all non-significant components were discarded, the PCR model using 2 MPCs revealed that all independent variables accounted for only 76.40% of the total variation of the mussel growth rate. Both MPC1 and MPC2 showed a negative relationship to the mussel growth rate (Equation 5.15). Coefficient values of parameters are shown in Table 5.29.

$$Y = 2.8740 - 0.3184*7MPC1 - 0.0295*MPC2$$

Adjusted- R^2 = 76.40%

F-test (2, 93,416) = 140,918 Equation 5.15

Table 5.29. The 2 of 7 components regressions' coefficients and related statistical test.

Parameters	Coefficient	T-test	R^2
Intercept	2.8740	2,461.6262	76.40%
MPC1	-0.3183	-549.2603	
MPC2	-0.0295	-27.0268	

Note: All coefficient values are significant at α <0.001.

Maximum growth rate from the 7 PCs and 2 MPCs (out of 7 PCs) were 4.33 and 4.00 g./month, respectively. Spatially, the high predicted growth rate area of this section was similar trend to those of the previous 2 sections, but the maximum growth rate obtained from the 2 MPCs was very close to that of the field sampling value (Fig. 5.11).

Although all PCR models formulated by MPCs are relatively simple in term of function form and number of parameters, each MPC is the linear combination of the original water quality parameters. The MPCs are the representative of all extracted PCs and they cannot obtained by direct measurement as for normal water quality parameters, such as salinity, DO and *etc*. Because of this, the study established the practical and simple MLR models using reliable water quality which measured from the field. For that reason, the WQ of each MPC was directly applied as independent variable of the MLR models and the suitability of established models can be evaluated by coefficient of determination values (R^2).

5.3.4.2 MLR models using the highest loading water parameters (WQs)

From the PCA analysis, there were 2 different sets of the WQs. The first set comprised 3 variables comprising salinity, chlorophyll-a and POM, derived from 12 water quality parameters extraction. The second set had 2 variables, salinity and chlorophyll-a, obtained from 9 and 7 water quality parameters extraction, respectively. Additionally, to create the simplest model, simple regression using only salinity was also formulated. Because the salinity carried the highest loading on the first MPC of all 3 different combination of water parameters. All selected WQs met the basic requirements of the MLR model.

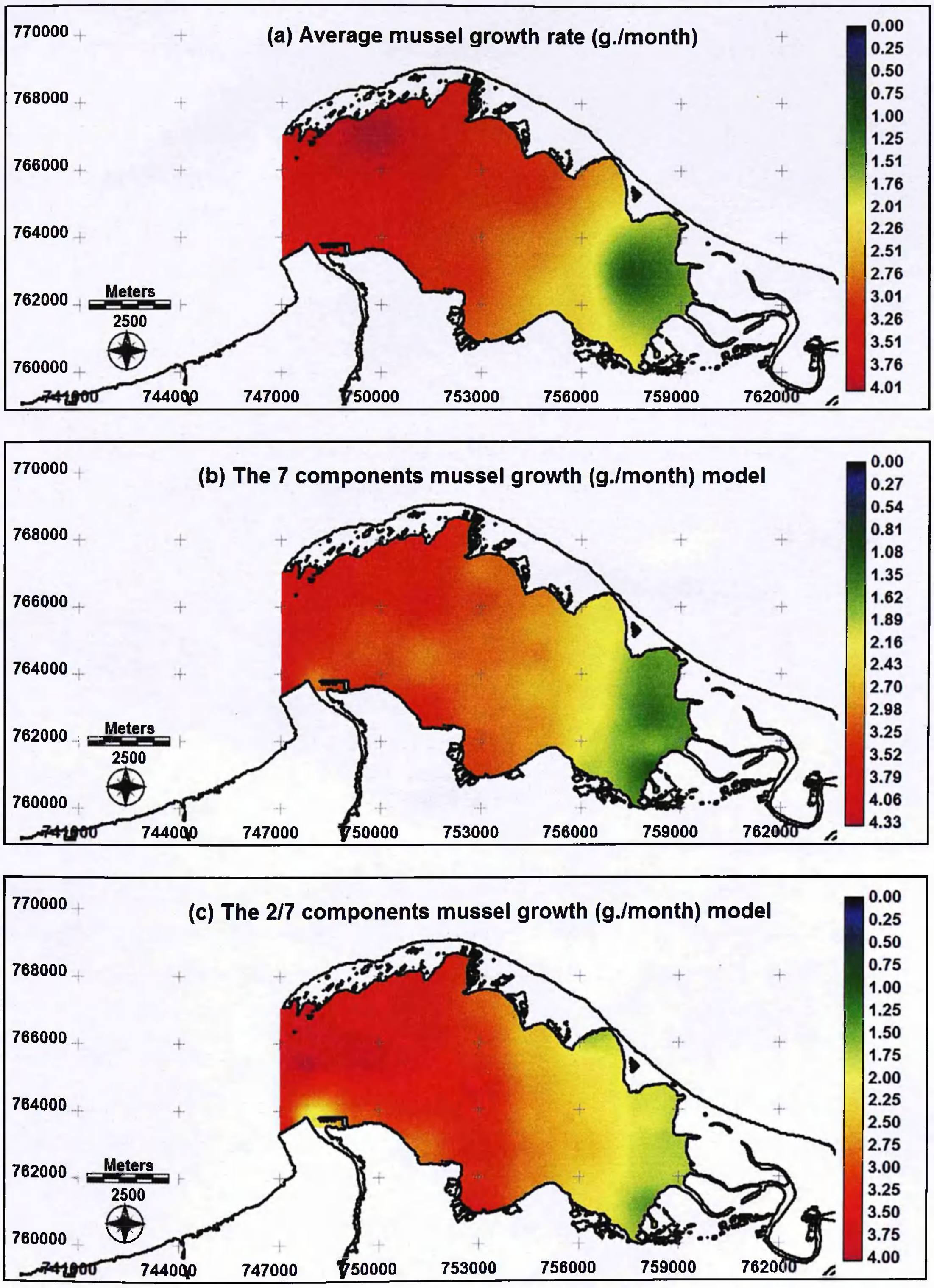


Fig. 5.11. Average mollusc growth (g/month) of (a) sampling data, (b) 7PCs, and (c) 2/7 MPCs models.

5.3.4.2.1 MLR model using 3 WQs

The 3 WQs model showed that 85.18% of variation in the mussel growth rate could be explained by salinity, chlorophyll-a and POM. The salinity and POM revealed positive relation with the mussel growth rate while the chlorophyll-a showed a negative relationship (Equation 5.16). T-test values of all coefficients are shown in Table 5.30 and were significant at $\alpha < 0.001$.

Y = 1.4193 + 0.1409*SAL - 0.0322*CHL + 0.0060*POM

Adjusted- R^2 = 85.18%

F-test (3, 93,415) = 179,040 Equation 5.16

Table 5.30. The coefficients and T- test of the MLR model using 3 WQs.

Parameters	Coefficient	T-test	R^2
Intercept	1.4193	95.5019	85.18
SAL	0.1409	595.2927	
CHL	-0.0322	-104.0115	
POM	0.0060	40.7289	

Note: All coefficient values are significant at $\alpha < 0.001$.

5.3.4.2.2 MLR model using 2 WQs

The MLR from 2 WQs indicated that 84.92% of the mussel growth rate was explained by salinity and chlorophyll-a. The salinity indicated a positive relationship with the mussel growth while the chlorophyll-a revealed a negative relationship (Equation 5.17). T-test coefficients are given in Table 5.31 and showed significant at $\alpha < 0.001$.

Y = 1.5546 + 0.1350*SAL - 0.0291*CHL

Adjusted- R^2 = 84.92%

F-test (2, 93,416) = 263,063.03 Equation 5.17

Table 5.31. The coefficients and statistical test of the MLR model using 2 WQs.

Parameters	Coefficient	T-test	R^2
Intercept	1.5546	106.3796	84.92
SAL	0.1350	716.7131	
CHL	-0.0291	-96.1296	

5.3.4.2.3 Simple regression model with salinity

Result from the correlation matrix of all parameter using in this study (Table 5.20) showed very high correlation (91.3%) between average monthly mussel growth rate and average salinity. Moreover, salinity was found as the WQs of the first MPC of all PCA extraction outputs. The simple regression model using the salinity was formulated to evaluate the prediction capability of the mussel growth. The salinity explained 83.43% of the mussel growth rate (Equation 5.18) and the coefficients' T-test are shown in Table 5.32 and they were significant at α <0.001. In case of lacking equipment or resource for water quality analysis, salinity can be used as a proxy parameter for mussel growth estimation in the bay.

$$Y = 0.199049 + 0.135382\ SAL$$

Adjusted-R^2 = 83.43%

$F_{(1, 93,417)}$ = 470,361.56 Equation 5.18

Table 5.32. The coefficients and T- test of simple regression using salinity.

Parameters	Coefficient	T-test	R^2
Intercept	0.199049	49.50	83.43
SAL	0.135382	685.829	

Spatial average growth rate of mussels of the whole bay obtained from different combinations of WQs is shown in Fig 5.12. The highest predicted average growth values of mussel of the 3, 2 and 1 WQs were 4.16, 4.04 and 3.91 g/month, respectively. These values were similar to that of the measured growth rate levels during the field survey, at 4.01 g/month. An obvious characteristic that was found in common from the 3 spatial outputs is the low average growth rate in areas near the two river mouths. This was mainly due to the low salinity. This conclusion was supported by the R^2 of all WQs models, which ranged from 83.43 - 85.18%. When POM and chlorophyll-a are discarded, the R^2 of the model decreased <2%.

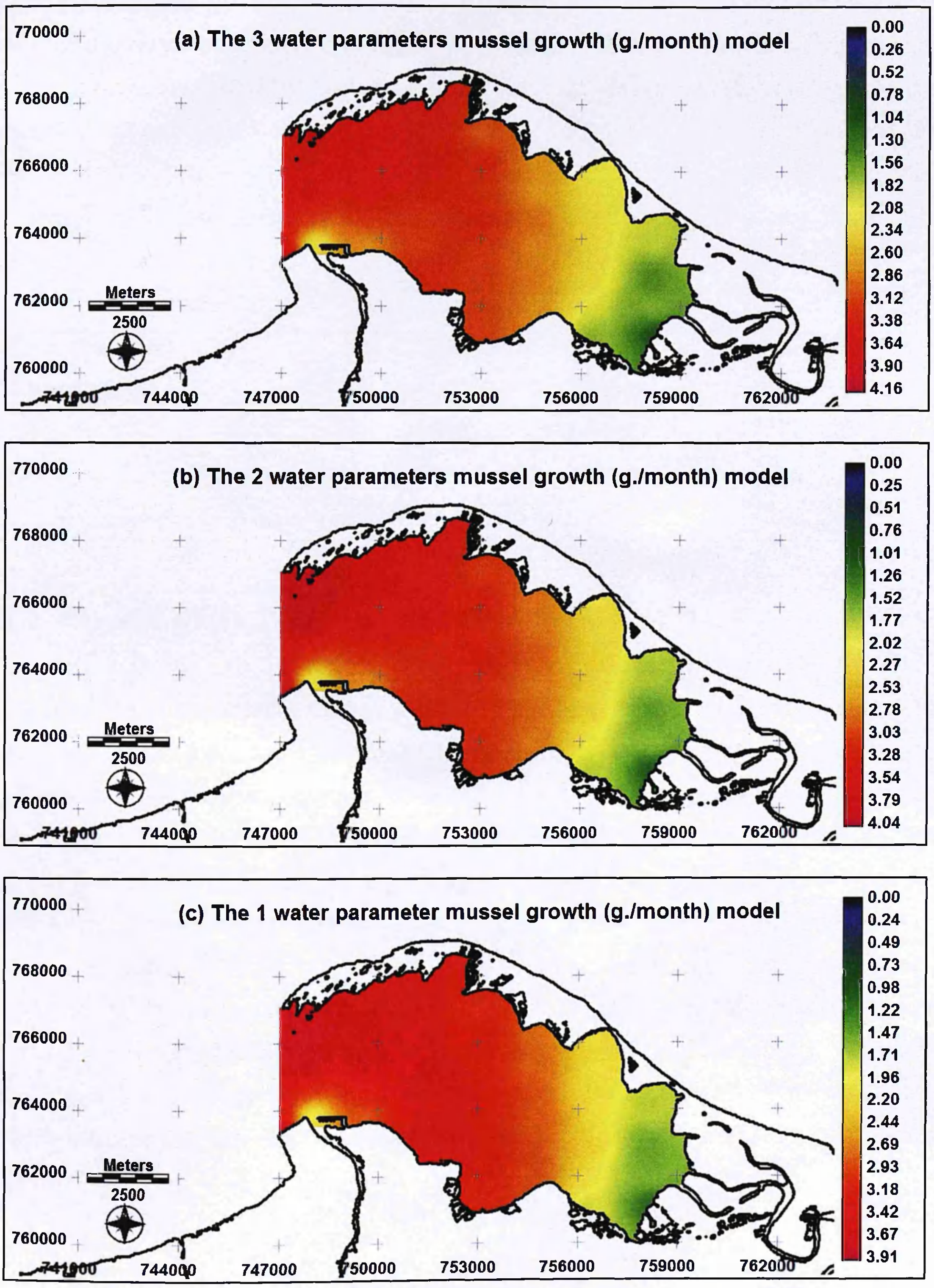


Fig. 5.12. Average mollusc growth (g/month) from sampling data and various WQs models.

Based on loading values of the first MPC from the 7 water quality data set, a series of simple regression equations using the less important loading parameters, which are TDS, temperature, pH, and flood current (Table 5.23). The coefficient of determination (R^2) for the regression equations varied from 53.62 - 82.71%. Other than the salinity, these parameters hold a progressively lower capability to explain the average mussel growth in the bay (Table 5.33).

Table 5.33. Simple regression models between an average mussel growth and some other potential parameters.

X Parameter	Equations	R^2
Total dissolved solid	Y = -0.132783 + 0.144118X	82.71%
Temperature	Y = -24.090604+ 0.882354X	61.85%
pH	Y = -33.582353 + 4.738167X	53.62%
Current (flood)	Y = 0.860090 + 13.230210X	55.01%

Note: All coefficient values are significant at α <0.001.

5.4 Mussel growth and harvestable area models

The mussel culture areas of the bay in 2009 were classified into two main sources. The first was mussel produced from stationary fishing gear, which were established at the bay opening area. The second was areas used for farmed production of mussels, which were distributed along the middle part of the southern coastline of the bay. Raft and pole culture techniques were employed at the farm area no. 1 (Fig. 5.13) while the rest areas applied only the pole culture technique. The minimum, mean and maximum values of water depth of all farmed areas were 1.00 m., 1.29 m. and 1.58 m., respectively. The minimum depth of area number 1, 2 and 3 were 1.00 m., 1.48 m. and 1.45 m, while the maximum were 1.25 m., 1.58 m. and 1.56 m., respectively. The water depth data was collected in June, when the average water level was the lowest annual depth according to the reported data from 2004-2009 (The Marine Department, pers. comm.).

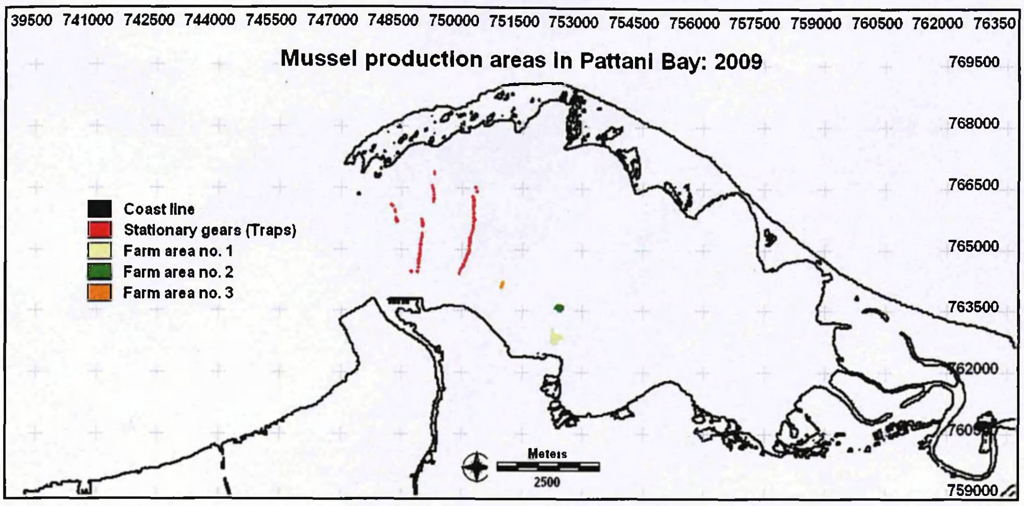


Fig. 5.13. Mussel production areas in Pattani Bay.

5.4.1 General assumptions of the models

Assumptions used during this study were based on both secondary and field sampling data. There were:

- Potential farm area: the water depth is ≥1.5 m. (from field data) and threshold value for water salinity is ≥15 ppt. (Rawchai, 2003).
- Rearing technique: pole culture with bamboo stake as the main culture method in the bay.
- Stocking density: base on the stocking density of mussel growth trial, which was 400 pieces/ 1m of submerged pole length. This similar to Chaitanawisuti & Menasaveta (1987) who reported that the density of mussel from raft culture using natural setting spat was naturally decreased to around 420 piece/m at the 8th month of rearing period.
- Marketable size is at least 6 cm in total length or 15 g in total weight.
- Mussel growth was based on empirical growth functions from field experiment.

5.4.2 Model components and framework

There were 3 main sub-models involved in this section (Fig. 5.14). The constraint sub-model was a general limitation of the possible mussel culture sites, which was defined by water salinity, water depth and transportation route. The linear growth sub-model illustrated spatial mussel growth based on linear growth functions. The logarithmic growth model showed the spatial growth of mussel based on logarithmically derived growth functions. Potential mussel harvesting area was predicted and illustrated in every 10 days intervals from the Julian day of 255 (12 Sep 2009) until all mussels reached the marketable size as mentioned previously. The model was mainly established for the pole culture technique.

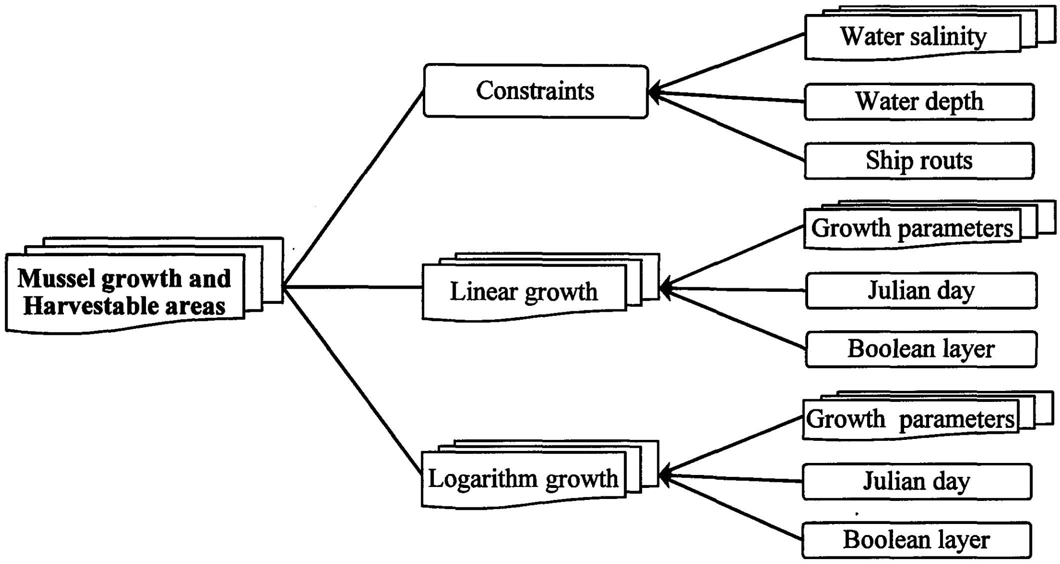
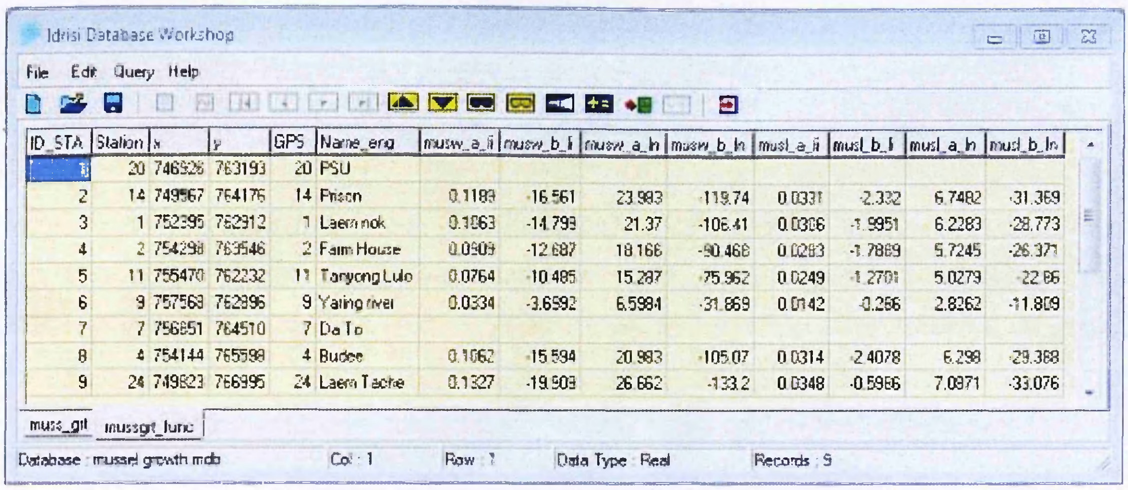


Fig. 5.14. Diagram of mussel growth and harvestable area models for Pattani Bay.

5.4.3 Data layer constructions from mussel growth functions

All coefficients (a) of independent variables and constant values (b) from mussel growth functions in terms of total length and weight, from Table 5.12 and 5.13, respectively, were arranged in database based on sampling station with their corresponding spatial coordinates to become a mussel growth function database (Fig. 5.15). Thereafter, these point values were exported to create vector point files of the coefficient and constant values of mussel growth functions. Raster layers of these files were created by interpolation as same as the detail mentioned in Chapter 4 (section 4.3). For example, the logarithmic growth function of mussel; $Y = a*\ln(X)+b$ (where Y= mussel length(cm.) or weight (g.), X = Julian day and b = constant value). Raster layers of the coefficients and constant values could be illustrated as in Fig 5.16. The Julian day layer was done by ASSIGN module.



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1	20	746926	763193	20	PSU								
2	14	749967	764176	14	Prison	0.1189	-16.561	23.983	-119.74	0.0331	-2.332	6.7482	-31.369
3	1	752395	762912	1	Laem nok	0.1063	-14.799	21.37	-106.41	0.0306	-1.9951	6.2283	-28.773
4	2	754298	763546	2	Farm House	0.0909	-12.687	18.166	-90.468	0.0283	-1.7869	5.7245	-26.371
5	11	755470	762232	11	Tanyong Lulo	0.0764	-10.485	15.287	-75.962	0.0249	-1.2701	5.0279	-22.66
6	9	757563	762996	9	Yaring river	0.0334	-3.6592	6.5984	-31.869	0.0142	-0.266	2.8262	-11.809
7	7	756851	764510	7	Da To								
8	4	754144	765598	4	Budee	0.1062	-15.594	20.983	-105.07	0.0314	-2.4078	6.298	-29.388
9	24	749823	766995	24	Laem Tache	0.1327	-19.909	26.662	-133.2	0.0348	-0.5966	7.0971	-33.076

muss_grt mussgrt_func

Database : mussel growth mdb Col : 1 Row : 1 Data Type : Real Records : 9

Fig. 5.15. Database of growth functions' coefficients and parameters.

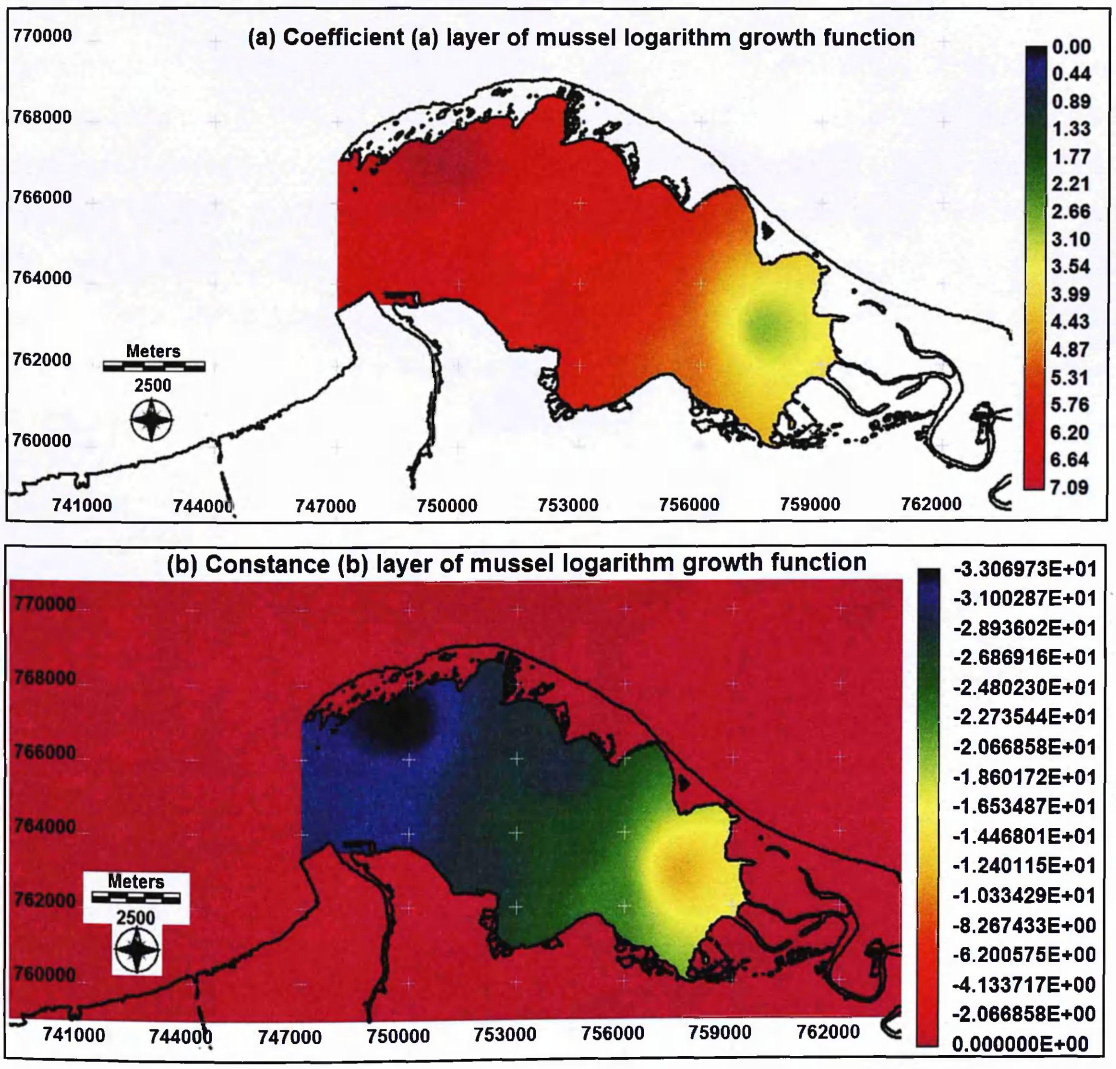


Fig. 5.16. Coefficient (a) and Constant value (b) layers of logarithm function by mussel weight.

5.4.4 Model formulation and results

5.4.4.1 Constraint sub-model

Salinity layers for the 9 sampling occasions from 2 sampling periods were classified by the threshold value of ≥15 ppt. Suitable salinity areas of all sampling times were combined by overlaying using the minimum approach. Water depth in the lowest period of the year was also used as a limiting parameter. Too shallow water affected, at least, on the living space of seed mussels. The threshold value of water depth was 1.5 m. The last limitation factor was ship route. Pattani River mouth had a fishing port from which these were exported/ transported. As a result, the area within the vicinity of the transportation route was excluded by onscreen digitizing based on field survey and general discussion with local farmers.

The constraint sub-model output found the suitable salinity area about 39.16 km^2 (Fig. 5.17a). Around one third of the bay's area was considered less suitable, especially area form Tanyong Lulo and Budee to Yaring River. The area of suitable depth was 15.87 km^2 in total. The main suitable depth was at the bay centre area extending from the bay opening to Laem Nok village (Fig. 5.17b). When combined all constraint factors, the suitable area decreased to 13.275 km^2 (Fig. 5.17c). In summary, suitable salinity covered almost all the suitable depth. The loss of the suitable depth area was mainly caused by the ship route.

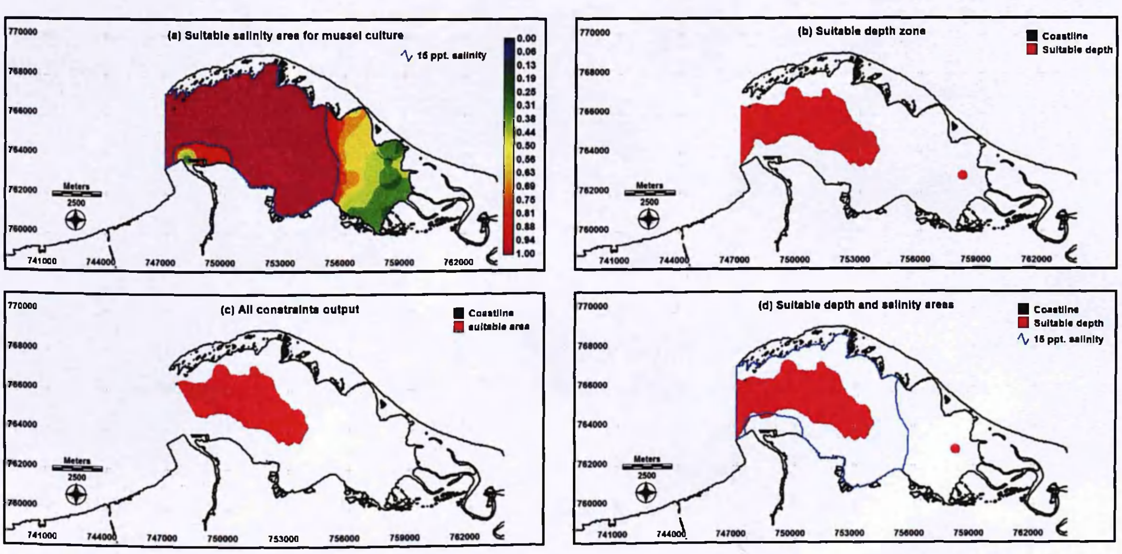


Fig. 5.17. Outputs of constraints sub-model for mussel culture in Pattani bay.

5.4.4.2 Spatial growth sub-model using linear growth function

This sub-model was based on a series of mussel linear growth functions in Table 5.12 and 5.13. Spatial growth and harvestable areas were predicted in every 10 days intervals until all mussels in potential culture site reached the marketable size. Spatial outputs in terms of total weight and length were illustrated in Fig. 5.18 and 5.19. Dark uniform colour areas in these pictures showed the area of marketable size mussels.

By length, all marketable mussels in potential culture site could be harvested by the 12rd of October 2009 or around 4 months after the experiment was started. The highest possible mussel lengths of all prediction intervals were 8.25-9.29 cm.

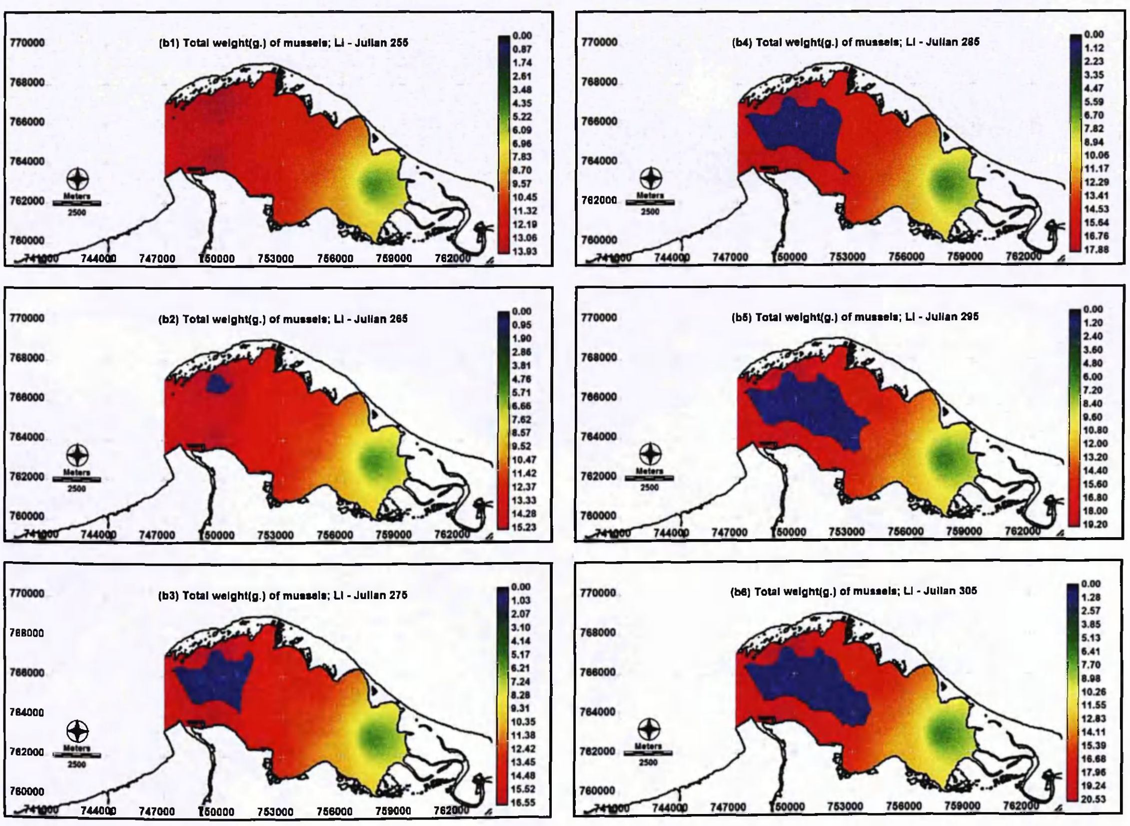


Fig. 5.18. Weight of mussels in different times predicted by linear growth functions.

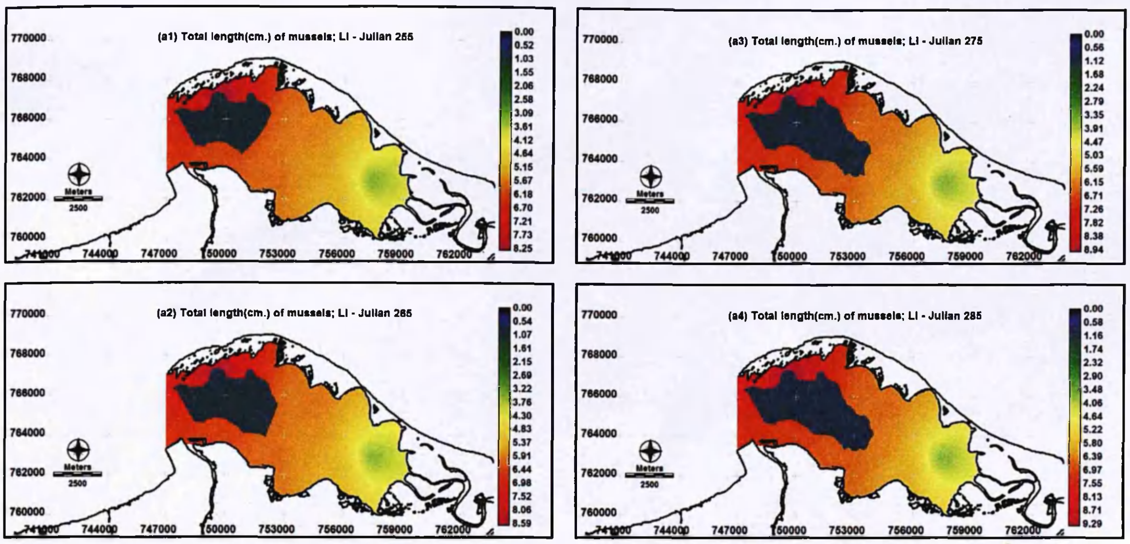


Fig. 5.19. Length of mussels in different times predicted by linear growth functions.

5.4.4.3 Spatial growth sub-model using logarithm growth functions

Mussel growth of this sub-model was based on logarithmic growth functions. Spatial growth outputs were also illustrated in the same 10 days interval until mussels reached marketable size. Mussel growth by length and weight were illustrated in Fig. 5.20 and 5.21, respectively. Dark uniform colour areas showed the marketable size mussels.

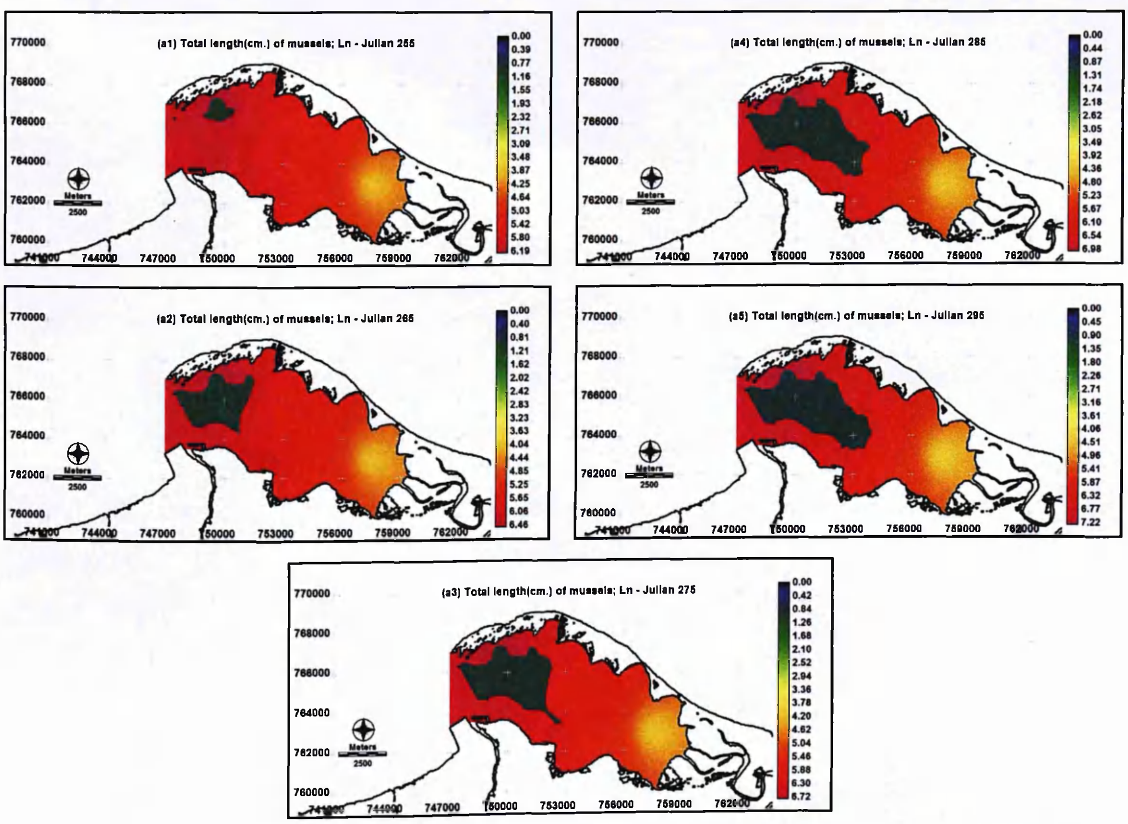


Fig. 5.20. Length of mussels in different times predicted by logarithm growth functions.

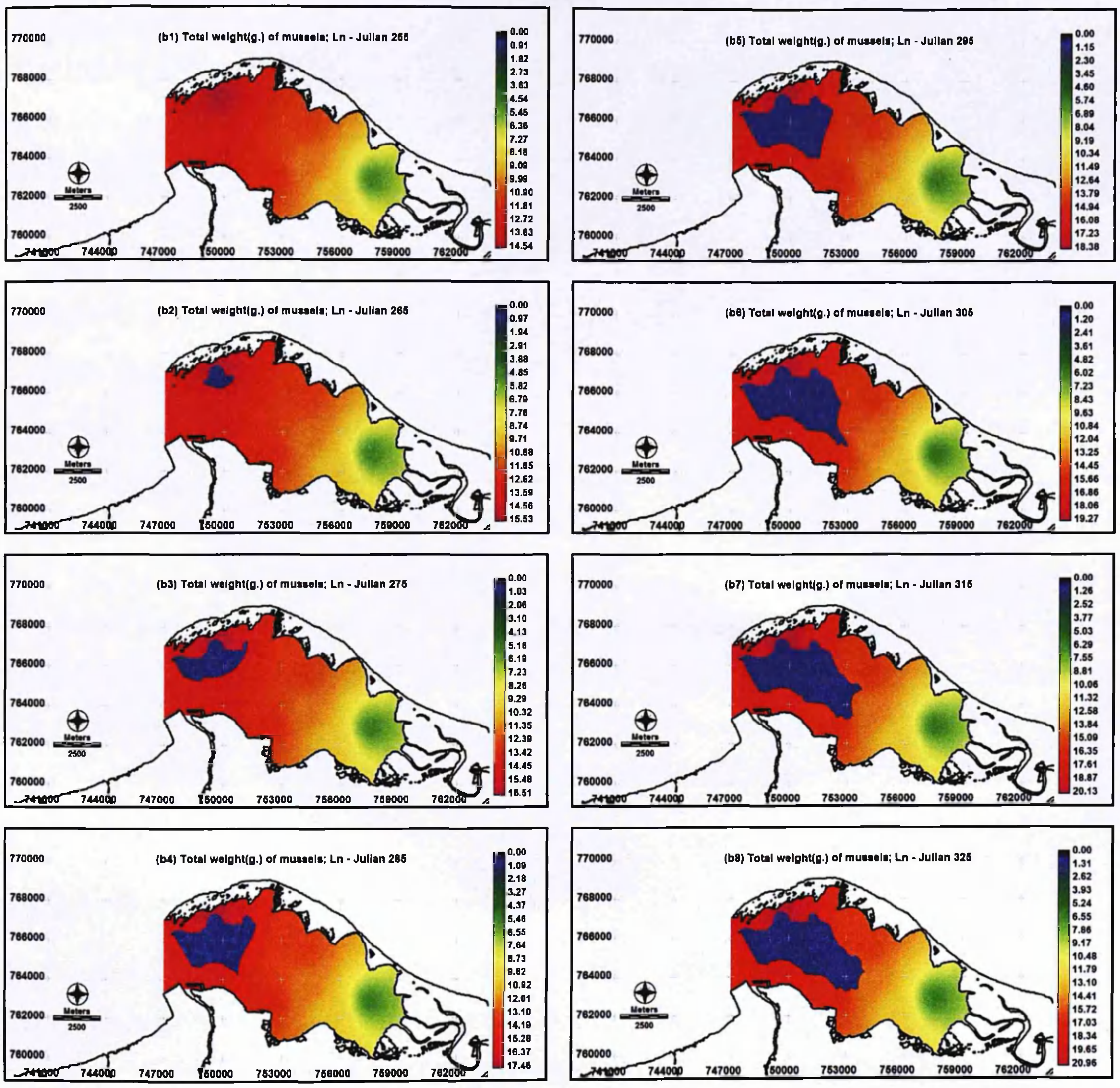


Fig. 5.21. Weight of mussels in different times predicted by logarithm growth functions.

Based on mussel length models, the harvestable mussels were found firstly in 12 September 2009 (around 3 months after the experiment culture was started). Based on mussel length, the biggest possible sizes of mussels for different periods of time are shown in Table 5.34. Mussel harvesting was found firstly at 3.5 months after the experiment was started.

Table 5.34. Summary of mussel's size obtained from all different prediction models.

Julian day (Date)	Lin-L	Log-L	Lin-W	Log-W
255(12 Sep 2009)	8.25	6.19	13.93	14.54
265(22 Sep 2009)	8.59	6.46	15.23	15.53
275(02 Oct 2009)	8.94	6.72	16.55	16.51
285(12 Oct 2009)	9.29	6.98	17.88	17.45
295(22 Oct 2009)	-	7.22	19.20	18.38
305(1 Nov 2009)	-	-	20.53	19.27
315(11 Nov 2009)	-	-	-	20.13
325(21 Nov 2009)	-	-	-	20.96
335(01 Dec 2009)	-	-	-	-

Lin-L = Linear function by length; Log-L = Logarithm function by length.

Lin-W= Linear function by weight; Log-W= Logarithm function by weight.

Note: All numbers are possible biggest size of corresponding times without harvesting.

According to the field experiment results, the highest average sizes of mussel at Laem Tachi were 6.03±0.62 cm and 14.84 g by length and weight, respectively. The result obtained from logarithmic models showed more precise values than that from linear models. However, the R^2 values of both growth functions showed slightly difference in prediction capability.

5.4.4.4 Mussel harvestable area model

The potential mussel harvestable areas of various prediction methods, from all sub-models, are given in Table 5.35. The results can be summarised as follows:

- By total length: Based on linear growth functions, mussels from the area of 8.729 km^2 reached marketable size on the 255th Julian day. By the following 30 days, all mussels in potential culture site were ready to harvest. Similar to the former approach, the logarithmic growth functions showed the harvestable area of 1.087 km^2 and all mussels also reached marketable size by the same period to that of the linear growth functions.

- Based on weight: On the 255th Julian day, all mussels were under marketable size. The linear growth function model found harvestable area of 0.826 km^2 in the next 10 days (the 265th Julian day) and all mussels reached marketable size by the 305th Julian day. The prediction by logarithmic approach found harvestable mussels in the 265th Julian day (1.076 km^2). By the 335th Julian day, all mussels in the potential culture sites could be harvested.

Table 5.35. Harvestable area (km^2) of mussel from different calculation criteria.

Julian day (Date)	Lin-L	Log-L	Lin-W	Log-W
255(12 Sep 2009)	8.729(65.7)	1.087(6.2)	0	0
265(22 Sep 2009)	10.529(79.3)	6.818(51.4)	0.826(6.2)	1.076(8.1)
275(02 Oct 2009)	12.983(97.8)	9.965(75.1)	6.970(52.5)	4.213(31.7)
285(12 Oct 2009)	13.275(100)	12.790(96.4)	10.013(75.4)	7.288(54.9)
295(22 Oct 2009)	-	13.275(100)	12.658(95.4)	9.086(68.4)
305(1 Nov 2009)	-	-	13.275(100)	11.140(83.9)
315(11 Nov 2009)	-	-	-	12.572(94.7)
325(21 Nov 2009)	-	-	-	13.179(99.3)
335(01 Dec 2009)	-	-	-	13.275(100)

Lin-L = Linear function by length; Log-L = Logarithm function by length.

Lin-W= Linear function by weight; Log-W= Logarithm function by weight.

Note: The value in bracket (...) is the percentage of total potential culture area.

The harvesting time for all predictive approaches was from 12 October – 21 November 2009 or 3-5 months after the experiment was established. The prediction based on mussels' length found that almost 100% of the potential mussel culture site was harvestable at the 285th Julian day (or 12 October 2009) and all mussels in the potential culture area reached market size during the next 10 days. The harvestable time based on mussel weight extended longer than that of by length, especially when predicted by logarithm function (Fig. 5.22). In summary for all prediction approaches, more than 80% of mussels were ready to harvest by the by the end of October 2009.

The prediction by mussel length is more suitable because: Firstly, farmers can observe easily in the field. Secondly, pricing of whole fresh mussels sold in the market is dependent on size class. Biologically, the weight of mussels show greater fluctuation over time (see Karayücel *et al.*, 2010). Condition index is one factor that describes the variations of mussel weight. In Pattani Bay, the condition index of mussel during October 2009-March 2010 varied from 50.81-98.76%. The lowest value is found in October (Niyomdecha, 2009). If compared to the seed settling peak of mussel in Pattani Bay, which shows the highest density in October (Niyomdecha, 2009), it can be assumed that low condition index may be caused by mussel spawning activity, which can be effected on yield of mussel meat (Campbell & Newell, 1998; Cheung & Shin, 2005).

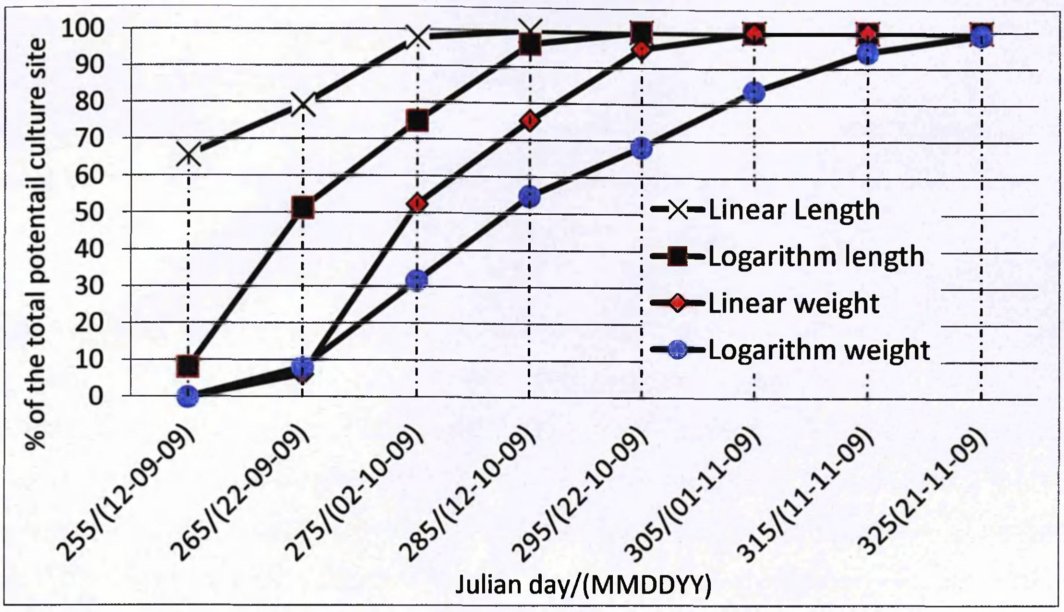


Fig. 5.22. Percentage of harvestable areas based on different growth functions over a culture period.

5.5 Discussion and conclusions

Although mussels were introduced to the Pattani Bay in 1979 and it is known that natural reproduction and farming are feasible (Brohmanonda *et al.*, 1988), mussel farm areas and mussel production in Pattani Bay is very small when compared to that of cockle (Fishery Statistics Division, 2007a; Fishery Statistics Division, 2007b). There is only one reported document about suitability of mussel farming sites in the bay, and in this only a small area near the northern coast nearby the bay opening (Predalumpaburt & Chaiyakam, 1994). This study found more suitable sites for mussel as well as its growth determination parameters and possible harvest areas.

Growth trial data in Table 5.11 showed that mussels can survive at all experimental sites throughout the bay area, but a significant difference in mussel size was found just after 1 month within the rearing period. At the end of the experiment, the average length of mussels from the Yaring River station was <50% of that from Laem Tachi, where some mussel reached marketable size.

Although mussels from different locations showed significant differences in sizes, progressive growth curve by weight (Table 5.12) and length (Table 5.13) of mussels from each station, this was explained very well through the application of regression and logarithmic functions, indicating by the R^2 of >94%. This is comparable to the growth function from data provided by Brohmanonda *et al.* (1988b) in the same bay and also that of data provided by Sreenivasan *et al.* (1989) (Fig. 5.2 and 5.3). These two reported sources showed an R^2 of >92% for both function types. Mussel growth curves provided by Rajagopal *et al.* (1998b) also revealed high R^2, but was separated into two different phases over a 1 year rearing period.

Point sampling data in the bay during the experiment showed various ranges of water parameters (Table 5.15). In comparison with reported values, salinity was in both suitable (Tookwinas *et al.*, 1985b) and lethal risk (Rawchai, 2003) ranges. Similarly water currents and depth were both suitable for mussel growth, though some parts of the bay had a low velocity (Cheong, 1982; Lovatelli, 1988a; Rajagopal *et al.*, 1998a) and low water depth (Tookwinas *et al.*, 1985b; Tuaycharoen *et al.*, 1988). Transparency was also low and sometimes found at less than the lower limit value of 0.15 m (Lovatelli, 1988a).

Some water parameters were considered suitable for growth, such as TSS (Shin, Yau, Chow, Tai, & Cheung, 2002), temperature (Nilkerd, 2001; Intarachart & Rermdamri, 2005), water pH (Brohmanonda *et al.*, 1988b; Dato-Cajegas & Lin, 1996; Intarachart & Rermdamri, 2005) and DO (Brohmanonda *et al.*, 1988b; Nilkerd, 2001).

POM in the bay was considerably higher than at other comparable sites (Wong & Cheung, 2003) as well as chlorophyll-a, which was considered very high compared to previous levels found in the Pattani Bay (Tookwinas *et al.*, 1985b), and at other sites in Thailand (Tookwinas *et al.*, 1985b; Nilkerd, 2001) and nearby countries (Cheong, 1982; Rajagopal *et al.*, 1998a; Rajagopal *et al.*, 1998b; Inglis *et al.*, 2000)

Spatially, mean values of water quality parameters in the bay revealed inter-correlation indicating by high correlation between them (Table 5.20). Some of the water parameters revealed high correlation to average mussel growth rate. According to the reported information about correlation between water parameters, and between mussel growth and environmental parameters (Rivonkar *et al.*, 1993; Blanchette *et al.*, 2007; Karayücel *et al.*, 2010), the correlation level and direction were site specific.

Mussel growth determination in this study was identified mainly by PCA, PCR and MLR techniques. All these processes were operated within IDRISI environments to analyze and illustrate spatially. The PCA was applied for data pre-processing, simplification and

WQs selection while PCR and MLR were employed for mussel growth determination models.

The PCA outputs from the different sets of 12, 9 and 7 water parameters showed 3, 2 and 2 MPCs, which accounted for 77%, 83% and 84% of the total variation of each data set, respectively. The number of MPCs obtained from this study is similar to the 3 MPCs extracted from 10 water parameters (Joseph & Ouseph, 2010) and 2 and 3 MPCS out of 12 water parameters from two different sites (Sasikumar & Krishnakumar, 2011). The MPCs obtained from this study explained more percentage of the total parameters variation when compared to the studies of Sasikumar & Krishnakuma (2011), Lee (1988) and Çamdevýren *et al.* (2005).

PCR models using all extracted PCs showed the R^2 of 90-92%. This reduced to 75-76% when only 2-3 MPCs were selected, but the R^2 of MLR (including simple regression) models increased to 84-85% when different combinations of PCs, MPCs and WQs were applied (Table 5.36).

Table 5.36. Adjusted R^2 and F-value of MLRs from different independent variables.

Independent variables	Adjusted-R^2	F- value
12 PCs model	92.23%	92,459.80
9 PCs model	92.00%	119,319.00
7 PCs model	90.12%	121,732.28
3 MPCs model from 12 PCs	75.90%	98,046.13
2 MPCs model from 9 PCs	75.11%	140,918.39
2 MPCs model from 7 PCs	76.40%	151,208.62
3 WQs (salinity, chlorophyll-a and POM) model	85.18%	179,040.00
2 WQs (salinity and chlorophyll-a) model	84.92%	260,063.03
1 WQs (salinity) model	83.43%	470,361.56

Note: All coefficient values are significant at α <0.001

The R^2 form the PCR models with all PCs is in comparable to that of a chlorophyll-a prediction model (Çamdevýren *et al.*, 2005) while the PCR models using MPCs showed considerably higher R^2 when compare to that of a model for mussel GSI prediction (Lee, 1988).

However, both MPCs and PCs values are not able to be collected from the field, but the value of WQs comprising salinity, chlorophyll-a and POM from the field are able to be collected. By these parameters, the application of the MLR (including simple regression) models is practical. Moreover, some more models formulated by the lower important water parameters can be included, but lower R^2 (Table 5.33)

Based on the 3 main parameters (WQs) comprising salinity, chlorophyll-a and POM, spatially, the positive relationship of the salinity to the average mussel growth rate may be explained by the fact that the average mussel growth rate (Fig 4.30) gradually increased from the East end of the bay to the bay opening and this was similarly found from the salinity trend (Fig. 4.17). The chlorophyll-a showed negative relation to the mussel growth rate while the remaining parameters revealed positive relation.

Although chlorophyll-a represents mussel food source, the negative relation still exists probably due to very high chlorophyll-a concentration in the bay when compared to other reported levels (Rajagopal *et al.*, 1998a; Rajagopal *et al.*, 1998b; Nilkerd, 2001; Rajagopal *et al.*, 2006a). The chlorophyll-a level of 32.97-79.19 µg/l (average = 45.28 µg/l) in the bay is at a level described as hypereutrophic water (>20.00-≤ 60 µg/l) or eutrophication (>60 µg/l) (Bricker, Ferreira, & Simas, 2003). These levels cause low dissolved oxygen in water (Bricker *et al.*, 2003) and may have a negative impact on mussel growth. As a filter feeder, the mussel filtering mechanism is vulnerable to suspended solid concentration (Shin *et al.*, 2002). So, other than chlorophyll-a parameter, TSS parameter may have some impacts on mussel growth, but it was not considered as WQs in this study. The TSS comprises both organic and inorganic matters while the chlorophyll-a is considered an organic. Allowing both organic and inorganic matters to be involved in mussel growth prediction model, the organic seston parameter (*f*) may be applied in modelling processes.

The POM was the least influence among these three predictors, this can be explained by its small coefficient value in the model. Furthermore, when it was discarded, R^2 reduction was found to be <1% (Table 5.41). Among the independent parameters of MLR models, salinity and chlorophyll-a showed considerably less correlation (-0.02) while that of POM was considered moderate at -0.61. This may be due to the reason that POM can be omitted because there was some degree of multi-collinearity in the MLR model.

The main three predictors found in this study were found to apply for average mussel growth prediction. For example, the chlorophyll-a concentrations showed a negative relationship to mussel growth (Blanchette *et al.*, 2007), mussel GSI (Lee, 1988) and dry meat weight (Karayücel *et al.*, 2010), but a positive relationship to mussel weight and average shell length (Rivonkar *et al.*, 1993; Karayücel *et al.*, 2010). Salinity reveals a negative relationship to mussel mussel growth (Rivonkar *et al.*, 1993), GSI (Lee, 1988), DWCI and VCI (Brown & Hartwick, 1988) while Lee (1988) reported positive relationships to mussel GSI. Similar to the previous two factors, POM shows a positive relationship to mussel live weight, but a negative to dry meat weight (Karayücel *et al.*, 2010).

In conclusion, PCA is a useful tool for data extraction and facilitates mussel growth determination parameters identification. However, the magnitude and direction of the relationship between the main predictors and mussel growth rate is site specific. For Pattani Bay, the salinity is the most important factor for mussel culture for two main reasons; the salinity level in some areas of the bay is within the range lethal to mussels, if exposure is for too long (Rawchai, 2003), and the second, around 85% of the average growth of mussel can explained by the salinity. The increasing of the R^2 by adding chlorophyll-a and POM to the model was only 1-1.5%. These may be because natural food is not a limiting factor in Pattani Bay.

Progressive growth functions of tested mussels from different locations within the bay was formulated by linear and/or logarithm functions to calculate mussel growth by total length (cm) and live weight (g). The R^2 obtained from the two function types were similar. Ranges of all R^2 values were between 93.5-100%, which is considered very high and similar to the values found in previous studies (Brohmanonda *et al.*, 1988b; Sreenivasan *et al.*, 1989; Rajagopal *et al.*, 1998b).

The potential mussel culture area for Pattani Bay was modelled as 13.3 km^2, determined mainly by the best mussel growth predictor (salinity), a water depth of 1.50 m and the existence of a shipping route. The mussel harvestable area was predicted periodically and the harvestable period was within 2 months, which would end by the middle of November annually. However, >80% of mussel in the potential culture site could be harvested by the end of October. Based on this time frame, mussel culture can avoid the low salinity risk caused by heavy rain during October to December (Hemsuhree, 1997).

Progressive mussel growth function by weight may be affected by spawning activity, which results in meat yield and CI decreasing (Campbell & Newell, 1998; Cheung & Shin, 2005). The CI of mussel in the Pattani Bay varies from 51-99% (Niyomdecha, 2009). As a result, mussel growth prediction by total length may be a more suitable factor. Moreover, mussel growth function in the Pattani Bay using total length, calculated based on data provided by Brohmanonda *et al.* (1988b), shows the R^2 from both function types of >92% during the culture period of around 1 year to the maximum mussel total length of 10 cm.

Importantly, the mussel growth data using in this study was obtained from very small culture site. Thus, some growth effecting factors, such as food competition, seston depletion, current flow and particle distribution among mussels under actual culture conditions were not included. As a result, the modelled data obtained may be slightly over estimated when compared to that from actual farming system. However, a comparison of the culture periods for mussels based on total length of around 2.0-6.0 cm, which takes around 4 months (Brohmanonda *et al.*, 1988b; Sreenivasan *et al.*, 1989), shows good agreement with the rearing time during this study.

Finally, GIS technology proves here that it is a powerful tool using for various data sources incorporating a wide variety of formats, for analysing and for spatial modelling. As it has been used for modelling and managing mollusc production (Radiarta *et al.*, 2008; Longdill, Healy, & Black, 2008), and others fisheries and aquaculture related activities worldwide (Nath *et al.*, 2000; Asmah, 2008; De Freitas & Tagliani, 2009).

Chapter 6

GIS modelling for optimisation for cockle culture in Pattani Bay

This chapter comprises 3 main sections; introduction to cockle culture in Thailand, culture area parameters of cockle and suitable cockle culture sites modelling. The last section was formulated mainly by fuzzy classification and Multi-Criteria Evaluation (MCE) technique within GIS framework in order to determine the suitable area for cockle culture in the bay.

6.1 Introduction

Cockles (*Anadara spp.*) are important culture species in Thailand. Large quantities of cockles are imported from Malaysia to meet consumer demand and this results in loss of foreign exchange (Hansopa *et al.*, 1988). In Thailand, cockle (*Anadara granosa*) culture began at least 100 years ago (around 1900) at Baan Laem District, Petchaburi Province, based on traditional methods in which the area of a farm will be approximately 1-1.5 ha and seeds are collected from the area nearby. In 1973, some cockle seeds were imported from Malaysia for on-growing in Satun Province, since when farm sites have expanded, accompanied by further development of culture techniques (Tookwinas, 1983; Siripan, 2000). Cockle culture promotion was explicit in the Fifth National Economic and Social Development Plan (1982-1986) and aimed to provide alternative income sources for small-scale fishermen, to fulfil excess domestic demand and to reduce cockle importing (Tangputtaruk, 1985; Kanpittaya, 1987). In the initial phase of the cockle culture development, it was intended that Malaysian investors would play an important role in all operation, investment (a business partnership) technology and knowledge transfer to farmers in Satun Province. The cockle culture site and technology transfer were then rapidly expanded to many provinces in the Southern Thailand, such as Trang, Ranong, Nakhon Sri Thammarat and Surat Thani. By 5-6 years into the culture period, growth rate was found to be decreasing and culture site deterioration was found as well as decreasing survival rate (Tookwinas, 1983).

The total culture area of Thailand is around 8,673 ha with other potential site of up to 8000 ha. Approximately 96% of cockle production is consumed domestically and the remaining 4% (5,000 tonnes) is exported to Hong Kong, China and Taiwan. However, cockles have been imported for a very long time. For instance, during 2001-2005, Thailand imported around 16,000-22,000 tonnes/year of frozen and fresh cockle, mainly from Malaysia. In 2005, total imported cockle was around 21,897 tonnes, of which 21,866 tonnes was from Malaysia (Office of Agricultural Economics, 2009).

Cockle culture activities in Thailand are classified into 3 different types (Office of Agricultural Economics, 2009).

- Young cockle culture: farmers rear young Malaysian cockles from the size of 2,000-4,000 pieces/kg in a small culture area. By 6-8 months, cockle seeds of 300-1,000 pieces/kg are collected and sold to other farms for rearing to market size.
- Seed to market size culture: farmers use the seed from the previous group and rear them for around 8-10 months to produce marketable cockles, at 100-120 pieces/kg.
- Young cockle to market size culture: young cockles are reared to reach market size. It takes 1-1.5 year to harvest at the size of 100-120 pieces/kg.

In the upper Thai Gulf provinces of Thailand, all three culture types are applied within a farm area of 1.6-3.2 ha. Most farms employ traditional methods using bamboo fences. In eastern Thailand, the second and third culture types are found. Farmers in Chonburi Province buy cockle seeds from the central region and rear them for 8-10 months to marketable size. Other farmers in Chonburi and Chanthaburi Provinces rear young Malaysian cockles to marketable size in 1.0-1.5 years. All farmers in this region use poles to indicate their farm boundary. In Southern Thailand, almost all farmers in the main culture areas (Phuket, Satun, Pattani and Ranong Provinces) use the first culture system with rearing period and farm boundary indication being similar to those in Eastern region. Production and economic indicators of all culture types in different regions of Thailand are shown in Table 6.1 and 6.2 (Office of Agricultural Economics, 2009).

6.1.1 Cultured species of cockle

Tookwinas (1983) reported that four species of cockle were found in Thailand; *Anadara granosa*, Linn; *A. (Tegellarca) nodifera*, E. Von Martens; *A. (Scapharca) trocheli*, Dunker and *A. (Scapharca) satowi*, Dunker. Of all four species, only *A. granosa* and *A. nodifera* were reared or imported for culture in Thailand. The common characteristics and habitat ecology of the two cultured species are:

- *Anadara granosa*: The common name is arc shell, bloody clam or blood cockle due to the presence of haemoglobin in the haemolymph. It inhabits fine muddy sand in shallow coastal water. Mature cockle size is around 4-5 cm in width.
- *Tegillarca nodifera*: Its habitat ecology is similar to that of *A. granosa*, but different in terms of body width and height relationship. This species has been cultured in Petchaburi Province.

Table 6.1. Parameters comparison between 2 regions of the 2nd culture type

Parameters	Central	East
Stocking density (kg/ha)	1,519	3,150
Production (kg./ha)	4,034	10,250
Production/seed ratio	2.66	3.25
Unit price (USD/kg.)	24.25	25.50
Total income (USD/ha)	3,260	8,713
Total cost (USD/ha)	2,198	7,058
Profit (USD/ha); (USD/kg.)	1,063; 0.26	1,655; 0.16
Culture period (month.)	10	8

Note: 1USD=30THB

Source: Office of Agricultural Economics (2009).

6.1.2 Seed collection and seed source

Cockle seed size of 170-1,700 pieces/kg are collected from cockle beds by sifting (Tookwinas, 1983), hand dredging with mud ski (Broom, 1985) , boat dredging or trawling (from a field survey). Some seeds are imported from Malaysia (Tookwinas, 1983). Seeds are packed in sacks at 60-80 kg/sack for transportation, which should take <36 hours, avoiding direct sunlight and fresh water exposure (Tookwinas, 1983 referred to Tookwinas, 1981; Office of Agricultural Economics, 2009).

Table 6.2. Parameters comparison between 3 regions of the 1st culture type.

Parameters	Central	East	South
Stocking density (kg/ha)	1,925	1,900	1,188
Production (kg./ha)	9,363	9,288	6,910
Production/seed ratio	4.86	5.00	5.80
Unit price (USD/kg.)	0.83	0.87	0.67
Total income (USD/ha)	7,802	8,049	4,660
Total cost (USD/ha); (USD/kg.)	4,786; 0.51	3,950; 0.43	3,160; 0.46
Profit (USD/ha); (USD/kg.)	3,018; 0.32	4,099; 0.44	1,500; 0.22
Culture period (month.)	16	14	16

Note: 1USD=30THB

Source: Office of Agricultural Economics (2009).

6.1.3 Stocking density and survival rate

In general, stocking density in Thailand is 600 piece/m^2 for seed size of <1,500 piece/kg and 300-500 piece/m^2 for the larger seeds (Office of Agricultural Economics, 2009). Moreover, it depends on culture periods; 400-450 pieces/m^2 for <1 year culture period and 100-200 pieces/m^2 for the longer period (Tookwinas, 1983), locations; 421-549 piece/m^2 for seeds size of 500-6,000 piece/kg in Petchaburi (Samtheon, 2002) and 0.26-12.50 ton/ha for seed size of 180-3,000 piece/kg (mean size = 1,500) in Bandon Bay (Kaewnern & Yakupitiyage, 2008), and culture purposes; 170 pieces/m^2 for stock enhancement (Thamasavate *et al.*, 1988).

6.1.4 Farm management and operation

Farm management and operation comprises site selection, seed preparation and sowing, sorting, thinning, guarding and harvesting (Tookwinas, 1983 referred to Tookwinas 1981). Small scale farmers use split bamboo screen to prevent cockle seed lost (Narasimham, 1983; Wuttichan, 2009) while big farm operators use only poles to indicate farm boundary. Seeding is done in the evening or early morning for better survival rate. During the first 3-6 months, growth and survival rate monitoring is practiced monthly. Dense cockles are thinned and re-distributed (Tookwinas, 1983).

6.1.5 Rearing period and harvesting

The general cockle rearing period is 1-2 year to reach the marketable size (Office of Agricultural Economics, 2009) , but the culture period is also dependent on location and seed size; 1-2 years in Kanchanadit, Surat Thani (Vichaiwattana & Thepphanich, 2008; Kaewnern & Yakupitiyage, 2008; Wuttichan, 2009) and 1.5-2 years in Petchaburi (Samtheon, 2002). The marketable size varies from 40-130 pieces/ kg. Harvesting is done by powered boat using a rake (Broom, 1985). Another primitive tool used in shallow mud flat is a mud ski (Tookwinas, 1983).

6.1.6 Marketing and transportation

Cockle marketing is well established. Cockles are distributed through local collectors, provincial collectors, Mahachai Central Market, wholesalers and retailers. Farmers sell 1% of their cockles directly to consumers. Around 96% of cockles are for domestic consumption and the remaining 4% is exported (Tookwinas, 1983; Office of Agricultural Economics, 2009). Live cockles are packed in a sack at 60-70 kg/sack, sprayed with seawater and are transported by truck from local farms/collectors in the late afternoon or evening reaching wholesalers in Bangkok by early morning of next day with 98% survival rate. For northern or north-eastern regions, more time is required resulting in losses and a higher price (Tookwinas, 1983).

6.1.7 Production level, price and investment indicators

An average production of cockle culture in Thailand is 3,962-6,910 kg/ha (Office of Agricultural Economics, 2009). All farm sizes form 0.8-1.6 ha show financial feasible, but the level of profitability is partly depend on farming skills, bottom fertility and ecology (Wuttichan, 2009). For example, break-even production of cockle in Bandon Bay is ≥8,938 kg/ha/yr. (Kaewnern & Yakupitiyage, 2008; Wuttichan, 2009), which is considerably higher than that of the whole country. Cost of production seems to vary depending on stocking density.

6.1.8 Culture problems and limitations

- Seed cost and seed shortage: due to lower seed availability, seed bed destruction and no artificial breeding. These result in higher seed price and culture schedule changing (Office of Agricultural Economics, 2009). Seed cost is around 84%

of operating cost and some farm areas have to import around 95% of total seed used (Kaewnern & Yakupitiyage, 2008).

- Low stocking density: this is the consequence of seed shortage. This results in low productivity (Office of Agricultural Economics, 2009).
- Labour cost: The commercial farms have to employ labour for site preparation, seed sowing, guarding and harvesting. But, in traditional farming systems, almost all work is done by the family (Office of Agricultural Economics, 2009).
- Waste water discharge: These are from many sources, factories, pesticides, shrimp farms and communal wastes. These causes low growth and survival rates, and low production (Office of Agricultural Economics, 2009). Discharge water form sugar factories through Mae Klong and Petchaburi Rivers in 1972 resulted in oxygen depletion, seed shortage and production decline (Tookwinas, 1983).
- Seed bed destruction: Trawler and push nets are examples of harmful fishing gears to natural cockle bed productivity (Kaewnern & Yakupitiyage, 2008).
- Culture site deterioration: After a period of culture, dead shells result in bottom sediment hardening. Moreover, using trawlers during the harvesting period also results in sediment destruction and reducing cockle larvae (Tookwinas, 1983).

For cockle production, suitable farm location is very important for many reasons. Technically, cockle culture is quite simple to operate and requires limited labour input (Tookwinas, 1983) and its economic and financial feasibility is well known. In non-polluted areas, farmers generate a profit of around 5-10 times the variable cash cost (Tookwinas, 1983). The average net profit from cockle farms is around 7,198 to 19,678 baht/rai (1,500 to 4,100 US$/ha) at the average production level of 1,106-1,498 kg/rai (6,910 to 9,393 kg/ha). An excess demand of cockle has been reported (Office of Agricultural Economics, 2009) and in comparison with oyster culture in the same culture space, profit from cockle culture is more than double (Kaewnern & Yakupitiyage, 2008) . Biologically, there is no need to provide supplemental food for cockles (Tookwinas, 1983). For these reasons and also because of the cockle seed shortage, the selection of suitable sites is considered to be one of crucial steps for cockle production. Moreover, it contributes to improved production and economical sustainability for cockle culture.

This work focuses on identification of suitable sites for cockle culture (*Anadara sp*) in Pattani Bay. A wide range of data is reviewed mainly related to the ecological conditions of the natural cockle beds, cockle farms and experimental sites. These data are then used as control points for fuzzy functions to classify tolerances and suitable ranges for cockle for each environmental parameter. The fuzzy classified data is then used in a multiple criteria evaluation (MCE) using weighted linear combination to combine all environmental parameters and to identify areas suitable for cockle culture. Vulnerable parameters are also identified and illustrated spatially and the study results can also support coastal resources management and allocation for sustainable use.

6.2 Culture area parameters

Generally, suitable sites for cockle culture should be near the river mouth or in wind-sheltered coastline areas where bottom sediments are mud or silty clay without sand, bottom slope should be less than 15 degrees and daily exposure period should be <2-3 hours (Tookwinas, 1983). More information is constantly becoming available but, to simplify the suitable area determination for cockle culture, this study will classify the data for each environmental parameter. From detailed data on each parameter, fuzzy control points will be selected for use in the fuzzy classification process.

The optimum data ranges reported for each environmental parameter is summarised in the following sections.

6.2.1.1 Sediment pH

Based on many area observations in Thailand, the most suitable sediment pH for cockle culture is 7.14-8.34 (Tookwinas *et al.*, 1985b). However, the sediment pH in an experimental site of 5.45-7.32 is reported (Bhramchu-em & Jitphakdee, 2009) and the highest reported value from culture site is 7.85-8.66 (Hansopa *et al.*, 1988).

6.2.1.2 Bottom slope

The suitable bottom slope should be <15 degrees (Tookwinas, 1983; Tookwinas *et al.*, 1985b). On steeper slopes, cockles may be moved along the bottom surface by wind and wave influences (Tookwinas *et al.*, 1985c).

6.2.1.3 Bottom soil type/soil separates

Bottom sediments can be classified into 2 ways; as soil types and particle size analysis (%sand, silt and clay). The most reported soil type is silty clay soil (Tookwinas, 1983; Tookwinas, Mongkolomann, & Pongmaneerat, 1985a; Hansopa *et al.*, 1988; Lovatelli, 1988a) follow by silty loam (Tookwinas, Perngmark, Sirimontaporn, Tuaycharoen, &

Sangsakul, 1986; Thamasavate *et al.*, 1988) and sandy loam (Bhramchu-em & Jitphakdee, 2009). *A. granosa* shows rapid growth rate in soft mud containing up to 90% silt particles and very few types of other shellfish inhabit such environments (Narasimham, 1983). However, it is found on sandy mud bottom, but at lower density (Broom, 1985 refered to Pathansali, 1966.). Some selected of sediment particle size studies are given in Table 6.3. However, some reports show cockle suitable sediment types by common name, such as muddy and sandy mud (Zhong-Qing, 1982; Thamasavate *et al.*, 1988).

Table 6.3. Particle size combinations selected form some studies in Thailand.

Sites	%sand	%silt	%clay	Data sources
Farm area	3-14	40-46	41-45	Hansopa *et al.* (1988)
	30-56	33-63	11-13	Tookwinas *et al.* (1986)
Experimental site	78-67	8-14	4-8	Bhramchu-em & Jitphakdee (2009)

6.2.1.4 Sediment organic matter

The range of sediment organic matter (SOM) in culture areas of Thailand is 1.43-2.47% (Tookwinas *et al.*, 1985b; Hansopa *et al.*, 1988; Vichaiwattana & Thepphanich, 2008), but that from an experimental site is 8.52-9.04% (Bhramchu-em & Jitphakdee, 2009). This is similar to the reported SOM from some farms in Malaysia; 6-11% (test by ignition loss method) (Broom, 1982) and 6.2-19.1% (Onn, 1986).

6.2.1.5 Water pH

The range of water pH in culture areas of Thailand is 7.10-8.77 (Tookwinas, Chindanond, Limsakul, & Pongmaneerat, 1985b; Tookwinas *et al.*, 1986; Samtheon, 2002; Nudee & Mahasawat, 2007; Vichaiwattana & Thepphanich, 2008) and the water pH from cockle culture in a mangrove area is 6.56-9.22 (Bhramchu-em & Jitphakdee, 2009).

6.2.1.6 Water depth

Cockle inhabits a wide range of shore profiles; in air-exposed area (Broom, 1985; Tookwinas *et al.*, 1985a; Tookwinas *et al.*, 1985b), in shallow water of 0.25 m (Narasimham, 1983) and in deeper water of 1.5-2.5 m (Kimura, 1992). In Thailand, the reported depth of 0.37-2.55 m covers all farming areas (Tookwinas *et al.*, 1985b). This does not include the depth of 0.77-2.69 m from an experimental culture site (Bhramchu-em & Jitphakdee, 2009).

6.2.1.7 Salinity

During 1981-1985, Tookwinas *et al* (1985b) showed data from various culture sites, ranging from 2 to 32 ppt. This salinity range covers all reported studies in the country including the reported salinity from Malaysia, which is 14-31 ppt (Onn, 1986). However, all previous data is less than that from India; 14.46-35.53 ppt in natural cockle bed (Narasimham, 1985) and 13.69-34.40 ppt in an experimental site (Narasimham, 1983). In laboratory conditions, the study found the suitable salinity levels of 13.0-32.0 ppt because at the salinity >13 ppt has no mortality found after 24 hours acclimation (Tookwinas, 1985).

6.2.1.8 Water temperature

The highest temperature of natural cockle site exposed to the sun is 40°C (Broom, 1985). In Thailand culture areas, the water temperature is around 24-35°C (Tookwinas *et al.*, 1985b; Tookwinas *et al.*, 1986; Nudee & Mahasawat, 2007; Vichaiwattana & Thepphanich, 2008). The higher reported temperature of 24.80-33.50°C is from natural bed and experimental culture sites in India (Narasimham, 1983; Narasimham, 1985).

6.2.1.9 Transparency

Tookwinas *et al.*(1985b) reported many ranges of the transparency from cockle culture sites, ranging from 0.11 to 1.45 m. This covers almost other reported values, except the range of 0.46-1.79 from the experimental culture site (Bhramchu-em & Jitphakdee, 2009). Malaysian cockle farms locate in more turbid water, at the transparency of 0.3-0.5 m (Kimura, 1992).

6.2.1.10 Dissolved Oxygen (DO)

Almost all DO values in Thailand cockle farms is between 3.8 – 7.8 mg/l (Tookwinas *et al.*, 1985b; Thamasavate *et al.*, 1988; Nudee & Mahasawat, 2007). The lowest DO value of farmed area is 2.13-4.80 (Samtheon, 2002) while the highest one of 4.36-8.09 mg/l is from an experimental farm area (Bhramchu-em & Jitphakdee, 2009). Additinal DO value from India are 4.98-7.0 mg/l. (Silas, Alagarsawami, Narasimham, Appukuttan, & Muthiah, 1982), 4.45-7.0 mg/l. (Narasimham, 1983), and 3.78-7.0 mg/l. (Narasimham, 1985).

6.2.1.11 Chlorophyll-a

Only few reports mention about chlorophyll-a in cockle farm areas, such as 6.87-54.73 μg/l (mean = 20.7 μg/l) (Tookwinas *et al.*, 1986), 0.16-2.99 μg/l (Thamasavate *et al.*, 1988) and 1-7 μg/l (Kaewnern & Yakupitiyage, 2008) . These can be concluded that the range of chlorophyll-a level in culture sites is very wide.

6.2.1.12 Total Suspended Solid (TSS)

In general, the suitable TSS value for bivalve culture is <400 mg/l (Tiensongrusmee, Pontjoprawiro, & Soedjarwo, 1986) while the TSS in cockle farms in Malaysia varies from 10-400 ppm (or 0.01-0.40 g/l) and farms near the river mouth shows higher TSS (Onn, 1986). The study in green mussel found that oxygen consumption and gonadosomatic indexes (GDSI) at the TSS of <600 mg/l are not significant difference while clearance rate is not significant for all TSS levels (Shin *et al.*, 2002).

6.2.1.13 Particulate Organic Matter (POM)

The POM is a part of cockle feeds (Hansopa *et al.*, 1988; Navarro, Iglesias, & Ortega, 1992; Iglesias, Urrutia, Navarro, varez-Jorna, Larretxea, Bougrier, & Heral, 1996), but no report about the POM in cockle farm is found. However, the successful cockle culture is proved in the previous transplanted mussel culture site (Thamasavate *et al.*, 1988). This can assure that cockle can survive in the similar POM level as mussel.

6.2.1.14 Water current

The water current affects cockle feeding and food particle distribution (Widdows & Navarro, 2007). Generally, the water current of 0.02-0.1 m/s is suitable for bottom culture (Lovatelli, 1988a referred to Tiensongrusmee, 1986) while the higher current of 0.1-0.3 m/s is suitable for hanging method (Lovatelli, 1988a). However, the water current at natural bed of *C. edule* is found at the higher range of 0.11-0.44 m/s (Smaal & Haas, 1997). At the current of 0.15-0.45 m/s, there is no significant effect on cockle clearance rate. At the higher current, cockle is moved along the sediment surface. For food particle distribution, a homogeneous food distribution (within 25 cm above sediment surface) is found at the current of >0.05 m/s. Moreover, the current affects on bottom sediment and biodeposited particles as given in Table 6.3 (Widdows & Navarro, 2007).

Table 6.4. Water current and its effect on bottom and biodeposited particles.

Velocity (cm/s)	Effects
7.5-10.0	Pseudofaeces roll over the substrate bottom
12.5-15.0	Pseudofaeces start to be resuspened particle
15.0-17.0	Pellet of faeces start to roll over the substrate bottom
20.0	Almost pseudofaeces become suspended particle
25.0	Small faeces (Ø ~1 mm) become suspended particle but large size stand still
32.5	Both small and large faecaes become suspended particle
40.0	All biodeposit is suspended in water

Source: Widdows & Navarro (2007).

6.3 Suitable site model formulation

6.3.1 Conceptual model

Environmental parameters in this study were classified into 3 groups, water quality, sediment quality and constraint factors. All parameters in the first two groups including water depth and current were then classified using fuzzy classification, thus representing all parameters on a common numerical scale. These parameters (excluding water depth and currents) were then combined by the Multi Criteria Evaluation (MCE) technique using weighted linear combination to obtain water and sediment suitability sub-models. The Boolean constraint sub-model was developed by overlaying. Final models were formulated by overlaying sub-model outputs and the Boolean image using various options.

In summary, there are 4 main steps involved in the optimisation model formulation; input data preparation, data layer classification, sub-model and component formulations, and final model construction. The stages and sequences are summarised in Fig 6.1. The input data preparation is mentioned in section 4.1 and 4.3. The other steps will be explained in the following sections.

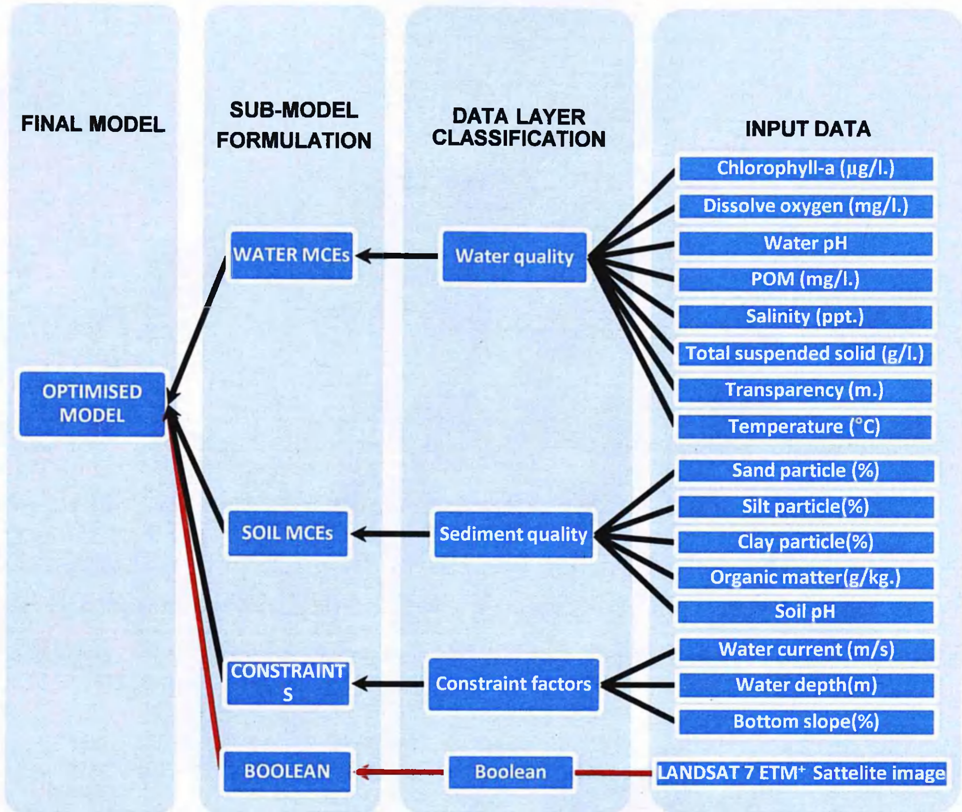


Fig. 6.1. Conceptual structure and sequence of the cockle farm suitability area model.

6.3.2 Data layer classification

Fuzzy classification using a sigmoidal function was applied to transform interpolated data layers with different units to a common scale, namely a suitability score ranging from 0-1. Sigmoidal fuzzy sets are controlled by four control points (a,b,c and d) along an x-axis (Fig. 6.2). The *a* value indicates where the sigmoidal function rises above 0, the *b* value shows where the function reaches 1, the *c* value indicates the starting point of that function declines from 1 and the *c* value reveals where the function becomes 0. However, any 3 values in a row can be identical to indicate the monotonic change of the function. The fuzzy set is different from a classic crisp set, which has sharp boundaries. However, a sharp boundary can be found in the case where fuzzy membership changes abruptly from 0 to 1 (Eastman, 1999a). The fuzzy classification is a data reduction tool, which transforms a complex set of data to an easily understood format, minimizing information loss and providing a convenient means for information transfer (Burrough, 1989). Control point (CPs) values of each parameter in this study were mainly extracted from reported data related to cockles and also some data from field sampling. Summary of CPs for sediment and water parameters are given in Table 6.5 and 6.6, respectively.

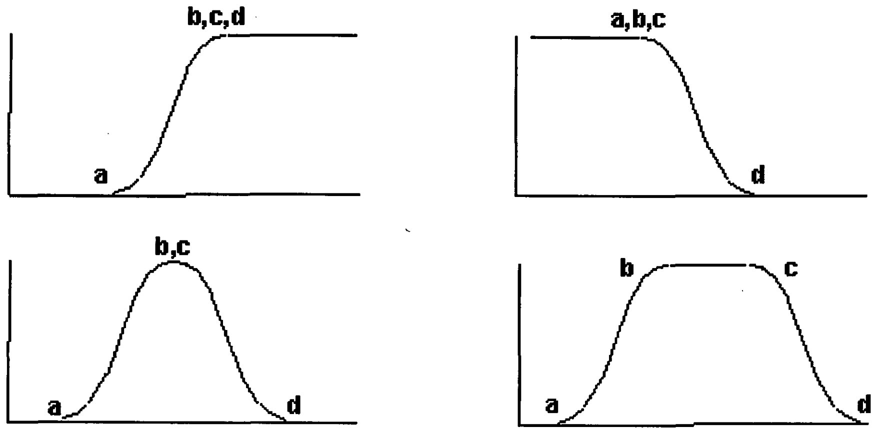


Fig. 6.2. The sigmoidal membership functions and control points.

Outputs of this step were then used as input factors for the MCE process. Bottom slope suitability was classified by a cut-off value of <15 degrees (Tookwinas, 1983).

The CPs of %sand, %silt and %clay, used in this study, were considered to be compatible with silty clay and silty loam soils. Sandy loam was excluded because of farmer's preference due to farm operational problems (from the general survey of this study). By these assumptions, The CPs of sediment particles can be described as the follows:

- Sand particles should be <40% based on the percent sand in silty loam soil.
- Silt particles should be >40% to cover the range of silt particle in silty clay and silty loam soils.
- Clay should be <50% to cover the range of silt particle in silty clay and silty loam soils.

Based on these criteria, theoretically, silty clay loam soil is also considered as a suitable for cockle culture.

Table 6.5. Control point (CPs) values selected for sediment parameters used in the cockle farm site suitability model.

Parameters	CPs	Values	Data sources
Sediment pH	a	5.45	The lowest value in experiment farm (Bhramchu-em & Jitphakdee, 2009)
	b	7.0	Farm area in Pattani bay (Tookwinas *et al.*, 1986)
	c	8.0	The highest pH value extracted from field sampling of this study.
	d	8.66	The highest reported pH from cockle farm (Hansopa *et al.*, 1988)
Bottom slope	a	<15°	The recommended value in Thailand (Tookwinas, 1983; Tookwinas *et al.*, 1985b) and culture site in Sawi Bay (Thamasavate *et al.*, 1988)
%Sand	a,b,c	20%	Adjusted value to cover silty clay soil (Tookwinas *et al.*, 1985a; Hansopa *et al.*, 1988; Lovatelli, 1988a) and silty loam (Tookwinas *et al.*, 1986; Thamasavate *et al.*, 1988)
	d	40%	
%Silt	a	40%	
	b,c,d	50%	
%Clay	a,b,c	40%	
	d	50%	
OM*	a	3.2 g/kg.	The lowest value in natural bed (Narasimham, 1985)
	b	20 g/kg.	An average value in Sawi Bay, Chumphon (Thamasavate *et al.*, 1988)
	c	110 g/kg.	The maximum value in Salangor, Malaysia (Broom, 1982)
	d	191 g/kg.	The maximum value in Malaysian farms (Onn, 1986)

Note: * some parameter units are changed to be compatible with field sampling data.

Table 6.6. Control point (CPs) values selected for water parameters used in the cockle farm site suitability model.

Parameters	CPs	Values	Data sources
Water depth	a	0.10 m.	Adjust to cover some intertidal zone (Broom, 1985)
	b	0.50 m.	General Thai cockle farm (Tookwinas *et al.*, 1985b)
	c	2.00 m.	Suitable area in Bandon Bay (Jarernpornpipat *et al.*, 2003)
	d	2.7 m.	The maximum depth in Thailand and Malaysia cockle farms using similar culture technique (Broom, 1985)
Salinity	a	6.00 ppt.	The minimum value from farm areas in Surat Thani (Vichaiwattana & Thepphanich, 2008)
	b	15.00 ppt.	The average minimum value of farm areas in Pattani Bay (Tookwinas *et al.*, 1986) and Natural cockle bed in India (Narasimham, 1985)
	c	30.00 ppt.	The upper range of farm areas in Pattani and Surat Thani (Tookwinas *et al.*, 1985b)
	d	35.53 ppt.	The highest reported salinity in natural bed (Narasimham, 1985)
Temperature	a	20.0°C	Estimated value during night time
	b	24.0°C	The minimum of Thailand culture sites (Tookwinas *et al.*, 1986)
	c	35.2°C	The maximum value in Pattani cockle farm (Tookwinas *et al.*, 1985b)
	d	40.0°C	Bottom soil temperature of cockle habitat during neap tide (Broom, 1985)
Transparency	a	0.11 m.	The lowest reported value in Pattani Bay (Tookwinas *et al.*, 1985b)
	b	0.30 m.	The minimum value in farm and experimental areas in Bandon Bay (Nudee & Mahasawat, 2007)

Note: * some parameter units are changed to be compatible with field sampling data.

Table 6.6. Control point (CPs) values selected for water parameters used in the cockle farm site suitability model (cont.)

Parameters	CPs	Values	Data sources
Transparency	c	1.00 m.	The maximum value in farm and experimental areas in Bandon Bay (Nudee & Mahasawat, 2007)
	d	1.79 m.	The highest reported value in experiment area in Thailand (Bhramchu-em & Jitphakdee, 2009)
DO	a	2.13 mg/l.	The lowest reported value in Thailand (Samtheon, 2002)
	b	4.0 mg/l.	The minimum value of cockle farm in Bandon Bay (Vichaiwattana & Thepphanich, 2008) and cockle farms in Nakhon Sri Thammarat (Tookwinas *et al.*, 1985b)
	c	4.0 mg/l.	
	d	4.0 mg/l.	
Chlorophyll-a*	a	0.16 µg/l	The minimum reported value from farm areas in Sawi Bay (Thamasavate *et al.*, 1988)
	b,c,d	3.0 µg/l	Maximum reported value from cockle farms in Sawi Bay (Thamasavate *et al.*, 1988)
TSS	a,b,c	0.40 g/l.	Maximum suitable value (Tiensongrusmee *et al.*, 1986) and empirical study in commercial farms (Onn, 1986)
	d	0.60 g/l.	Biophysical study in green-lipped mussel (Shin *et al.*, 2002)
POM	a	0.60 mg/l.	data from mussel (Wong & Cheung, 2001a)
	b	7.44 mg/l.	data from mussel (Wong & Cheung, 2001a)
	c	22.5 mg/l.	data from mussel (Grant & Bacher, 1998)
	d	150 mg/l.	Maximum value from the field survey of this study.
Current	a	0.02 m/s	The minimum suitable current for bottom cockle culture (Lovatelli, 1988a referred to Tiensongrusmee *et al.*, 1986)
	b	0.05 m/s	Food particles mix homogeneously within water column of 25 cm above bottom sediment (Widdows & Navarro, 2007)
	c	0.325 m/s	Small and large faeces at the bottom sediment become suspended particles (Widdows & Navarro, 2007)
	d	0.45 m/s	Sand particles >1 mm and cockle are moved by current (Widdows & Navarro, 2007)

Note: * some parameter units are changed to be compatible with field sampling data.

Final outputs from this stage provided suitability scores, ranging from 0-1, for each parameter, the higher value being more suitable. As an example, original salinity values varying from 11.0-31.14 ppt (Fig.6.3a) result in a reclassified output layer with values from 0-1 (Fig.6.3b). This is because salinity levels between 15-30 ppt are considered suitable and are transformed to become the suitability score of 1. Salinities of <15 ppt and >30 ppt are considered gradually less suitable. Thus, the low salinity area around Yaring River mouth appears as the least suitable zone. The outputs from this step were used as an input to the MCE process.

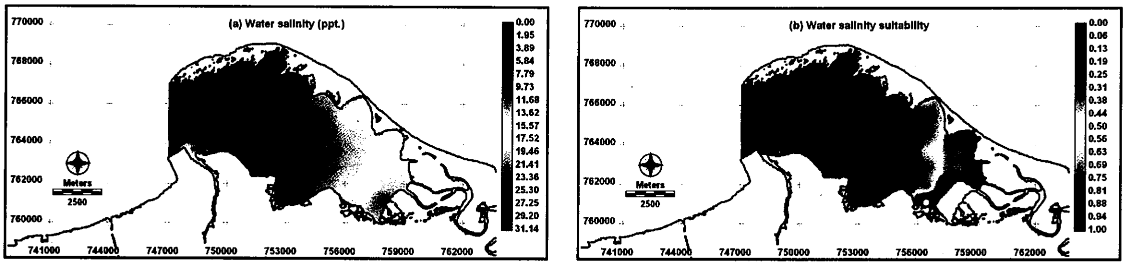


Fig. 6.3. Water salinity (a) and salinity suitability (b) by fuzzy classification.

6.3.3 Sub-model formulation

The MCE using weighted linear combination was applied to spatial models for water and soil suitability. The overall process, starting from classified layers (output of fuzzy classification step) are illustrated in Fig. 6.4. Outputs obtained from all sub-models become inputs to the final model.

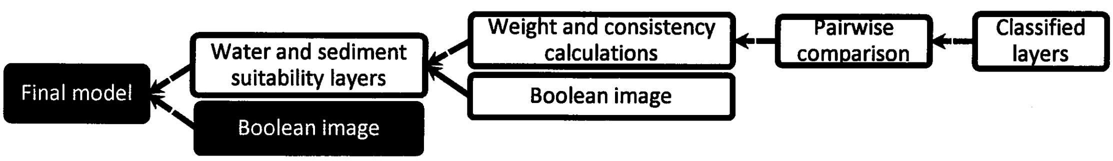


Fig. 6.4. Process summary of the MCE using weighted linear combination.

6.3.3.1 MCE for water suitability

The water suitability was modelled based on sampling occasion. There were 8 sampling occasions over a 7 month period, from June 2009 to February 2010. Most sampling was done monthly, but twice in July 2009. Allowing for missing data, sampling parameter combinations for each occasion varied from 6-8 parameters. The parameter combinations for each sampling time are summarised in Table 6.7.

Table 6.7. Parameter combinations for each sampling time.

Occasion	Date	CHL	DO	pH	POM	SAL	TSS	TRAN	TEMP
1	29/06/09	√	√	-	-	√	√	√	√
2	15/07/09	√	√	√	-	√	√	√	√
3	31/07/09	√	√	√	√	√	√	√	√
4	16/08/09	√	√	√	√	√	√	√	√
5	01/09/09	√	√	√	√	√	√	√	√
6	13/12/09	√	-	√	√	√	√	-	√
7	20/01/10	√	√	√	√	√	√	√	√
8	23/02/10	√	√	√	√	√	√	√	√

Note: The names of parameters are defined in Table 5.14.; (-) is missing data

For the water quality MCE, fuzzy classified layers were used as factors. Pairwise comparisons between factors were established based on a 9 point continuous rating scale, ranging from 1/9 to 9. The smallest value (1/9) indicates the least importance of rows compared to columns while the highest value (9) shows the most importance (Table 6.8) (Eastman, 1999a). The pairwise scoring constructed based on this rating scale is shown in Table 6.9. Although missing parameters from some sampling occasions were not identical, the pairwise score of each pair factors was similar.

Table 6.8. Continuous rating scale and meanings.

Rating scale								
1/9	1/7	1/5	1/3	1	3	5	7	9
Extremely	Very strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely

Based on the pairwise scores, the relative weight of each factor was calculated by WEIGHT module in IDRISI. An acceptability of a factors' weight is indicated by a consistency ratio (CR) of <0.10 (Saaty, 1977). The factor weights and the CRs of different factor combinations are shown in Table 6.10. The CRs vary from 0.05-0.06 and are all acceptable. Finally, the MCE was calculated by sampling occasion using the given weights. The MCE outputs expressed a suitability level ranging from 0-1. Because cockles have a certain degree of environmental toleration and water quality is also subjected to daily variation, this study assigned the area of suitability score of >0.95 to be the suitable water quality for cockle farming.

Table 6.9. Pairwise comparision matrix of the 8 parameters.

	CHL	DO	pH	POM	SAL	TSS	TRANS	TEMP
CHL	1							
DO	1	1						
pH	1/2	1/2	1					
POM	1	1	1/2	1				
SAL	3	3	2	2	1			
TSS	1/5	1/7	1/3	1/5	1/5	1		
TRANS	1/4	1/3	1/3	1/3	1/5	2	1	
TEMP	1/2	1/3	1/3	1/3	1/5	2	1/3	1

Table 6.10. Relative weighting of water quality factors and CR values for factor combinations.

No.	Factor	8 Factors	7 Factors	6 Factors	6 Factors
1	SAL	0.2874	0.3392	0.4053	0.3478
2	DO	0.1581	0.1862	0.2030	NA
3	CHL	0.1521	0.1783	0.1993	0.1903
4	POM	0.1332	NA	NA	0.1678
5	pH	0.1310	0.1316	NA	0.1795
6	TRAN	0.0591	0.0717	0.0895	NA
7	TEMP	0.0477	0.0561	0.0668	0.0700
8	TSS	0.0313	0.0370	0.0422	0.0446
CRs		0.05	0.05	0.06	0.05

NA = not available.

6.3.4 MCE for sediment suitability

Bottom sediment quality comprised particle size analysis (% sand, silt and clay), sediment organic matter and pH. These data were collected from two sampling occasions, in June 2009 and February 2010. The former represents dry season while the latter is just at the end of rainy season. Similar to water suitability, bottom sediment suitability was analysed on a sampling occasion basis. Pairwise scores of each pair of parameters for all sampling times were the same. The factor weight calculation process was similar to that for water factors and the CR of weight for all factors was 0.02, which is considered acceptable (Table 6.11). All factors of each sampling time were combined by MCE using weighted linear combination to identify the bottom sediment suitability on a 0-1 scale. The cut-off point of sediment suitability area was >0.95. Overall suitability of sediment was generated by overlaying the suitability outputs using the minimum approach.

Table 6.11. Pairwise comparison matrix and sediment factor weights.

Factors	%Sand	%Silt	%Clay	SOM	SpH	Weight
%Sand	1					0.0979
%Silt	5	1				0.3045
%Clay	3	1/2	1			0.2134
Sediment organic matter (SOM)	3	1	1	1		0.2433
Sediment pH (SpH)	2	1/2	1/2	1/2	1	0.1490
CR						0.02

6.3.5 Constraint sub-model

This sub-model comprises 3 factors, water currents (ebb and flood tides), water depth and bottom slope. Because of electronic equipment and resources limitations these factors were collected on only a few occasions, but at several sampling stations (as data summarised in Table 3.4-3.5 and Fig. 3.6). The first two factors were classified by fuzzy classification. The suitable area of these layers were determined by cut-off value of >0.95. The bottom slope suitable area was specified by the cut-off value of <15 degrees. Final output of the constraint sub-model was formulated by overlaying using the minimum approach.

6.4 Study results

6.4.1 Water suitability sub-model

The MCE result not only revealed the spatial distribution of water suitability, but also explained vulnerable water parameter(s) at each sampling occasion. These can be illustrated and explained as follows:

6.4.1.1 Suitable area in June 2009 (29/06/2009)

In June, almost the entire area, except the area from Tanyong Lulo to the Yaring River mouth, was suitable for cockle farming (Fig. 6.5a). The suitable area was 43.9 km^2 (Fig. 6.5b). The most vulnerable factor was salinity. The salinity data in this month was obtained from 2 sampling times, one from another project (Fig. 6.5c) and the other from this study (Fig. 6.5d). The different features of these two data sets probably relate to tidal regimes and fresh water supply. During low tide, fresh water occupies a larger area and reduces the salinity around the Yaring River mouth.

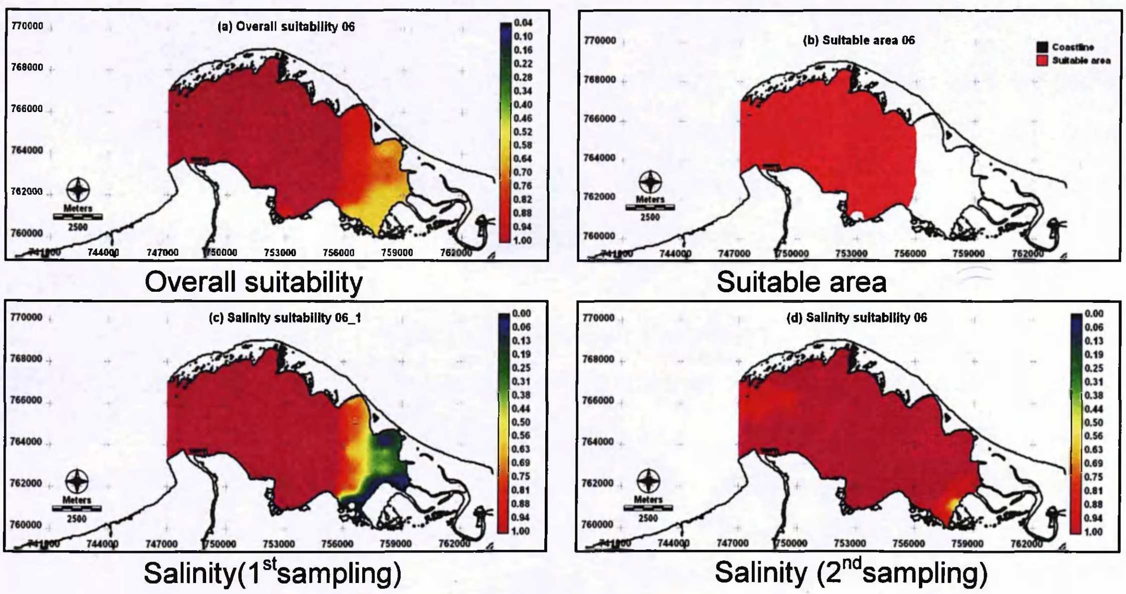


Fig. 6.5. The suitable area and vulnerable factors in June 2009.

6.4.1.2 Suitable area in July 2009 (15/07/2009)

Generally, there were 2 areas classified as unsuitable (Fig. 6.6a). The bigger area was the Yaring River mouth and the small area was just next to the Industrial zone. Total suitable area in this sampling time covered 52.6 km^2 (Fig. 6.6b). Not only salinity (Fig.

6.6c) influenced suitability near the river mouth, but also water pH (Fig. 6.6d). The area near the Industrial zone was solely affected by low water pH of around 7.0.

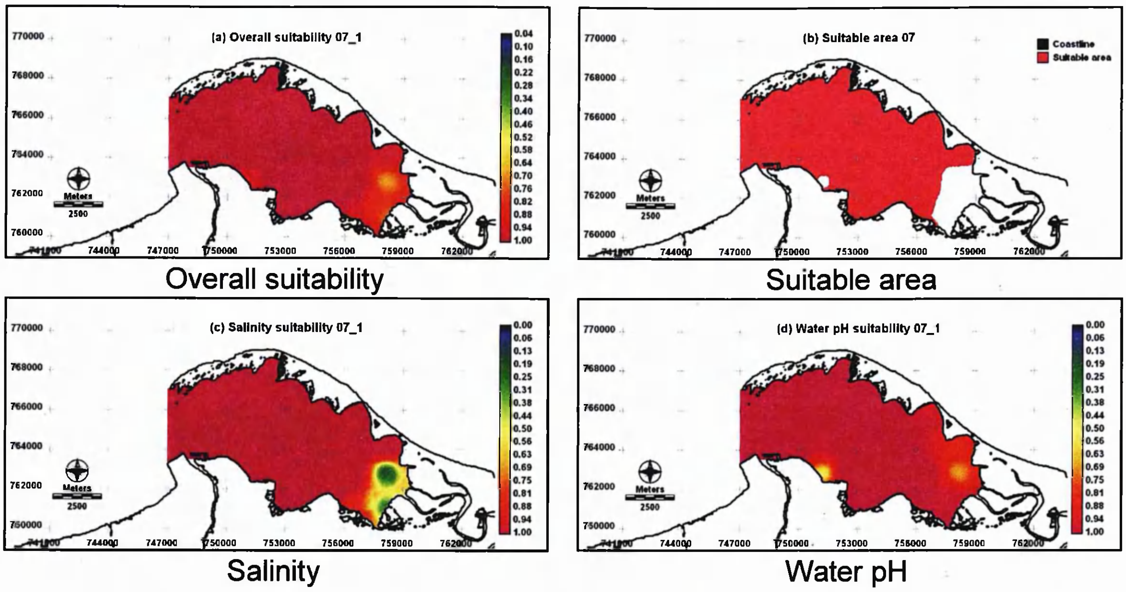


Fig. 6.6. The suitable area and vulnerable factors in 15 July 2009.

6.4.1.3 Suitable area in July 2009 (31/07/2009)

The suitable water area was very similar to the previous sampling time, but with some low suitability areas sparsely distributed along the south shoreline; from Pattani River mouth, Industrial zone, nearby Tanyong Lulo until Yaring River mouth (Fig. 6.7a). Total suitable area covered 44.7 km^2 (Fig. 6.7b). Vulnerable sites were caused by 4 parameters, salinity, water pH, POM and transparency. Low water salinity affected mainly in the Yaring River mouth area (Fig. 6.5c) covering a greater area than in the previous sampling time (Fig. 6.7c). The small area at Pattani River mouth was also included. The water pH had a similar influence to that in July (Fig. 6.7d) with a low value of 7.02. Low transparency extended from the lower part of the Pattani River mouth area and further into the bay (Fig. 6.7e). Turbid water was caused by both river supply and wind. The POM had a big influence in the Pattani River mouth area (Fig. 6.7f) as well as the Yaring River.

6.4.1.4 Suitable area in August 2009 (16/08/09)

Almost all areas of the bay were suitable except at the two river mouth areas (Fig. 6.8a). The total suitable area was 45 km^2 (Fig. 6.8b). Water salinity was the major factor responsible for low suitability (Fig. 6.8c). High POM, caused by re-suspension resulting from wind and wave actions, was also found at the northern part of the Yaring River mouth (Fig. 6.8d).

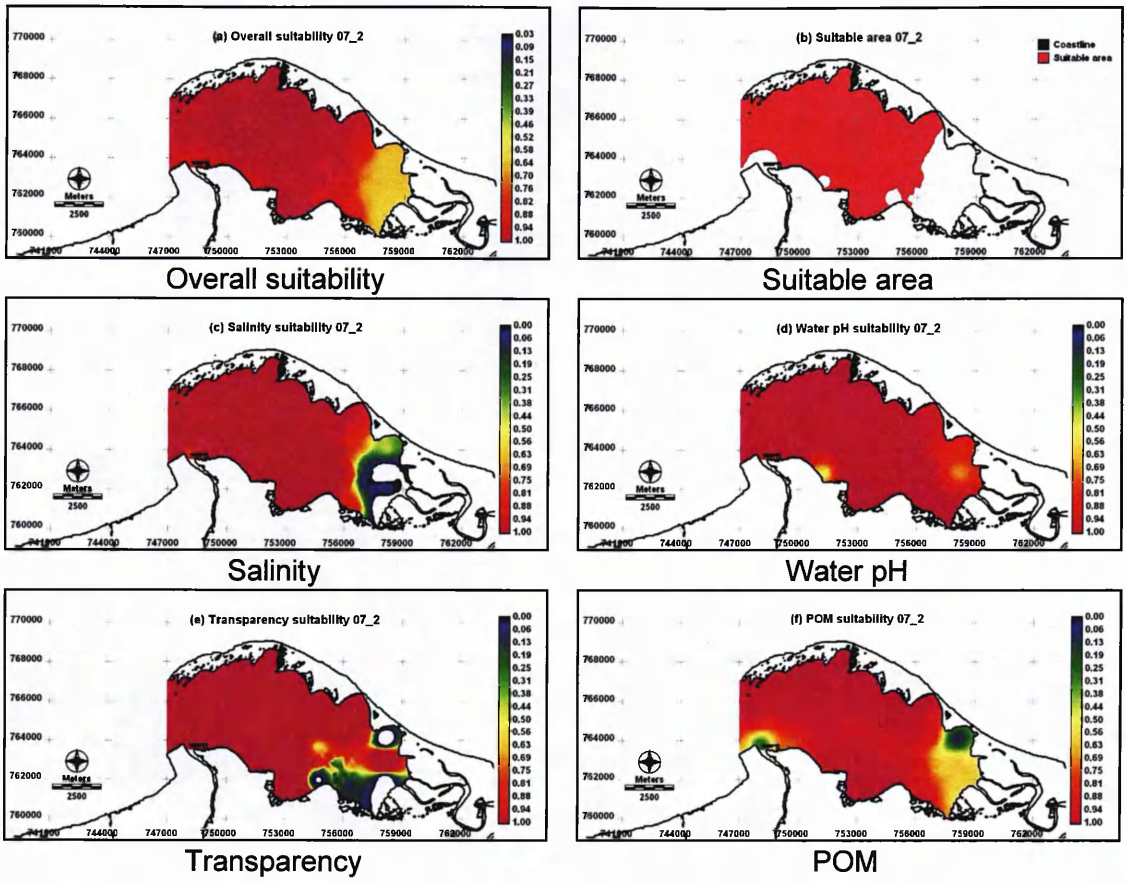


Fig. 6.7. The suitable area and vulnerable factors in 31 July 2009.

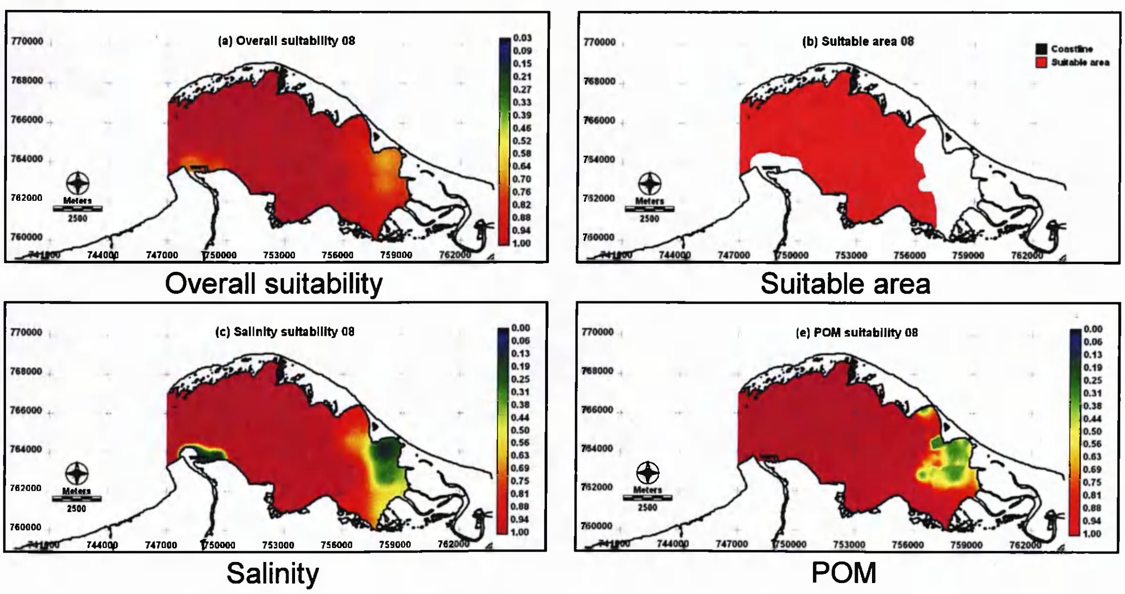
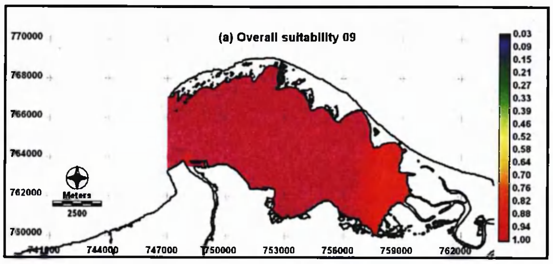


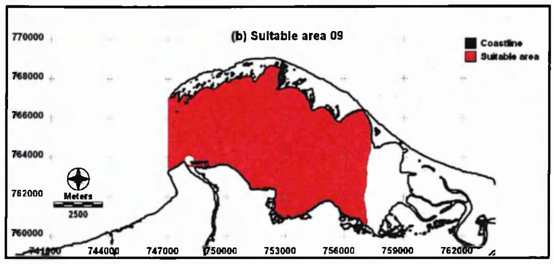
Fig. 6.8. The suitable area and vulnerable factors in August 2009.

6.4.1.5 Suitable area in September 2009 (01/09/2009)

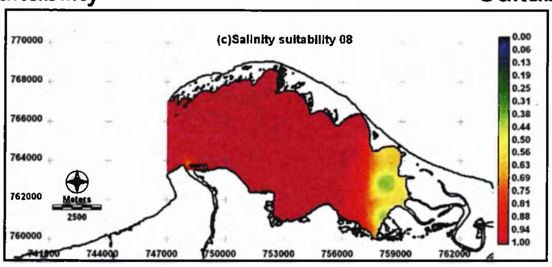
Less suitable culture areas were mainly at Yaring River mouth with only a very small affected area in the other river mouth (Fig. 6.9a). Total suitable area was 50.9 km^2 (Fig. 6.9b). Salinity was the only vulnerable factor for cockle farming (Fig. 6.9c).



Overall suitability



Suitable area

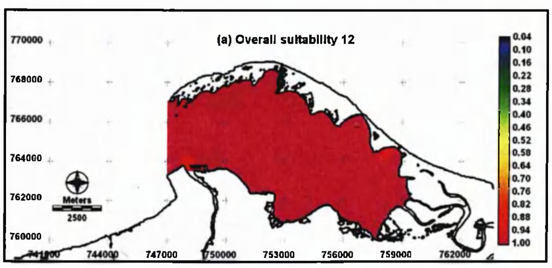


Salinity

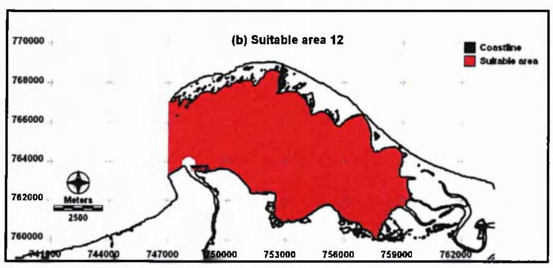
Fig. 6.9. The suitable area and vulnerable factors in September, 2009.

6.4.1.6 Suitable area in December 2009 (13/12/2009)

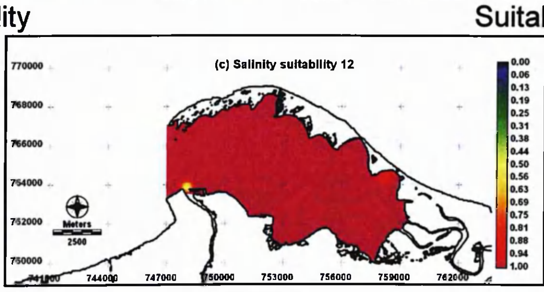
Only a small less suitable area was found at Pattani River mouth (Fig. 6.10a). Total suitable area was relatively high, at 58 km^2 (Fig. 6.10b). Similar to the previous months, the salinity was the responsible factor affecting area suitability (Fig. 6.10c).



Overall suitability



Suitable area



Salinity

Fig. 6.10. The suitable area and vulnerable factor in December, 2010.

6.4.1.7 Suitable area in January 2010 (20/01/10)

The suitable culture area in this month is similar to that of the December. Almost all of the bay area (Fig.6.11a), of around 58.3 km^2, was considered suitable for cockle farming with only a small area at the Pattani River mouth being excluded (Fig.6.11b). The main vulnerable factors were salinity (Fig.6.11c) and water pH which affected 4 small areas (Fig.6.11d).

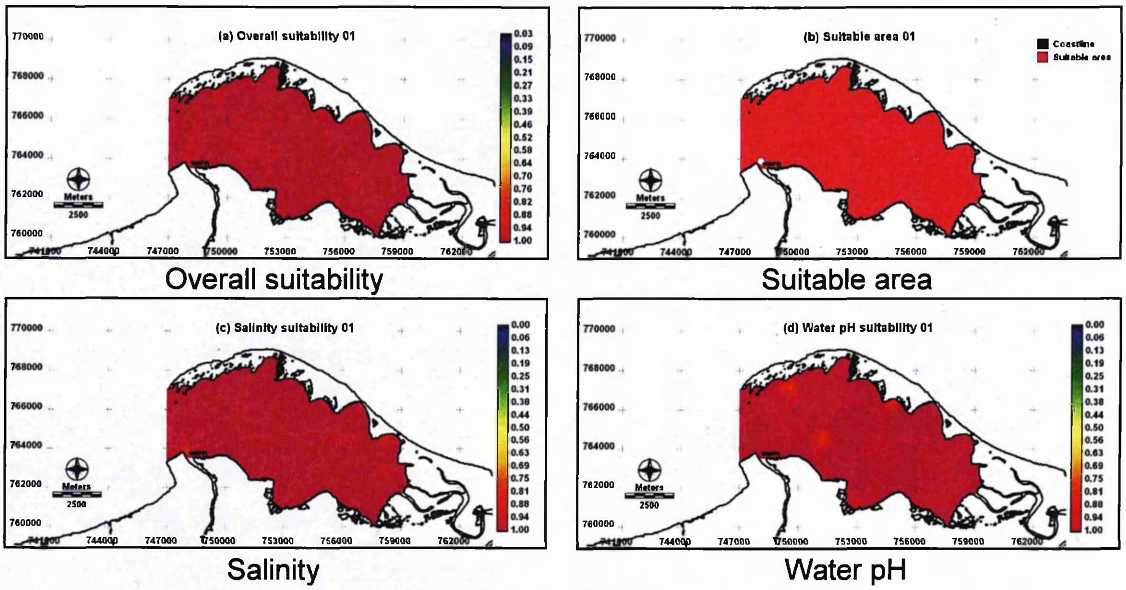
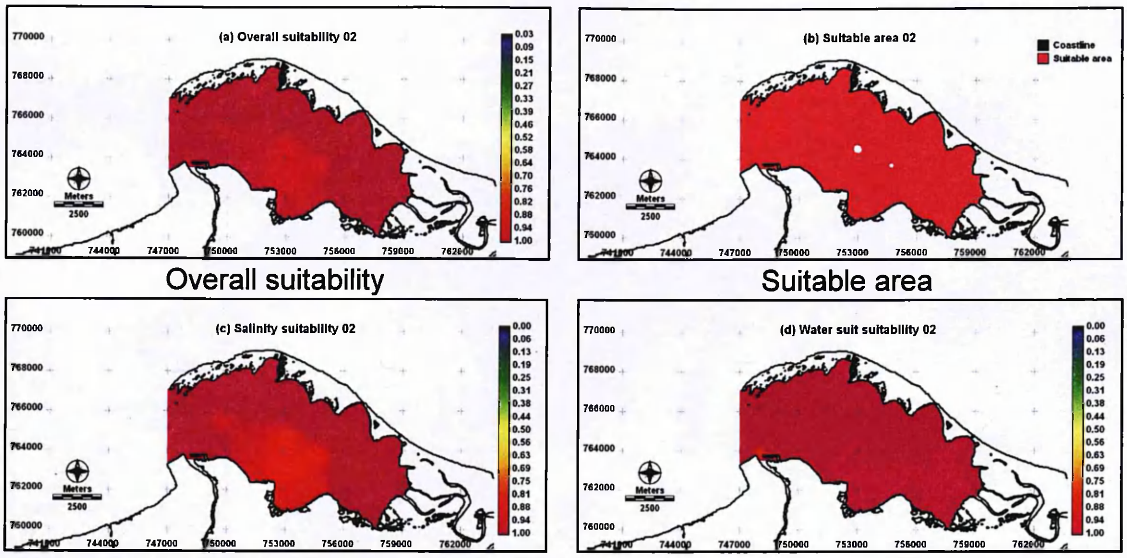


Fig. 6.11. The suitable area and vulnerable factors in January 2010.

6.4.1.8 Suitable area in February 2010 (23/02/10)

Lower suitability for cockle culture in this month (Fig.6.12a) was found at different sites because of low salinity found near Laem Nok (Fig.6.11c). This may be because of the tidal change during water sampling. The suitable area during this month was 58.2 km^2 (Fig.6.12b). Water pH had a small impact at Pattani River mouth, probably caused by inland water or waste water from the city and/or industrial areas, but it was not sufficient to reduce the overall suitability score.



Overall suitability | Suitable area

Salinity | Water pH

Fig. 6.12. The suitable area and vulnerable factor in February 2010.

6.4.1.9 Overall water suitability

Using the model outputs for all sampling occasions, a final water suitable area was calculated by overlaying the layers using the average option. The bay water body was classified into suitability zones with different average suitable scores of 0.375, 0.50, 0.75, 0.875 and 1.0 (Fig. 6.13). To avoid risk from water quality variability, this study defined only those areas with a suitability score of 1 as the water suitable area for cockle culture. The suitable culture area covered 40.6 km^2. Less suitable sites were mainly found adjacent to both river mouths, the largest unsuitable zone being at the Yaring River mouth, followed by that of Pattani River mouth with other small areas distributed along the south and around the middle of the bay. The water quality showed relatively high temporal and spatial variations. This is probably because of the bay location connecting the two main rivers. On seven of eight sampling occasions, salinity was the most vulnerable factor covering a maximum area of around 25% of the water space while some areas which were very close to urban and industrial locations were affected by water pH. The suitable culture areas varied from 43.9-58.3 km^2.

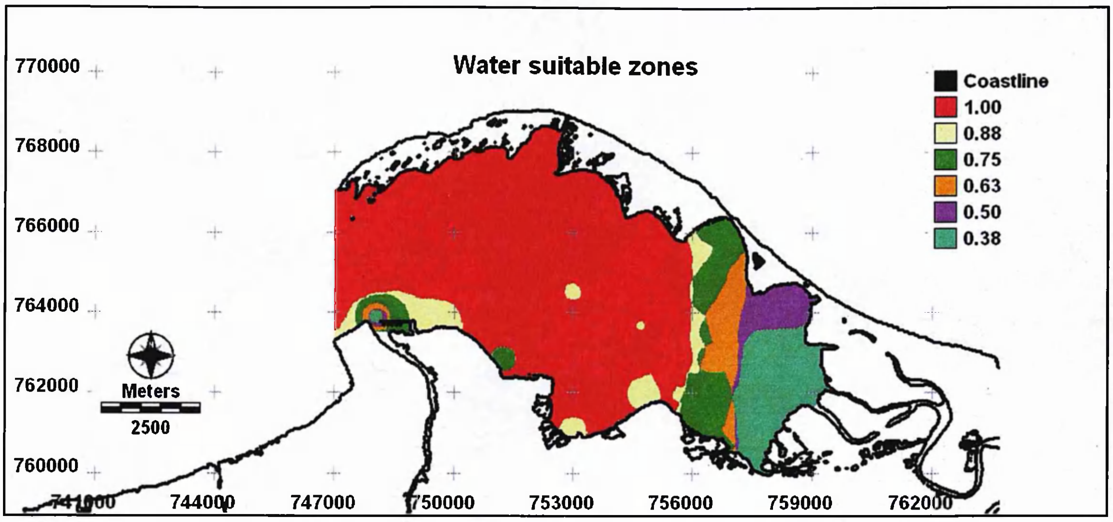


Fig. 6.13. Water suitability zones classified by overlaying.

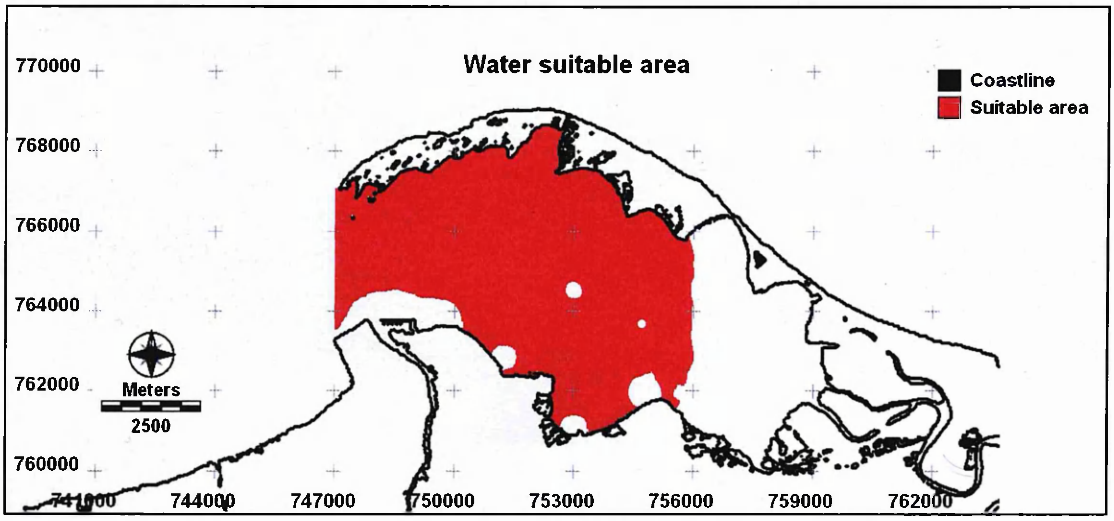


Fig. 6.14. Water suitable area for cockle culture in Pattani bay.

6.4.2 Sediment suitability

6.4.2.1 Sediment suitability in June 2009

Generally, bottom sediments along the northern coastline and a small area at Pattani River mouth were less suitable (Fig. 6.15a). Sediment pH, %sand and %silt were major parameters affecting suitability, while organic matter content was a minor factor. The percentage of sand (Fig. 6.15b) and silt (Fig. 6.15c) particles in bottom sediment along the northern coastline was very high compared to other areas, resulting in low suitability. Around the Yaring River mouth, low suitability was caused by a sediment pH of <6 (Fig. 6.15d). The organic matter was low in a small area around the middle of the northern coastline. In general, less suitable areas revealed high sand percentage and low organic matter (<17 g/kg).

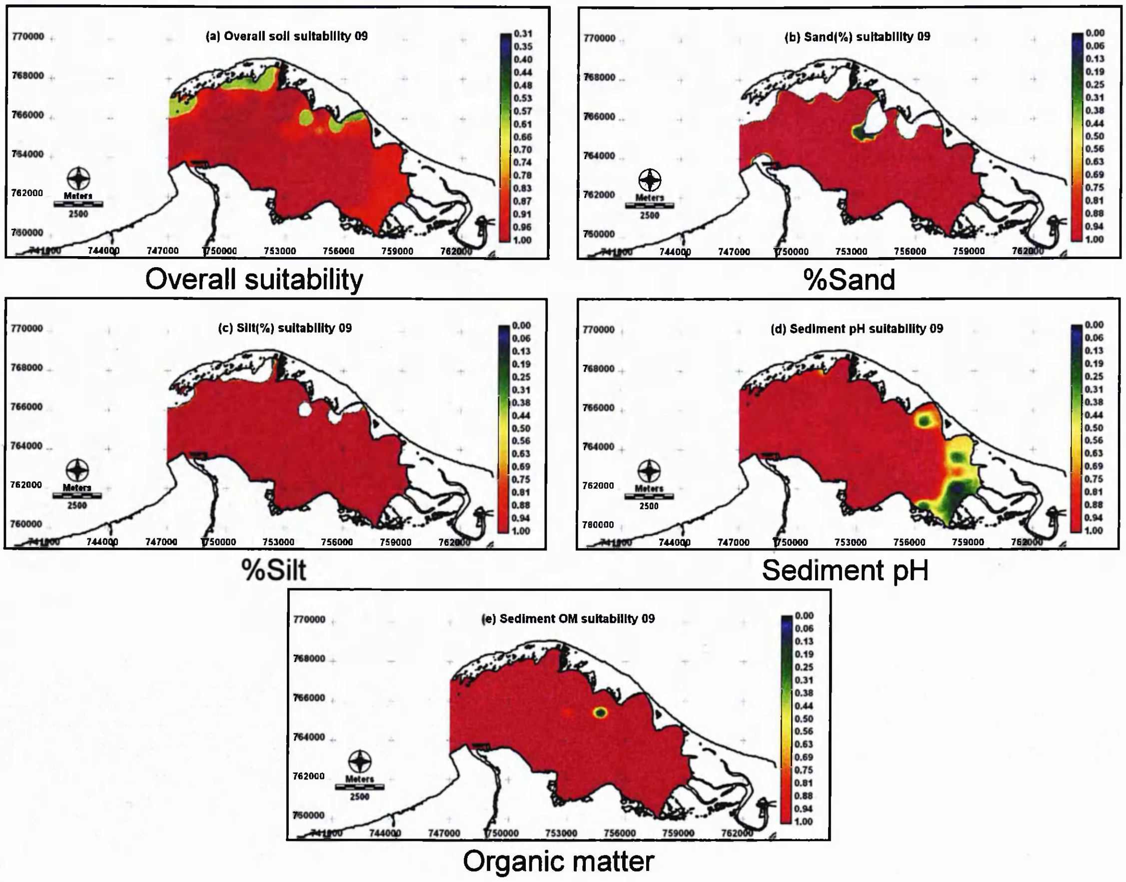


Fig. 6.15. Sediment suitability and some related parameters in June 2009.

6.4.2.2 Sediment suitability in February 2010

The overall sediment suitability in February 2010 was different to that in June 2009. The Yaring River mouth became a suitable area while the northern coastline area was little different (Fig. 6.16a). The major vulnerable factors were the same to those in the 2009 sampling, except for sediment pH. High sand percentage was found along the northern shoreline and this extended to a small area off shore of Talo Samilae (Fig. 6.16b). Silt particles were normally low in the area of high percentage of sand, except the sandy area at the bay centre (Fig. 6.16c). Organic matter was at generally high levels, but the lowest organic matter content being found in the sandy zone (Fig. 6.16d).

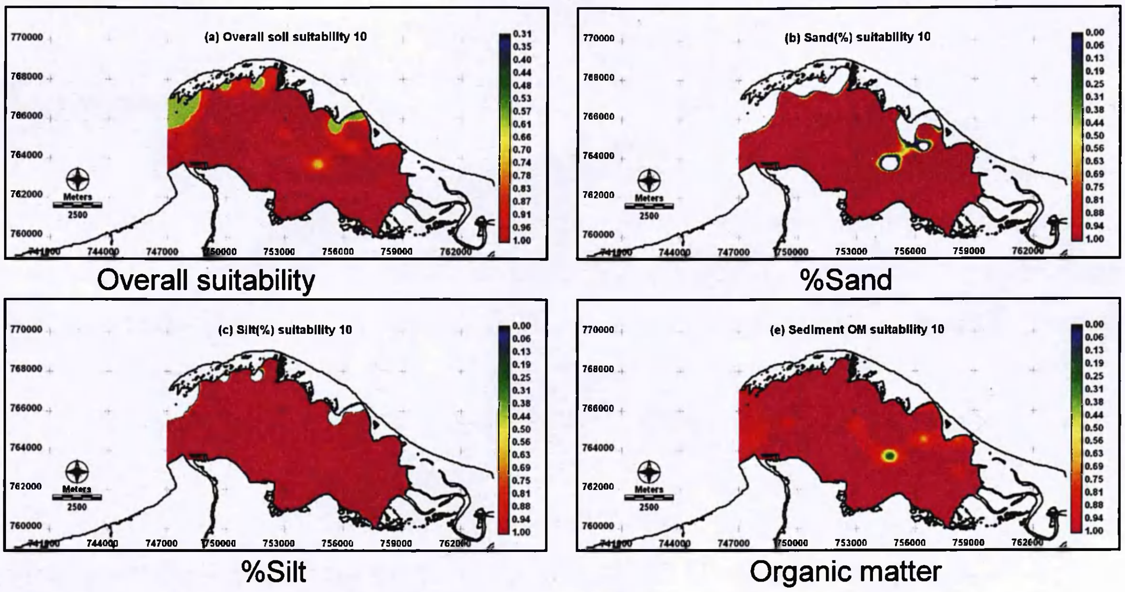


Fig. 6.16. Sediment suitability and some related parameters in February 2010.

6.4.2.3 Overall sediment suitability

The major factors affecting the sediment suitability were almost the same in both sampling periods, except for sediment pH, which had no effect on overall suitability in 2010. There were a high percentage of sand particles along the northern coastline with some temporal change and correspondingly low silt levels in the sandy areas. The overall sediment suitability was developed by overlaying the two suitability outputs using the minimum option. The most suitable sediment zone is shown as dark red areas in Fig. 6.17. Less suitable sediments are mainly along the northern coastline and Yaring River mouth with the remainder of the bay being considered suitable. The influence of sediment on the suitability is less than that of water quality because of lower spatial variation of sediments in the bay.

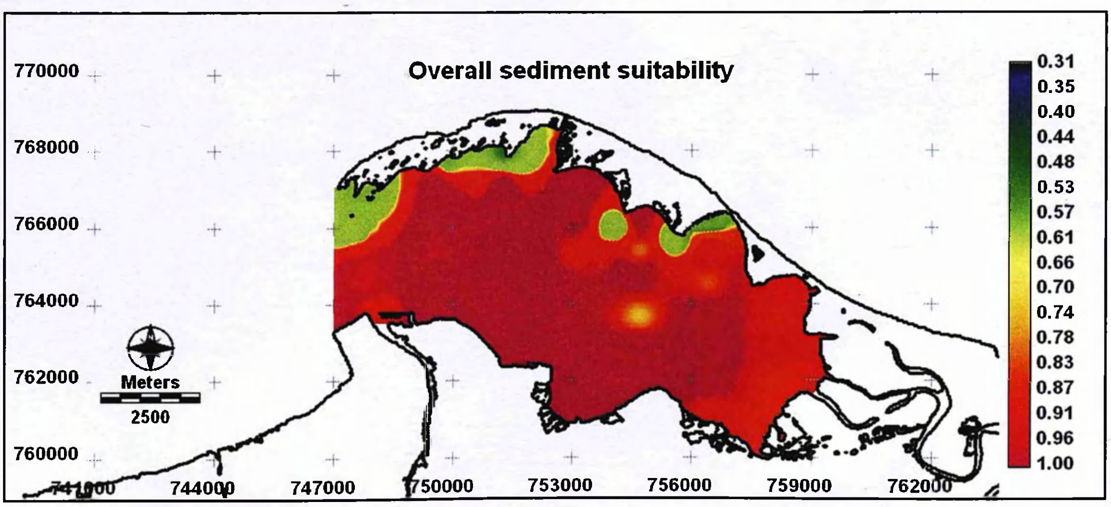
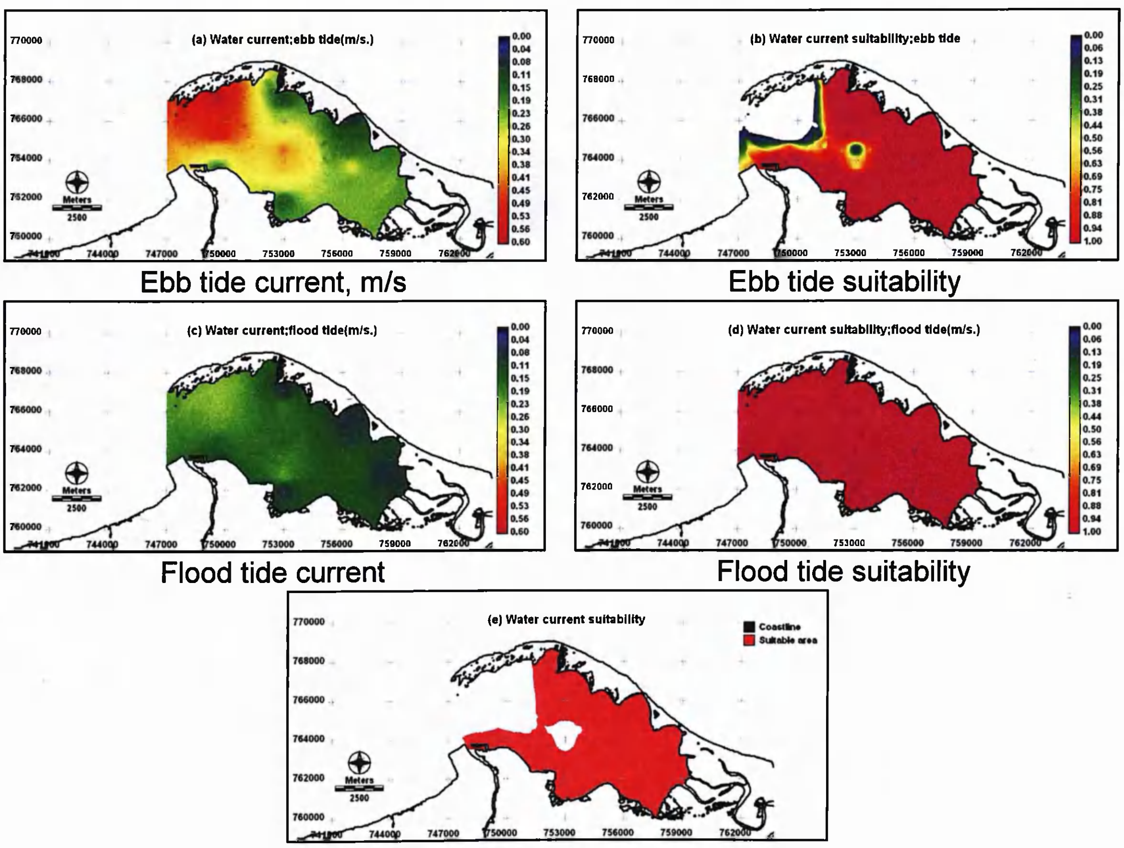


Fig. 6.17. Overall sediment suitability for cockle culture in Pattani bay.

6.4.3 Constraint components

6.4.3.1 Water current

Water current comprised flood and ebb tide currents. The ebb tide current velocities varied from 0-0.60 m/s (Fig. 6.18a). The high velocity area was nearby the bay mouth, extending to the northern shore line and around the bay's centre. These high velocities are unsuitable for cockle culture (Fig. 6.18b) but the lower ebb current in shallow water and some sheltered areas were suitable. The maximum flood tide velocity was 0.24 m/s, probably because of the flow direction against the east north fresh water flow from Yaring River. The entire bay was classified as suitable culture sites during the flood tide (Fig. 6.18d). Widdows & Navarro (2007) showed that re-filtering could occur because of faeces re-suspension and that between current velocities of 0.5-0.35 m/s there was no significant feeding, noting that part of a cockle's energy might be lost by the particle selection and re-filtering process. Consequently, this study uses 0.80 as a threshold value for suitable area in order to include some areas where the current speed is between 0.325-0.35 m/s. The overall water current suitability was identified based on both tidal currents and covered around 41.8 km^2 (Fig. 6.18e).



Ebb tide current, m/s

Ebb tide suitability

Flood tide current

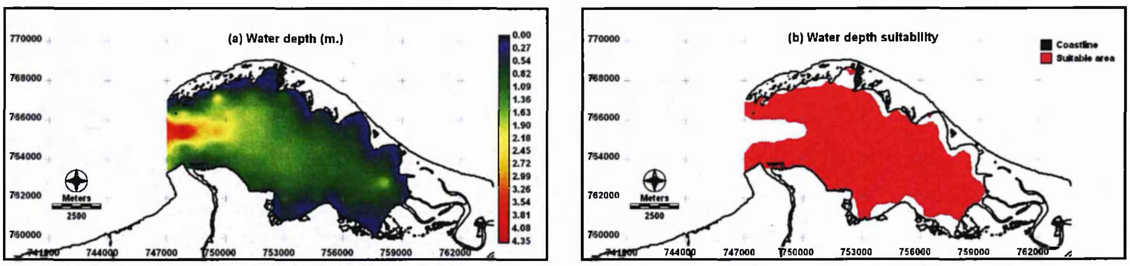
Flood tide suitability

Overall current suitability

Fig. 6.18. Water currents and the suitability for cockle culture in Pattani Bay.

6.4.3.2 Water depth

Although the water depth data was taken on each sampling occasion, insufficient sampling time was available to represent the bay bottom's profile fully. As a result, water depth data points from one dry season sampling session, the minimum depth of the year, was adopted to represent the water depth. The trend of water depth of the bay in a north-south direction showed a slight increase toward the bay's centre line and decreased towards the East end of the bay. The deepest area was around 4.35 m (Fig. 6.19a). Areas that were too deep or too shallow were excluded and around 48.2 km^2 was suitable for cockle culture (Fig. 6.19b).

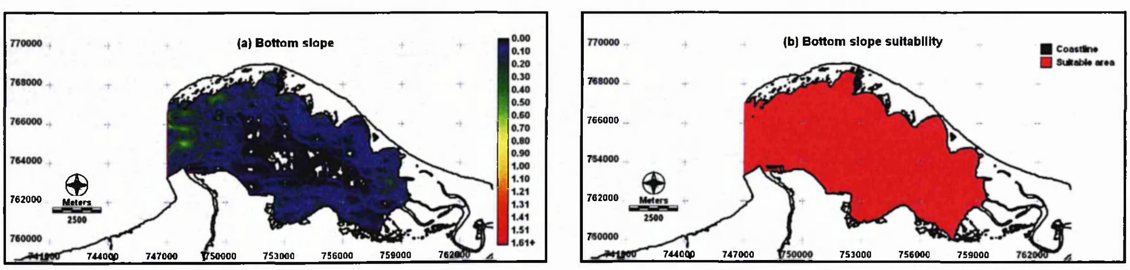


Water depth(m) | Depth suitability

Fig. 6.19. Water depth and depth suitable area for cockle culture in Pattani Bay.

6.4.3.3 Bottom slope

The bottom slope was calculated based on water depth layer (Fig. 6.19a). The bottom slope was very gentle, ranging from 0-1.6% (Fig. 6.20a), indicating that the entire area was suitable for cockle culture (Fig. 6.20b).



Bottom slope(%) | Bottom slope suitability

Fig. 6.20. Bottom slope and slope suitability of the bay.

6.4.3.4 Overall constraints

Of all constraint factors, only water current and depth had effects on area suitability while bottom slope was excluded because it was very gentle (<0.7%) throughout the bay. The total suitable area based on these constraint layers covered 35.8 km^2 (Fig.

6.21). The main constraint factor driving unsuitability was water current, which was around 0.33-0.60 m/s during the ebb tide. Some areas near the coastline were also excluded because they were too shallow. High current velocity or steep bottom slope can make some water and sediment suitable areas become technical unfeasible for cockle culture. For water depth, the deepest areas of 4.35 m and nearby areas might be subjected to oxygen depletion during night time or stagnant water periods.

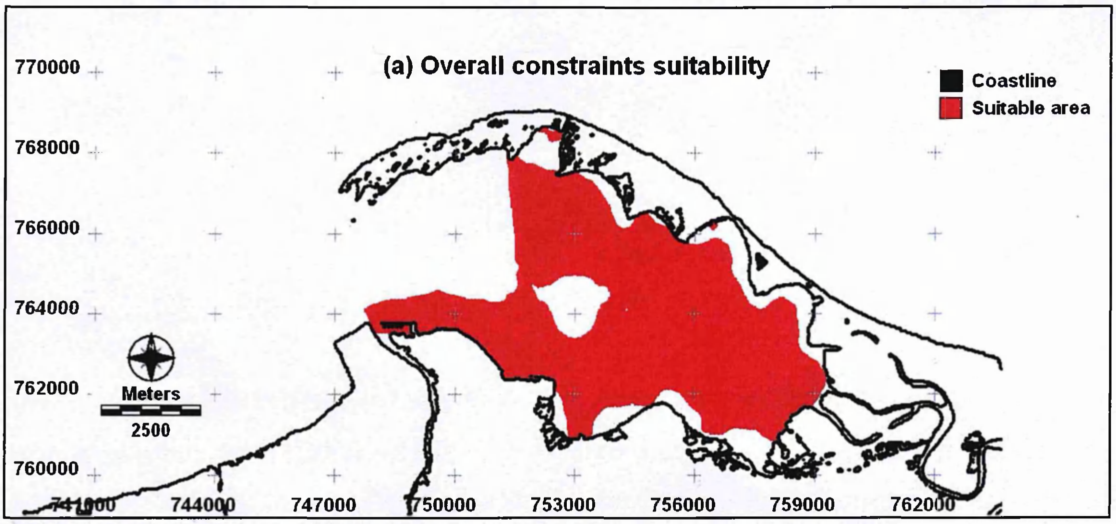
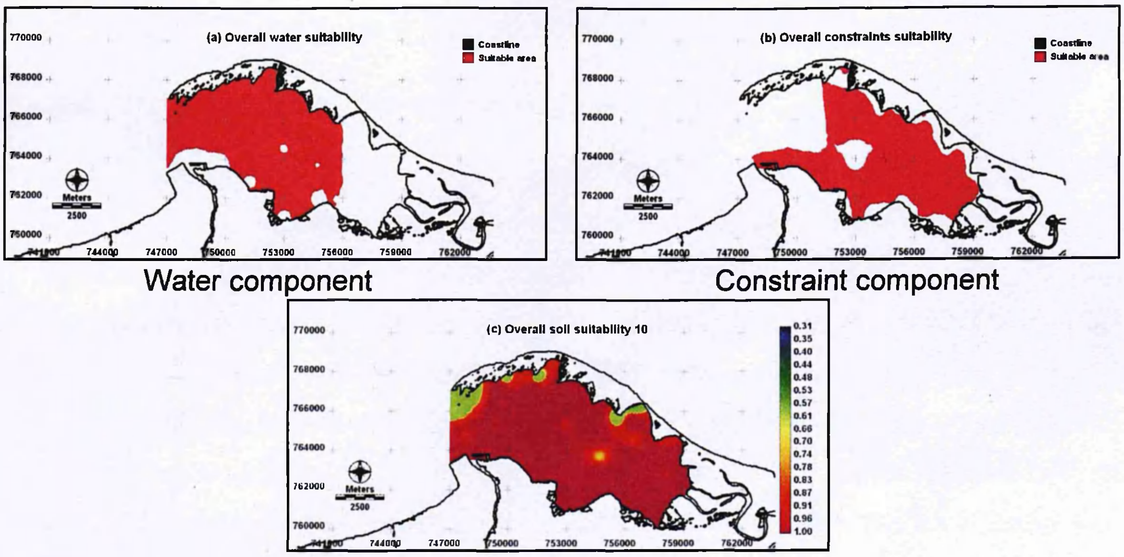


Fig. 6.21. Overall constraint components suitability in the bay.

6.4.4 Final suitability model

The final, optimized model output was formulated using 4 main components; overall water suitability (Fig.6.22a), overall constraints suitability (Fig.6.22b), overall sediment suitability (Fig.6.22c) and a Boolean layer defining the study area boundary. The final suitable site was based on the following assumptions:

- Water quality is the most variable component that influences cockle growth and survival. This can be confirmed by the temporal variation in water quality of this study.
- Cockles prefer muddy sea shore areas with high percentage of silt and clay, but minimal sand particles (Tookwinas, 1983).
- Cockles are sessile animals and are able to move to their preferable areas by themselves (Tookwinas, 1983), but only a few meters.
- Strong currents affect the filtering ability of cockle to and may even move them from their preferred location (Widdows & Navarro, 2007).



Water component

Constraint component

Sediment component

Fig. 6.22. Main sub-components of the final model

Based on the various assumptions, this study assumes that cockles are able to survive even when they are distributed to sandy bottom sediment. Moreover, it is possible for farmers to classify muddy sediments in the field by simple survey and so it is not necessary to reclassify the overall sediment suitability as a Boolean image. The final, optimised model was constructed by multiplying the suitable sediment layer with the water suitability and constraint layers. The final suitable area for cockle was found to be around 13 km^2 (Fig.6.23)

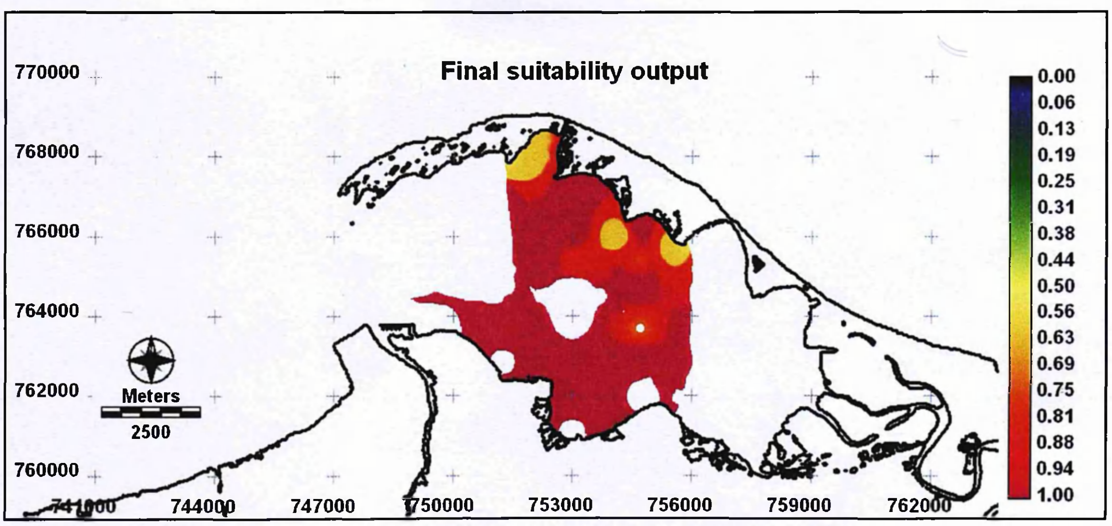


Fig. 6.23. Final model output of area suitability for cockle culture in the bay.

6.4.5 The model suitable area and existing cockle farms

6.4.5.1 Water suitability and existing cockle farms

Considering the actual farm area in the year 2009-2010 of 13.96 km^2, it is clear that around 75% of cockle farms were located in the suitable water zone (suitable score = 1) while around 11% was in the water suitable score of 0.88. The remaining 14% was in the lower water suitability area, with scores ranging from 0.38 - 0.75 (Table 6.12) However, discussion with some farmers and key stakeholders found that the production quantity and quality from the area within the 0.88 suitability score was not different when compared to that of the area within score 1.0. Some farmers had an understanding of the environmental factors and they considered that fresh water and some "invisible things" in that water had a negative effect on their product. As a result, farmers decided to start harvesting cockles from such areas as soon as cockles reached marketable size. The culture period of cockle in the other areas is often extended for a few months in order to obtain a better price from larger animals. Where scores of 0.75 are found near Yaring River (Fig. 6.24), farmers sometimes do not culture intensively. Stocking density is not high, harvesting is done by hand and culturing activity is postponed for some years. So, both the production and economic loss was small when compared to other more intensive areas.

Table 6.12. Distribution of average modelled suitability scores for cockle culture area and existing cockle farms.

Suitability score	Cover area	% of total farm area	Note
1	10.418	74.60	Total area of 13.966 km^2
0.88	1.534	10.98	
0.75	1.801	12.90	
0.63	0.209	1.50	
0.50	0.001	0.01	
0.38	0.003	0.02	

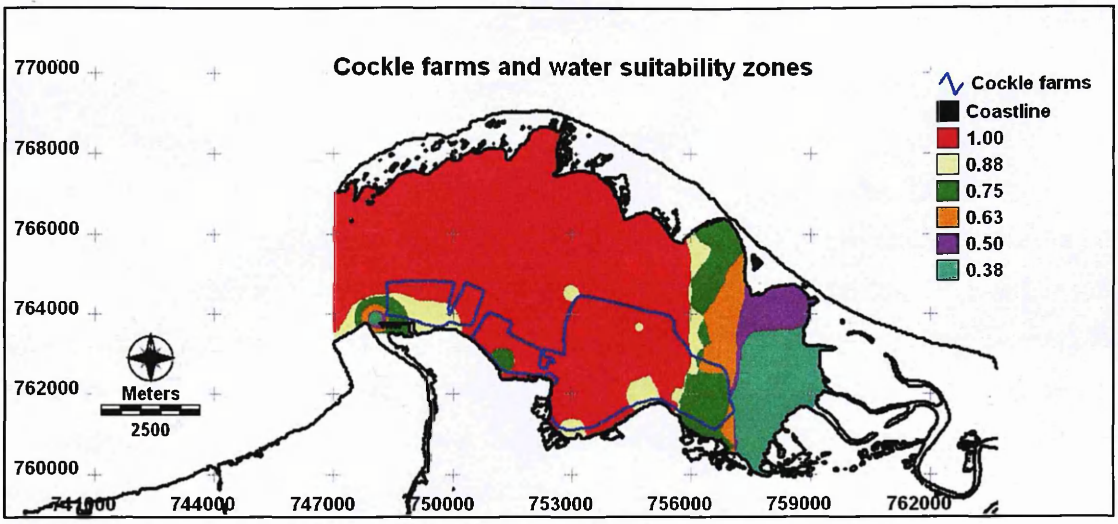


Fig. 6.24. Existing cockle farms and water suitability zones.

6.4.5.2 The sediment suitability and existing cockle farms

Almost all existing cockle farms were located in the suitable sediment area (Fig. 6.25) Small farm houses, usually set up for security purposes, were normally located on the less suitable sites. Practically, if some unsuitable areas were found within the farm area, cockle seed will not be distributed to those areas for the next crop. When comparing the existing farm areas with suitable sediment and water quality, it could be concluded that farmers are more likely to choose their farm sites based on the sediment parameters. This is simply based on their experience and comparison with other cockle production areas, such as the farms nearby or in Malaysia.

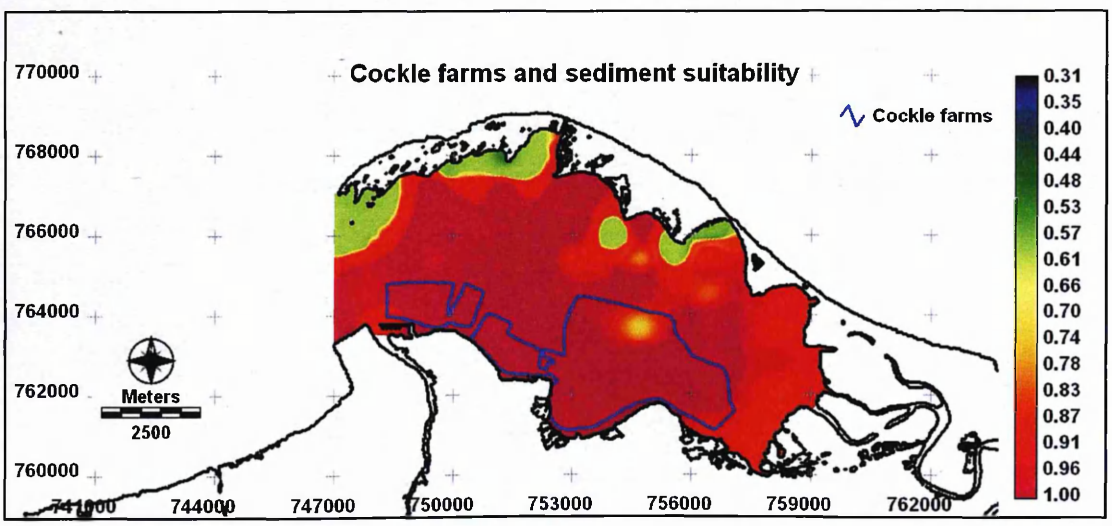


Fig. 6.25. The current cockle farm locations and suitability zones based upon sediments.

6.4.5.3 The constraint suitability and existing cockle farms

Of all 3 constraint parameters, only water current and depth had an influence on cockle culture suitability. The current farm areas were mainly affected by the water current, except for the farms area near the coastline, which were in shallow water (Fig. 6.26). However, in reality, culture practice in the shallow risk areas of the existing farm is not a problem for cockle survival because the sediments are suitable (see Fig. 6.25) and cockles can survive by burrowing themselves into the sediment during periods of exposure. Another technical problem in the shallow area is harvesting period and in this case farmers have two choices, either to wait for high tide or to collect by hand dredging if a powered boat cannot operate at the site.

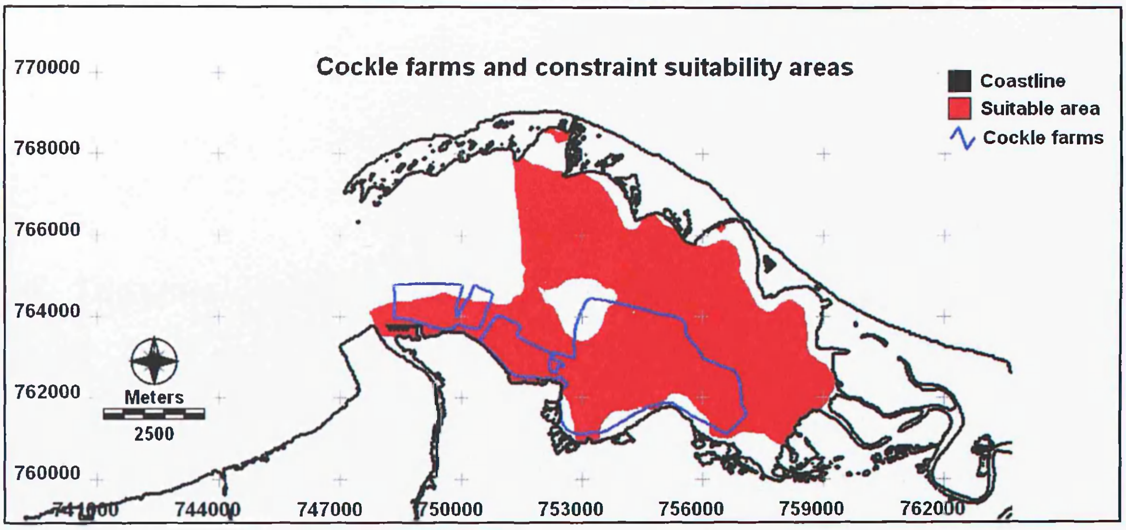


Fig. 6.26. The current cockle farm and constraint layers.

6.4.5.4 The overall suitability and existing cockle farms

Almost all of the existing cockle farms are located within the optimized suitable area (Fig. 6.27). However, based on the model output, there are more potential areas (indicated in dark red) where cockle farm extension could be feasible. Some of the existing cockle farms are located in less suitable zones based on the assumptions and threshold values used in this study. Water salinity, water pH, water current and sediment type seem to be the crucial parameters that should be taken into account for technical decision making for cockle farming site in the bay. Some important parameters in this study, such as water current and sediment type, were obtained from only 1-2 sampling times from different periods because of personal and equipment limitations. Temporal variability of these parameters might have an effect on the final output and more data of these parameters would be beneficial. Overall, however, the results from this study do depict the general ecological suitability of the area and prospects for bay management in the future.

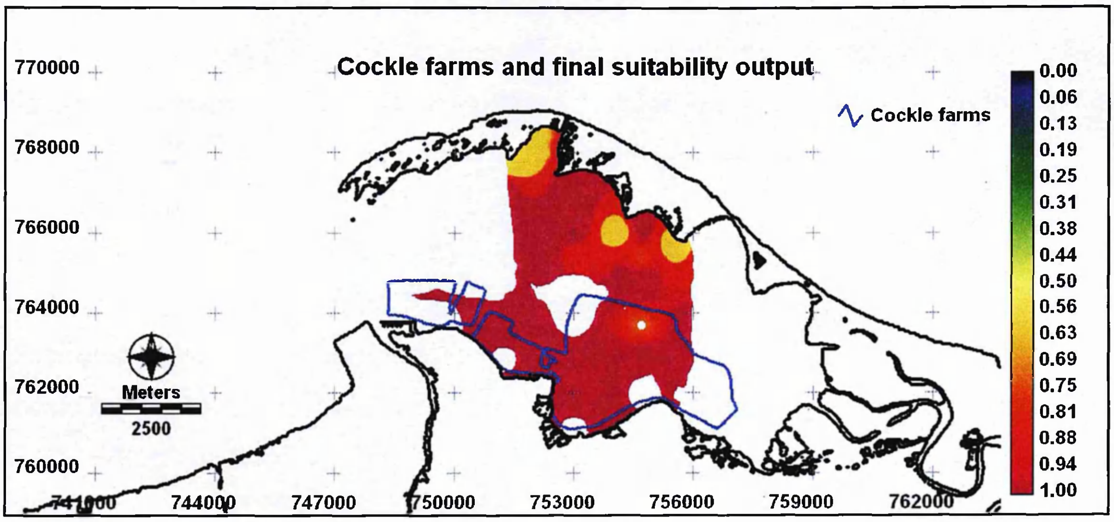


Fig. 6.27. Overall suitable area from modelling and existing cockle farms.

6.5 Discussion and conclusions

Based on each sampling occasion, water suitability area of 44-58 km^2 was identified. This suitable area reduced to around 13 km^2 when water depth, currents and sediment suitability were included. The main vulnerable factors for cockle suitability site were low salinity, low pH and high water current while Some water parameters, such as DO, TSS and chlorophyll-a had little influence on suitability for cockle culture.

Low salinity was usually found as the most vulnerable factor, affecting up to 25% of the water space. Moreover it can be considered a surrogate for high POM and low transparency because both were found in the same area. The salinity influences many aspects of cockle biology and physiology, such as valves opening, osmotic pressure, feeding and mortality (Tookwinas, 1985; Davenport & Wong, 1986) and consequently have an effect on cockle growth rate.

Water currents are known to affect cockle feeding ability, clearance rate, food particle distribution and biodeposit re-suspension. In fact, at >0.45 m/s cockles are moved along the sediment surface (Widdows & Navarro, 2007). High current speeds reduce the suitability of some parts of the bay area.

Water pH was found to be a vulnerable factor for cockle culture, especially in the areas nearby the Industrial zone and fishing communities within Pattani Bay. This is probably caused by water discharge, as has been found in the inner Thai Gulf (Brohmanonda *et al.*, 1988b), resulting in unstable water quality and marked oxygen depletion (Tookwinas, 1983; Office of Agricultural Economics, 2009). However, the lowest reported of water pH in shallow area of the Pattani Bay is 6.96 (Pianthumdee, 2004) and this is unlikely to have a big effect on site selection.

Chlorophyll-a, levels of up to 45.28 µg/l (Table 5.15) in Pattani bay found in this study were somewhat higher than those previously reported; 21 µg/l in Patani Bay (Tookwinas, Perngmark, Sirimotaporn, Tuaycharoen, & Sangsakul, 1987) and other cockle culture sites; 1-7 µg/l in Bandon Bay (Nilkerd, 2001; Kaewnern & Yakupitiyage, 2008), <3 µg/l in Sawi Bay (Thamasavate *et al.*, 1988) and 30 µg/l in German (Buck, 2007). The high chlorophyll-a in Pattani Bay ensures sufficient natural feed for cockles and promotes sustainable production. As a filter feeder, cockles can reduce plankton bloom in the bay (Gibbs, 2007; Kaewnern & Yakupitiyage, 2008)

Sediment quality shows less variability when compared to that of water quality. High percentage of sand particles can be considered a surrogate for low percentage silt and low organic matter, which results in low suitability for cockle farms. This is consistent with the fact that cockles prefer muddy locations (Narasimham, 1983) and normally inhabit sites with a high percentage of silt and clay, but low in sand particles (Silas *et al.*, 1982; Narasimham, 1983; Broom, 1985). Bottom slope was found to be very gentle, at < 0.7%, well within the suitable range of <15 degree reported by Tookwinas (1983)

When comparing to the model output to the existing cockle culture area, it is clear that there is a scope for further farming development and even some farm area relocation. Comparison of the study results to those of Predalumpaburt & Chaiyakam (1994) shows similarity in the suitable cockle culture area, although the present study identified a much bigger area of potential sites in the bay. Comparison of model outputs, previous results and current cockle farm areas allow partial model validation, and shows the capability for the application of GIS for aquaculture and natural resource management (Ross, 1998; Nath *et al.*, 2000; Longdill *et al.*, 2008).

Specific to cockle seed shortages at both national and local levels and a cockle rearing period of 8-24 months (Tookwinas, 1983; Office of Agricultural Economics, 2009) means that suitable site selection is one of the most important factors contributing to efficient use of limited seed. This study has shown how GIS technology can be an effective tool to combine spatial and temporal changes of the related ecological factors and to illustrate both suitable and vulnerable areas for cockle farming.

Chapter 7

Discussion and Conclusions

This study considers three main topics:

(a) Development of a mussel growth determination model,
(b) Development of a harvestable area model for mussels,
(c) Development of a suitable area model for cockle farming.

The study area was Pattani Bay, a small, intensively used bay in Southern Thailand. GIS technology was a major tool applied throughout the study processes. In order to address these topics, different combinations of original field work and related published data were incorporated (Table 4.3) through four core analytical techniques; Principal Component Analysis (PCA), Principal Component Regression (PCR), Multiple Linear Regression (MLR), and fuzzy classification and Multi-Criteria Evaluation (MCE).

For mussel growth determination, Principal Components (PCs), main principal components (MPCs) and the best representation of water parameters (WQs) were extracted using the PCA technique. The PCs and WQs were then applied for mussel growth determination models using PCR and MLR approaches including simple regression. The prediction capability of each model was indicated by the coefficient of determination (R^2) value. Additionally, mussel harvestable areas were calculated based mainly on mussel empirical growth functions. The model was mainly constructed using Macro Modeller coupled with DynaLink in IDRISI.

Fuzzy classification using sigmoidal function with 4 control points was applied to transform water and sediment parameters to the common scale from 0-1 to provide the input factors for the MCE. The MCE technique using weighted linear combination was applied to combine a set of factors to identify suitable sites of each sub-model by the suitable score of >0.95. Thereafter, overlaying was adopted for the final model formulation. Input parameters of each sub-model are shown in Fig 6.1.

7.1 Mussel and cockle culture in Pattani

Although a many kinds of molluscs are harvested from Pattani Bay, only green mussel (*Perna viridis*) and blood cockle (*Anadara granosa)* were targeted in this study for a number of reasons. They are the main cultured species in Thailand (Fishery Statistics Division, 2007a; Fishery Statistics Division, 2007b), they have a high market acceptance (Brohmanonda *et al*., 1988b; Office of Agricultural Economics, 2009), they have been cultured nationally over a long period (Tookwinas, 1983; McCoy *et al*., 1988; Brohmanonda *et al*., 1988b) and there is high data availability. In addition, the national production level is less than domestic demand and the marketing system is well established (Office of Agricultural Economics, 2009).

Pattani Bay was adopted as the study area because it has been an important cockle production area (Fishery Statistics Division, 2007a; Fishery Statistics Division, 2007b). At the same time, the bay and surrounding areas are used competitively as a nursery ground, fishing area, reserved natural resource site, for industrial plant, community settlement, as a sink for inland effluent and other aquaculture activities (Hoecharoen *et al*., 1998; Sukansil, 2000; Hajisamae *et al*., 2006). Spatially, the bay is surrounded by the densely populated area of Pattani Province (Department of Provincial Administration, 2010). This means that there is a considerable number of local consumers and consequently allows farming activities for various purposes, including natural production enhancement, food security and commercial purposes. On the other hand, the bay is also representative of, and can serve as a model for, other bays and semi-enclosure areas in Thailand, which are under competitive use.

Although a considerable numbers of factors are involved in aquaculture site selection (Lovatelli, 1988a; Salam, 2000), water and sediment qualities are the main focus of this study because they play an important role in farming of both targeted species, acting as the culture medium, providing a living substrate and also pole support for mussel culture. As a result, the study area is limited to the water space within the bay described in Section 4.1.

7.2 Water and sediment qualities

Water and sediment information were obtained from both field sampling and secondary data. Field sampling data was used as a baseline to illustrate existing ecological characteristics of the bay and was applied as an input for data layer construction. Water quality was mainly addressed because it is the culture media for both targeted species. Sediment is much more important for cockle than mussel because, for the mussel, it is only relevant for supporting poles.

A correlation matrix among average mussel growth and 12 water parameters (Table 5.20) showed a strong positive relation between mussel growth and salinity (0.91), TDS (0.91), temperature (0.79) flood current (0.74), pH (0.73) and ebb current (0.70), but revealed negative correlations with chlorophyll-a (-0.14) and POM (-0.54.). Additionally, these water parameters showed a correlation value of >0.70 among themselves, confirming the high correlation between water parameters, and between water parameters and mussel growth. This observation is similar to some previous reports which found a relationship between water parameters and mussel GSI (Lee, 1988), total length (Parulekar *et al.*, 1982), condition index (Brown & Hartwick, 1988) and young mussel settlement (Nilkerd, 2001)

Statistically, the relationship between environmental parameters and mollusc growth is more likely to be site specific. For example, chlorophyll-a shows positive relationship to mussel total weight (Rivonkar *et al.*, 1993), live weight and shell length (Karayücel *et al.*, 2010). However, the chlorophyll-a also shows a negative relationship to mussel growth (Blanchette *et al.*, 2007), which is similar to the present study.

For sediment, although no correlation value between sediment parameters and the growth of the target species are reported, the range of some sediment qualities in an experimental site (Bhramchu-em & Jitphakdee, 2009), farm areas (Silas *et al.*, 1982; Tookwinas *et al.*, 1986; Hansopa *et al.*, 1988) are available for comparison with the sediment parameters in this study.

7.3 Mussel growth determination and mussel harvestable area

From the growth trial, spatially, mussel can survive in almost all areas of the bay, ranging from the fresh water prone area at the East end of the bay to the bay opening. Mussel growth rate between growth trial stations revealed significant differences after one month of the rearing period. Some of mussels reached a marketable size at the end of the trial. Thus, the growth determinants, the suitable culture sites and the harvestable area are valuable information provided from the current study.

7.3.1 PCA and mussel growth determination models

As already shown, environmental parameters in the bay show high inter-correlation while the relation of those to mussel growth are more likely to be site specific. The application of the PCA in this study can be considered in three phases; (1) data pre-processing and transformation/standardization, (2) PCs and MPCs extraction, and (3) WQs identification. Outputs from these are then applied for PCR and MLR models for mussel growth rate prediction.

PCs and MPCs extractions were based on 7, 9 and 12 water parameters data sets. Total PCs of each data set was equal to its total parameters while the numbers of MPCs varied. The MPCs of the three data sets was 2, 3 and 3 MPCs, respectively (Table 5.21-5.23). The total MPCs of each data set accounted for 78%, 83% and 84% of the total water quality variation of each data set and the first MPC alone of each data set accounted for approximately 51%, 61% and 58% of the total water quality variation. From all data sets, three WQs comprising salinity, chlorophyll-a and POM, were identified. The POM was found from the 12 parameter data set only.

The PCA application for data simplification, grouping and exploratory variable pre-processing/selection to avoid problem of collinearity was established by Pires, Martins, Sousa, vim-Ferraz, & Pereira (2008). Additionally, the PCA provides more ecologically meaningful outcomes than some data handling and transformation methods, such as log(x+1) and standardizing to 0 mean and 1 variance (Cao *et al.*, 1999). The outputs of this were also used in the subsequent steps of PCR and MLR model formulation.

The number of MPCs obtained from this study is similar to other studies, such as 4 MPCs, accounting for 80% of total variation of 12 water parameters in Hong Kong

(Lee, 1988), 3 MPCs accounting for 65% of total variation of 10 water parameters in India (Joseph & Ouseph, 2010), and 5 MPCs, accounting for 56% of total variation of 16 water parameters (Çamdevýren *et al.*, 2005). The MPCs of the current study explain a higher percentage of the total water quality variation than that of the previous studies, with the exception of the study by Sasikumar & Krishnakumar (2011) who extracted 3 and 4 MPCs from 2 different areas and obtained 2 set of MPCs accounting for 87% and 85% of the total variation of 12 water parameters.

PCR models using all PCs from the 7, 9 and 12 water parameter data sets showed R^2 of 90-92% while the PCR models using only MPCs had an R^2 of 75-76%. Some PCR model applications have been reported previously, for example, a PCR model using 4 MPCs explained 54% of gonosomatic index (GSI) of mussel (Lee, 1988), and a PCR model using 5 MPCs predicted 56% of chlorophyll-a concentration and the prediction capability increases to 91% when 16 PCs is employed (Çamdevýren *et al.*, 2005). The PCR models from the present study showed higher R^2 than those of previous studies.

MLR models using WQs showed R^2 values of 83-85% (Table 7.1.). In summary, the major mussel growth rate (Y) determinations in Pattani Bay were salinity (SAL), chlorophyll-a (CHL) and particulate organic matter (POM). Salinity was considered as the best single mussel growth determination, and could account for 84.43% of the total variation of mussel growth. Simple regression models of the other lesser important water parameters, such as TDS, temperature, pH and flood current, had R^2 values of 55-83% (Table 5.33)

Table 7.1. Mussel growth model using the major water parameters

MLR and Simple regression models	Coefficient of determination (R^2)
Y = 1.4193 + 0.1409*SAL - 0.0322*CHL + 0.0060*POM	85.18%
Y = 1.5546 + 0.1350*SAL - 0.0291*CHL	84.92%
Y = 0.199049 + 0.135382 SAL	84.43%

Note: F-values of all models are significant at α <0.001

In comparison to other studies, POM and chlorophyll-a is involved in mussel condition index prediction models (Sasikumar & Krishnakumar, 2011) while salinity is applied as one of the mussel growth predictors (Parulekar *et al.*, 1982). An additional predictor reported by the two previous studies is temperature. All 3 models obtained from the current study shows higher R^2 than that of the previous two studies, at 56% and 39%, respectively. For oysters, salinity, chlorophyll-a and temperature are included in a dry weight condition index (DWCI) prediction model while that of volumetric condition index (VCI) was best predicted by temperature, salinity and whole oyster weight (Brown & Hartwick, 1988). These two models have R^2 values of 41% and 39%, respectively.

Focused on an individual predictor of this study, an increase in POM and salinity resulted in mussel growth rate increasing while chlorophyll-a had an inverse relationship. The positive relationship between salinity and the mussel growth rate found here can be explained by the trend of average salinity in the bay, which gradually increases from the East end to the bay opening (Fig 4.17). This is similar to the trend of the mussel growth rate (Fig 4.30) while the POM shows almost similar trend, except at the area of the two river mouths (Fig 4.16).

As found in this study, the POM has a positive relationship to shell length and live weight of mussel, but an inverse relationship to dry meat weight (Karayücel *et al.*, 2010). Salinity also has a positive relationship to mussel length (Parulekar *et al.*, 1982), but a negative relationship to mussel GSI (Lee, 1988), mussel growth (Rivonkar *et al.*, 1993), mussel DWCI and VCI (Brown & Hartwick, 1988).

Chlorophyll-a represents a proxy for phytoplankton quantity, considered an important food source of many bivalve species (Inglis *et al.*, 2000; Mazzola & Sarà, 2001). It shows a negative relationship to mussel spat settlement (Nilkerd, 2001), mussel growth (Blanchette *et al.*, 2007), mussel GSI (Lee, 1988) and dry meat weight (Karayücel *et al.*, 2010). In contrast, some reports note that it has a positive relationship to mussel weight (Rivonkar *et al.*, 1993), mussel DWCI (Brown & Hartwick, 1988), mussel mean shell length and live weight (Karayücel *et al.*, 2010).

The application of MLR together with PCA has been described by Çamdevýren *et al.* (2005) who found that 5 MPCs could explain 56.3% of chlorophyll-a variation. When all 16 PCs were included in their study, the prediction success of the model increases to 90.8%. The PCA extraction of water quality variation in riverine (RI) and remote riverine (RR) sites from 12 measured parameters found 4 and 3 MPCs, respectively. These 2 sets of MPCs could account for 87% and 85% of total water quality variation in the corresponding site. The first two MPCs from both areas explain 60% of the total water quality variation. Temperature, POM and chlorophyll-a are the main predictor for green mussel condition index (CI) while temperature explains 35% of the mussel CI variation, increasing to 52% and 63% by including POM and chlorophyll-a, respectively (Sasikumar & Krishnakumar, 2011). A PCR model using 4 MPCs, was responsible for 80% of water quality variation and could predict 54.3% of mussel GSI (Lee, 1988)

7.3.2 Mussel growth and mussel harvestable area

In the mussel growth experiment, initial mussel seeds at the size of 2.56±0.25 cm, 1.39±0.15 cm and 1.69±0.36 g in total length, height and weight, respectively were reared in 7 different locations in the bay until mussels started to reach marketable size. Progressive growth functions of mussel were formulated based on linear and logarithmic functions using the Julian date as an explanatory variable. The harvestable area of mussel was calculated at 10 day intervals until all mussels could be harvested.

Although many water parameters relate to mussel growth, as mentioned earlier, and the water quality data set from field sampling is available to identify the mussel suitable sites by MCE, as for cockles, the current study employed only salinity, water depth and shipping routes for suitable site evaluation. This was because the salinity alone is capable of predicting 83.4% of the mussel growth rate.

Progressive growth functions (Table 5.12 and 5.13) revealed R^2 values of 93.54 to 99.98%. All growth functions were incorporated into IDRISI through the Database Workshop to transform all functions' parameters, coefficients and constant values into raster files. The periodical harvestable areas could then be estimated using the Macro Modeler and DynaLink within IDRISI environments.

The harvestable period for mussels obtained from all progressive growth functions was during 12 October-21 November 2009 (or months 3-5 of the rearing period) and more than 80% of mussel in potential culture sites could be harvested by the end of October. All mussels in the potential culture area were able to be harvested by the middle of November. However, if evaluated by mussel length only, all mussels cold be harvested by the end of October (Fig. 5.22). This proposed mussel harvesting period can avoid low salinity risks caused by heavy rain which occur from October to December (Hemsuhree, 1997).

Mussel harvestable area prediction by mussel length seems to be the most suitable option for many reasons. Besides the fact that it is easily observed in the field, mussel pricing depends on size classes (from the survey) and mussel weight fluctuates over time (see Karayücel *et al.*, 2010). This is confirmed by bi-phasic regression growth functions of mussel growth by meat weight in two culture periods; 0-164 and 164-170 days. The R^2 of each period function is 43% and 53%, respectively (Rivonkar *et al.*, 1993) as well as growth function by meat and total weights in two culture periods; 1-180 day and 180-365 day) which has R^2 values of 94-99% (Rajagopal *et al.*, 1998b). The bi-phasic mussel growth function by length does not exist in cultured mussel in Pattani Bay (Brohmanonda *et al.*, 1988b) as well as in Muttukadu, India (Sreenivasan *et al.*, 1989) during 9-12 months period. The R^2 of linear and logarithmic functions at both sites are very high, ranging from 92 to 98%. The maximum total lengths of mussels from 12 and 9 months culture period are 10 and 5-6 cm, respectively (Brohmanonda *et al.*, 1988b; Sreenivasan *et al.*, 1989). Condition index (CI) is an indicator describing the variation of mussel weight. Low CI caused by spawning activity is reflected in a decreasing meat yield (Campbell & Newell, 1998; Cheung & Shin, 2005) while mussel gamete formation results in meat and body weight increasing (Rivonkar *et al.*, 1993). This mean mussel growth evaluation by weight is influenced by the CI. Variation of the CI in Pattani Bay is quite high, ranging from 50.81 to 98.76%. The lowest CI being found in October (Niyomdecha, 2009).

Based on the study of Nilkerd (2001) and Niyomdecha (2009) the mussel seed used this study was approximately 2-3 months old (after spat settlement). When the rearing period of at least 3 months and another 2 months extended for harvesting are included, the total rearing period to marketable size including spat collection is around 6-8 months. The rearing time of this study was comparable to that found in Pattani Bay by (Brohmanonda *et al.*, 1988b) and in India (Sreenivasan *et al.*, 1989) where the rearing period from an initial seed size of ~20 mm in length to the size of ~6 cm was 6 months. Moreover, Rivonkar *et al.* (1993) also reported that the rearing of mussel from 3.0-8.0 mm in length (1-2 weeks old) to marketable size took 164 days.

However, the mussel growth data in the current study was obtained from only a small number of culture poles. Some effects from large quantity mussel culture are not included, such as food depletion (Grant, Curran, Guyondet, Tita, Bacher, Koutitonsky, & Dowd, 2007) , seston depletion, feeding competition, current flow alteration, food particle distribution (Widdows & Navarro, 2007; Aure, Strohmeier, & Strand, 2007), water quality, lower growth rate and lower carrying capacity of culture location (Inglis *et al.*, 2000; Aure *et al.*, 2007). It can be assumed that the growth rate from a small mussel population, as in the current study, may be a little better than that in real farming conditions, which is able to be affected by the previously mentioned phenomena.

7.4 Suitable cockle culture area

Overall water suitable area for cockles was 41 km^2 with temporal seasonal change of ~44-58 km^2 (or 75-100% of the total water space). Less suitable areas from this were mainly found at Yaring River mouth; follow by minor areas at Pattani River mouth and nearby the Industrial zone (Fig. 6.13 and 6.14). The main factors contributing to lower suitability were low salinity (2-14 ppt), pH (≤7.0), transparency (<15 cm) and POM (60-149 g/kg). The highest coverage area of low salinity was up to 25% of all water space.

The influence of low salinity on the water quality in the bay in this study is consistent with the fact that salinity is the major factor affecting water quality in riverine areas (Sasikumar & Krishnakumar, 2011) and cockle culture near the river mouth is mainly influenced by river flow (Kimura, 1992). Water discharge not only results in low salinity, but also supplies plant nutrients, such as nitrogen. Additionally, the bay mouth is always affected by salinity and shows high salinity and chlorophyll-a (Gobler, Cullison, Koch, Harder, & Krause, 2005).

Salinity affects cockles in many ways, such as valves opening, osmotic pressure, feeding and mortality (Tookwinas, 1985; Davenport & Wong, 1986) and this was confirmed by the positive correlation of salinity to cockle CI of 0.83 (Nudee & Mahasawat, 2007) and to cockle scope for growth of 0.72 (Din & Ahamad, 1995) . From Table 5.20, salinity has a negative correlation with POM (-0.6), but not with transparency (0.4) and water depth (0.5). This confirms that high POM and low transparency are found in low salinity and shallow areas.

Water pH shows a positive correlation with cockle scope of growth (0.68) (Din & Ahamad, 1995). In the bay, this is presumably caused by waste water discharge as found in the inner Gulf of Thailand (Brohmanonda *et al.*, 1988b) as well as Mae Klong and Petchaburi Rivers (Tookwinas, 1983). Oxygen depletion, low water quality stability and slow growth as well as low survival rate of molluscs are the possible consequences of polluted water discharge (Tookwinas, 1983; Office of Agricultural Economics, 2009). The lowest pH found in the bay in this study is very close to the reported value of 6.96-9.02 in shallow water areas in the bay (Pianthumdee, 2004).

The area of suitable sediments covered almost all the bay, except for the East end of the bay, some areas along the northern coastline until Laem Tachi and a tiny area at the Pattani River mouth (Fig. 6.17). Vulnerable sediment factors were sand particles, which co-existed with low organic matter and silt particles. An additional vulnerable factor was low sediment pH (<6.5), found at the East end of the bay area (Fig 6.15).

Most of the areas with high sand particles in the current study are consistent with sand deposition are in the bay (Predalumpaburt & Chaiyakam, 1994) as well as Pitaksalee, Khongpuang, & Promdam (2003b) who reported that the main sediment types of the bay were silty clay loam and silty clay while the minority was sand, loamy sand and sandy loam, which is found in the northern coastline.

The constraint sub-model produced a suitable area ~36 km^2 and the most exclusions being due to water current and depth. These were important mainly near the bay opening to Lighthouse to offshore of Industrial zone (Fig 6.18). Shallow water area near the shoreline and deep areas at the middle part of the bay opening were included (Fig 6.19). At water current velocities of 0.05-0.45 m/s, there is no effect on the cockle clearance rate, but higher currents will move cockles along the bottom surface (Widdows & Navarro, 2007). This is one of the reasons for the lower suitability of the bay mouth area in this study.

The final model revealed an overall suitable cockle farming area of 13 km^2 located around the middle portion of the bay (Fig 6.23). Based on this area, the possible vulnerable factors would be water current, salinity and pH. When comparing the final output of the model to existing cockle farms of around 13.7 km^2, 75% of the culture area was located in the suitable area. There is a scope for farm relocation in order to optimise sites and to avoid possible production lost by low salinity. Moreover, comparison between water and sediment sub-model outputs for the existing cockle farms found that the percentage of existing farms covered by the suitable sediment area was higher than that of water suitable area. This may be because of the general characteristics of sediment, such as muddy or sandy, which can be easily observed by farmers rather than water quality, which require more skills and equipment.

In summary, water parameters play an important role in site suitability for cockle more than that of sediment. Of all 10 water parameters (including current and depth), salinity and water current were the most important factors follow by water pH while some parameters; DO TSS and chlorophyll-a had little or no effect. For the sediment parameters, sand particle content was the most prominent factor, which is also a surrogate for both low silt particles and low organic matter.

7.5 Overall summary and discussion

Based upon the overall study processes and outputs from the current study, suitable culture area identification can be evaluated by at least two approaches:

- The first is the minimalist approach. Analytical processes start by determining major parameters considered as the best representation for all water parameters (such as the salinity in this study). Thereafter, the major parameters are combined with other necessary physical parameters to evaluate the suitability of sites. In this context, PCA is considered a useful tool for both parameter selection and multi-collinearity evaluation. This approach was used in selecting optimised sites for mussel culture.
- The second approach uses all obtained ecological parameters and related secondary data of the targeted species for modelling using the fuzzy classification (or the conventional reclassification method) and combines them using Multi-Criteria Evaluation, as was used in the optimization model for cockle culture areas.

Technically, there is no doubt for some analytical techniques, such as PCA, PCR, MLR and MCE to deal with a large and comprehensive data set as was confirmed in a literature review including in this study, but the minimalist seems to be a better choice. An obvious example is the application of the PCA, PCR and MLR together with environmental parameters for mussel growth prediction. The using of multiple water parameters through the PCA and PCR application provides better prediction capability (R^2), but this approach is not practical when compares to the application of PCA and MLR, which can formulate prediction model by a few key parameter (WQs) and provide acceptable R^2. The WQs, in this study, also simplify the process of mussel suitable site identification, which can formulate by overlaying, instead of using MCE as that in cockle. There are some evidences from this study that support the benefit of data minimisation. The first is mussel growth shows some high correlation value to some water parameters while autocorrelation between water parameters is also exist (Table 5.20). The second evidence is some parameters including cockle MCE have no effect on site suitability for cockle. These two evidences confirm that some parameters can be ignored and some few parameters can represent the others.

This study provides systematic decision support systems and spatial outputs for mussel growth determination, mussel harvestable area, and mussel and cockle suitable culture areas. Additionally, vulnerable parameters for the target species farming and practical surrogate parameters for site selection are identified and located spatially. For cockle site selection, the surrogate parameters are water current, salinity and pH while that for mussel is salinity. These parameters have a robust mathematical basis and are easy to monitor in the field using affordable tools.

Comparision between the suitable sea farming area in the bay reported by Predalumpaburt & Chaiyakam (1994) to that of the current study, it shows similar results. The suitable cockle culture identified in the former study was between Laem Nok and Tanyong Lu Lo villages while the current study model output included those sites and other potential areas. The former study found small areas suitable for fish cage and mussel culture at upper part of the bay opening, whereas the present study identified a much bigger area. The modelled outputs of suitable cockle culture areas covered 75% of the existing farm areas and this congruency partially validates the model findings and indicates the capability of GIS application for aquaculture and natural resource management as has been repeatedly mentioned (see Ross, 1998; Nath *et al.*, 2000; Longdill *et al.*, 2008).

Generally, the suitable mussel farming area was in deeper water from offshore of Leam Nok to the bay opening while that for cockles occupied the middle portion of the bay. Spatially, the suitable cockle and mussel culture areas showed complementary relation, although some overlapping areas were suitable for the both species. In summary, the suitable area for cockle culture was ~13.20 km^2. That of mussel was ~9.75 km^2 and the overlapping area was ~3.53 km^2 (Fig. 7.1).

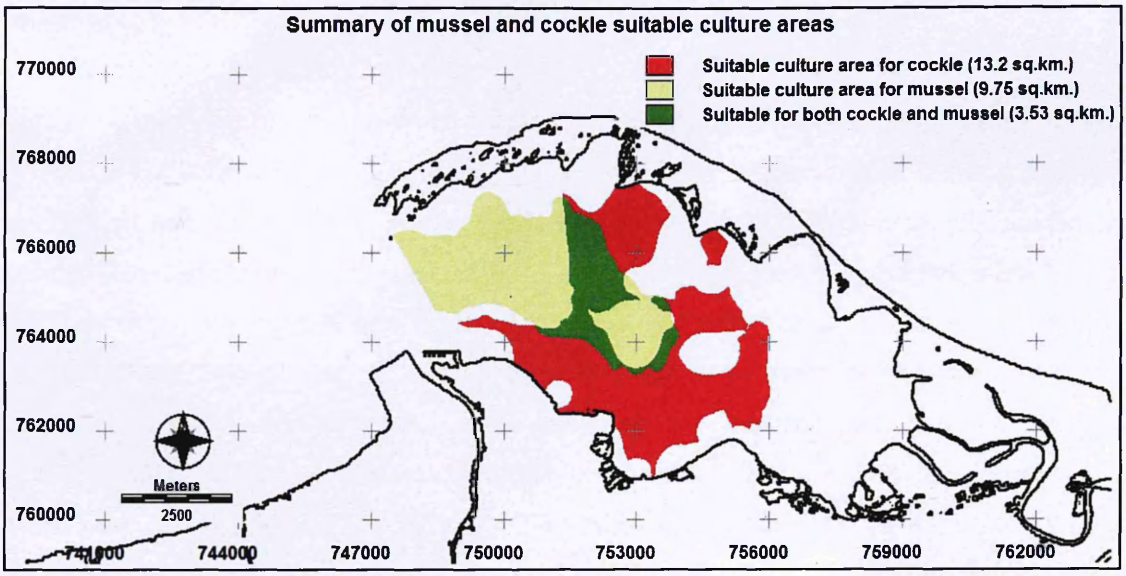


Fig. 7.1. Summary of mussel and cockle suitable culture area in Pattani Bay.

When comparing these areas to the bay fishing grounds (Sukansil, 2000), natural sea grass sites (Fig. 2.15) (Hengchuan, 2004), natural seaweeds areas (Fig. 2.12 and 2.13) (Ruangchuay *et al.*, 2004; Pianthumdee, 2004) and the field survey (Fig. 2.26), the conclusions can be summarised as the follows:

- The suitable mussel farming area is located separately from the natural sea grass and seaweed sites. This results from the required water depth of >1.5 m determined for suitable mussel sites while the water transparency of the seaweed sites is 10-87 cm (Pianthumdee, 2004). The suitable mussel culture sites overlap with crab fishing grounds (Fig 2.16) and in this case, mussel pole culture may cause a problem for crab gill net operators.

- The suitable cockle culture area covered some natural seaweed sites near Talo Samilae and Budee, principally due to shallow water. Moreover, seaweed and sea grass can survive in a wide salinity range of 7-26 ppt and in various sediment types, such as silt, silt clay, silty clay loam, silty loam, loam, loamy sand, sandy loam and sandy clay loam (Hengchuan, 2004) while the reported sediment types for cockle are silty clay (Tookwinas *et al.*, 1985a; Hansopa *et al.*, 1988; Lovatelli, 1988a), silty loam (Tookwinas *et al.*, 1986; Thamasavate *et al.*, 1988), sandy loam (Bhramchu-em & Jitphakdee, 2009). For fishing activities, based on Sukansil (2000), the suitable cockle culture area occupied some shrimp, fish and crab fishing grounds. However, bottom culture generates only a few problems on main fishing gear operation (gill net and trammel net).

Other than serving for the mentioned activities, the bay is a nursing ground and habitat of over 90 species of mollusc (Pitaksalee *et al.*, 2003b; Pitaksalee *et al.*, 2003c), 108 species of fish (Hoecharoen *et al.*, 1998; Hajisamae *et al.*, 2006) and 13 species of shrimp (Hajisamae *et al.*, 2006). These are existing components in the bay's food web. Establishing more mussel and cockle farms will not only occupy physical space, but also increase energy flow pathways (see Gibbs, 2007) including creation of other possible impacts on the bay ecology, such as seabed organic enrichment, hydrodynamic alteration and competition with natural benthic habitats (see more McKindsey *et al.*, 2006). In terms of the natural food supply, mean chlorophyll-a concentration found from the current study would ensure food sufficiency for the both targeted culture species and other organisms in the bay. The chlorophyll-a concentration in the bay is considerably higher than that previously reported from the same bay (Tookwinas *et al.*, 1987), and other mussel culture sites in many places; Pattani and Chachoengsao Provinces (Tookwinas *et al.*, 1985b), Singapore (Cheong, 1982), in India (Rajagopal *et al.*, 1998a; Rajagopal *et al.*, 1998b; Rajagopal *et al.*, 2006a) as well as from cockle culture sites in Thailand (Thamasavate *et al.*, 1988; Nilkerd, 2001; Kaewnern & Yakupitiyage, 2008).

Other than being the natural food source, chlorophyll-a levels of $>20\text{-}\leq 60$ µg/l and >60 µg/l, are classified as high level and hypereutrophic waters, respectively (Bricker *et al.*, 2003), and existing levels are enough to generate plankton blooms and eutrophication in the bay. The consequences of this could result in mortality of living organisms (Peperzak & Poelman, 2008). Additionally, the reported soluble phosphorus of >0.25 mg/l in the bay (Predalumpaburt & Chaiyakam, 1994; Hengchuan, 2004) may also contribute to eutrophication because phosphorus levels of ≥ 0.1 mg/l are considered high (Bricker *et al.*, 2003). Furthermore, the bay receives plant nutrients from a huge catchment area of 4,388 km^2. As a result, the targeted species farmed in the bay, through their filter feeding, may help to reduce or prevent the eutrophication (Bricker *et al.*, 2003; Ferreira, Hawkins, & Bricker, 2007) and build up of organic waste (Mazzola & Sarà, 2001).

Although some studies have been published on the application of ecological models, which can evaluate the physical and biological interactions including possible impacts on habitat carrying capacity caused by farming (Duarte, Meneses, Hawkins, Zhu, Fang, & Grant, 2003; Sequeira, Ferreira, Hawkins, Nobre, Lourenτo, Zhang, Yan, & Nickell, 2008; Ferreira, Hawkins, Monteiro, Moore, Service, Pascoe, Ramos, & Sequeira, 2008; Ren *et al.*, 2010; Silva *et al.*, 2011), the modelling processes are very complicated, have huge data requirements, and demand much time and technical input. Thus, it is not a simple matter to adopt such models, especially where these data is limited as Pattani Bay.

Mussel and cockle farming in Pattani Bay has an opportunity for further development, particularly due to the ecological suitability of the area, presence of experienced farming personnel, market acceptability, and the opportunity for earning additional income and food security for farmers. For cockles, the extension of farm areas is more likely to be limited. However, to deal with cockle seed shortage and effective limited seed utilisation, cockle farm relocation should be considered. For mussels, natural seed availability and culture technique are not a barrier for farming, but physical occupation of water space may create an opportunity cost on other fishing activities. The targeted species farming in the bay not only provide direct benefit through aquaculture production, more food and income sources, but may also have indirect benefit by preventing some adverse impacts from eutrophication, which is likely to occur in the bay.

Of all processes in this study, obtained outputs meet all main three objectives by the helping of GIS technology. The practical mussel growth determination parameters are defined. At least, some questions; "Where are the suitable sites for cockle and mussel culture?" and "Where and when mussel can be harvested?", are solved and illustrated spatially. Spatial output illustrated in this study is more meaningful when compares to that of mathematical models because it is easy to be understood by a many people, ranging from a policy maker to local fish folks. This study outputs will contribute a better spatial management, which may support a sustainable use of the bay in the future. Moreover, the GIS technology is shown to be a powerful decision support tool for temporal and spatial analyses, multi-criteria analysis and multi-decision making. At least, this technology facilitates spatial modelling with a series of beneficial outputs, which can provide some information for the bay management and support mollusc farming, not only in Pattani bay, but also elsewhere in Thailand and Southeast Asia.

7.6 Further recommendations and implication of this study

Some recommendation that should be included in the following study based on the priority can be summarised as follows.

Production estimation models for cockle and mussel in the bay or farm levels can be developed by using more farming parameters; stocking density, survival and growth rates. These can be extracted from secondary data or field sampling from the existing cockle farms. A similar approach has been used for natural clam production models (see Vincenzi *et al.*, 2006).

The production estimation model can clearly be extended to include an economic feasibility model for commercial culture. The investment and operating costs can be simply investigated as well as the return, which can be estimated using from proposed production. Using this data, total physical product (TPP), average physical product (APP), marginal physical product (MPP) and optimal production level can be evaluated (see Silva *et al.*, 2011). By including this concept, both physical and economical suitability area may be identified and trade-offs among competitive activities, such as fishing and aquaculture (mussel and cockle culture), can be evaluated.

Using the same study protocols as in this study, suitable site and spatial distribution of other prominent resources in the bay, such as seaweed and sea grass, could be established. These could be modelled to enable more holistic and sustainable bay management. Furthermore, this can be applied for the other bays in Thailand, where cockle and mussel farming is possible, such as Nakhon Bay, Bandon Bay and Sawi Bay, including other semi-enclosed and river mouth areas.

High heavy metal, such as Pb, concentrations have been reported in some areas of the bay (Sowana *et al.*, 2010). The spatial distribution and accumulation of such harmful factors in the environment and in the targeted species could also be included in suitable culture site modelling. Although a considerable numbers of cockle and mussel could be produced, this would be of little value if the consumers are at risk from heavy metal contamination in cockle or mussel.

However, adoption of the study approach and results needs to encompass more interrelations between culture activities, subsequent environmental and social impacts.

(Dumbauld *et al.*, 2009) summarised the possible impacts of bivalve culture on environment, and classified them into 3 groups; biological processes, physical processes and pulse disturbances. The physical process may disturb water flow because of farm structures. The biological process, for example feeding activity, could affect phytoplankton and nutrient deposition. Site preparation and harvesting are examples of pulse or short term events which may affect benthos and sea grass beds.

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