GIS-based modelling of agrochemical use, distribution and accumulation in the Lower Mekong Delta, Vietnam: A case study of the risk to aquaculture.

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For the degree of Doctor of Philosophy

By

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STATEMENT OF ORIGINALITY

I declare that the work contained in this thesis conducted independently by my own, and it has not been submitted to any other degree. All materials used in the dissertation has been acknowledged and cited.

Signature of candidate

Long Kim Pham

30th November 2012

ABSTRACT

In recent years, the Mekong delta has been strongly developed both for agriculture and aquaculture. However, there is scope for a negative impact of agriculture on aquaculture in term of production and quality of seafood products. Specifically, the large amount of pesticides imported and used in the Mekong delta not only help agriculture purposes but can also easily enter aquatic systems and affect aquaculture. Pesticides can be transported in the environment by chemo-dynamic procedures and hydrological processes. As a result, pesticides used in agriculture become dispersed and their residues in sediment, water and biota have been detected in the Mekong delta. This study investigated the overall pesticide process including pesticide use, modelling pesticide accumulation and evaluating the potential impact on aquaculture sites for some target aquatic species.

The risk of pesticides use in the Mekong delta was addressed in three stages: (1) investigating current pesticide use status in the Mekong delta; (2) modelling pesticide loss and accumulation; (3) classifying pesticide risk areas for aquaculture of target cultured species.

A survey of 334 farms covering a total area of ~20,000km^2 in the Mekong delta took place between 2008 and 2009. Information on pesticide types and quantities was recorded using questionnaires, and it was found that 96 pesticides in 23 groups were popularly used for agricultural purposes. Dicarboximide, Carbamate and Conazole had the highest use at ~3000, ~2000 and ~2000 g/ha/year respectively. The survey revealed an increase in pesticide use per hectare since previous surveys in the Mekong delta in 1994, 2000, and 2004. However, the highly persistent compounds (WHO classification classes II, III and IV) appeared to have reduced in use. Insecticides previously represented >50% of the total pesticides used, however, the resent survey has shown their use has decreased to ~38%.There was a parallel increase in use of fungicides from previous levels of <30% of total pesticides to more recently ~41%. The combination of pesticide information and geo-location data enabled display and analysis of this data spatially using a Geographic Information System (GIS).

A pesticide loss and accumulation model was established through combination of several sub-models including sediment loss and accumulation, direct loss, and water runoff, all of

which were implemented and integrated within the GIS environment. MUSLE (Modified Universal Soil Loss Equation) was used to estimate sediment loss and accumulation in the Mekong delta and the Curve Number method (CN Method) was applied to predict water runoff and discharges and flow accumulation. Modelling commenced from the first pesticide application in April, based on 4 day time-steps. All mathematical calculations run within each time step automatically reiterated in the following time step with the new input datasets. The results from fuzzy classification of the pesticide model outcomes were considered in terms of the 96hr lethal concentration (LC_{50}) in order to classify the risk and non-risk areas for catfish and tiger shrimp culture.

The sediment loss and accumulation model shows that the highest loss of sediment was in the rainy season, especially in May to October. Vegetables and short term crop areas were found be most strongly eroded. The MUSLE model showed that the highest sediment accumulation was in the hilly areas (~1066.42 tonne/ha/year); lower in riverside areas (~230.39 tonne/ha/year) and lowest in flooded paddy areas (~150.15tonne/ha/year).

Abamectin was used as an example throughout this study to estimate pesticide loss and its effects on aquaculture. The results showed that pesticide loss by runoff and sediment loss is less than the loss by half-life degradation (for Abamectin specifically). Accumulation of Abamectin occurred at highest rate in May and October and decreased with time. The spatial models showed that pesticide residues concentrated in the river and riverside areas.

In order to evaluate the acute toxicity impacts, three levels of water depth in ponds were modelled as culture depths for catfish and tiger shrimp. The results show that the highest risk areas for catfish occurred in May and October with ~333,000 and ~420,000 ha at a pond depth of 0.5 m; ~136,000 and ~183,000 ha at a pond depth of 1.0 m; and ~10,840 and ~19,000 ha at a pond depth of 1.5 m. Risk areas for catfish mainly concentrated at the riverside and in part of the coastal areas. For tiger shrimp, the risk periods during the year were similar to those found for catfish. The highest risk areas for shrimp were ~648,000 and ~771,000 ha at 0.5 m pond depth; ~346,000 and ~446,700 ha at 1.0 m pond depth; and ~185,000 and ~250,000 ha at 1.5 m pond depth. Overall, deeper ponds reduced the risk.

This study has developed a method to evaluate the negative impact of input pesticides to the environment from agricultural use related to fluctuation of aquaculture risk areas. The research indicates the potential relationship between pesticide input and the risk areas for aquaculture. The model has several significant uses: 1) it can provide information to policy makers for a more harmonized development of both aquaculture and agriculture in the Mekong delta in the future, 2) it provides data for aquaculture investment analysis to decrease the hazards caused by pesticide impacts, and 3) it provides a model capable of application to wide field scenarios and suitable for any pesticide type.

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General introduction

1.1 World fisheries and aquaculture

In recent years, there have been criticisms about the development of aquaculture which in some cases has caused negative impacts on the wild fish production. Naylor and colleagues specifically illustrated a case of lost wild fish production which had been effectively converted to the yield from aquaculture (Naylor, Goldburg, Primavera, Kautsky, Beveridge, Clay, Folke, Lubchenco, Mooney, and Troell, 2000). However, regardless of these negative views, aquaculture still needs to develop strongly in order to fill the growing fish supply gap, which is estimated to be of the order 82 million tonne (FAO, 2010). Moreover, aquaculture is considered as a feasible way to secure and maintain protein resources (Bondad-Reantaso, Subasinghe, Josupeit, Cai, and Zhou, 2012; Ahmed and Lorica, 2002). Indeed, aquaculture has gradually replaced capture fisheries and occupies a high position in the world seafood supply. Developing countries are potential target areas to develop aquaculture, produce rich protein resources and luxury aquatic products. Although global surveys have not yet been done, it is widely accepted that extensive aquaculture areas are always found in developing countries more than elsewhere (Pillay, 1973).

Many studies have illustrated how marine fish production has declined due to overfishing (Jiang, 2010; De Silva, 2003; Hannesson, 2003). An example of hundred year data on the biomass of fish in the North Atlantic Ocean combined with geographical data was mapped by David (2012) who showed that the biomass of fish in these areas decreased by two-third over 50 years (Christensen, Guenette, Heyman, Walters, Watson, and Zellar, 2003) (figure. 1.1). This dramatic reduction in yield underpins the timeliness of promoting aquaculture to compensate for over exploitation, aquatic production losses by environmental pollution and the effects of global climate change.

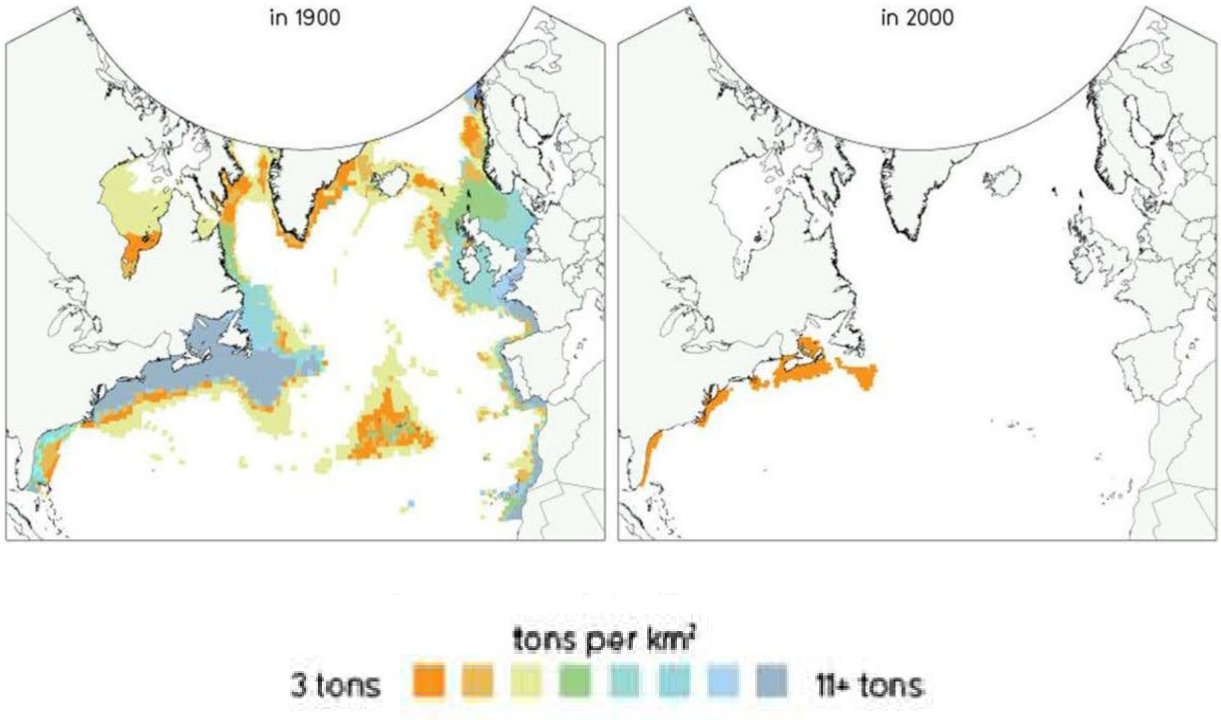


Figure 1. 1 An example fish biomass distribution of North Atlantic Ocean

1.2 Fisheries and aquaculture production in Vietnam

Vietnam has a large water surface for potential fisheries and aquaculture production, estimated at approximately 1.7 million ha (Ministry of Fisheries and World Bank, 2005). This comprises ~120,000 ha of ponds, lake, canals and garden fishponds; ~580,000 ha of paddies and mixed aquaculture and ~660,000 ha of tidal areas (excluding the areas of river, lagoons and bays).

In recent years Vietnam has had one of fastest fisheries and aquaculture production growth rates. Total fisheries and aquaculture production in Vietnam was less than 1 million tonne in 1990 but from 1993 production started to increase approaching ~1.78 million tonne in 1998 (figure 1.2). After that time, seafood production in Vietnam has increased sharply and hit over 5 million tonne in 2010.

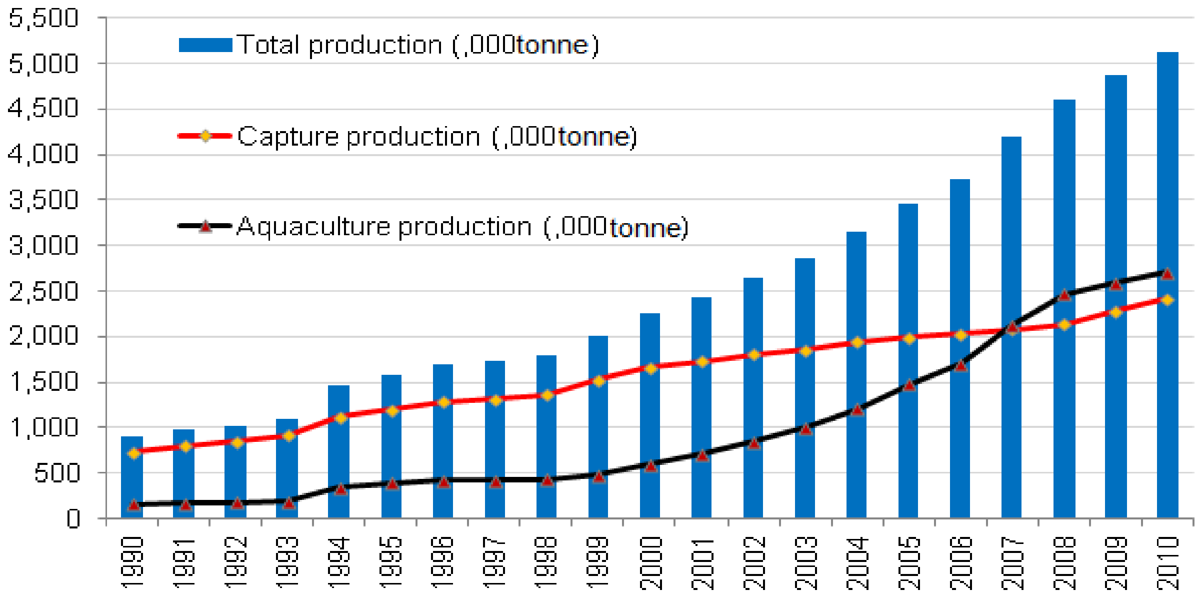


Figure 1. 2. Aquaculture and fisheries production in Vietnam

Source: GSO (2012a)

In 1990, production from capture fisheries was almost four times higher than the yield from aquaculture. Production of both has increased annually but, from a low base in 1990, aquaculture production has exceeded that from capture fisheries, at ~2 million tonne in 2007. Aquaculture now makes the most significant contribution to the national seafood production and reached ~2.7 million tonne in 2010 (figure 1.2).

Vietnam exported over 1.2 million tonne of seafood in 2008 to the international markets with a value of over US $4.5 billion in 2008. The key products for exporting were pangasius (32.2%), shrimp (36.1%), sea-fish (9.2%), Tuna (4.2%), cephalopods group (7.1%), and some others (VASEP, 2010). This recent growth has made Vietnam one of the largest seafood exporters in the world (FAO, 2004) with a large part of this now originating from aquaculture. Record from VASEP (2010) reveal the value and production of seafood from Aquaculture started to growth from the year 2000. Before this time, aquaculture contributed less than US $1 billion. Over the last ten years (from 2000 to 2010), aquaculture production and values in Vietnam increased over 5 times (figure. 1.3).

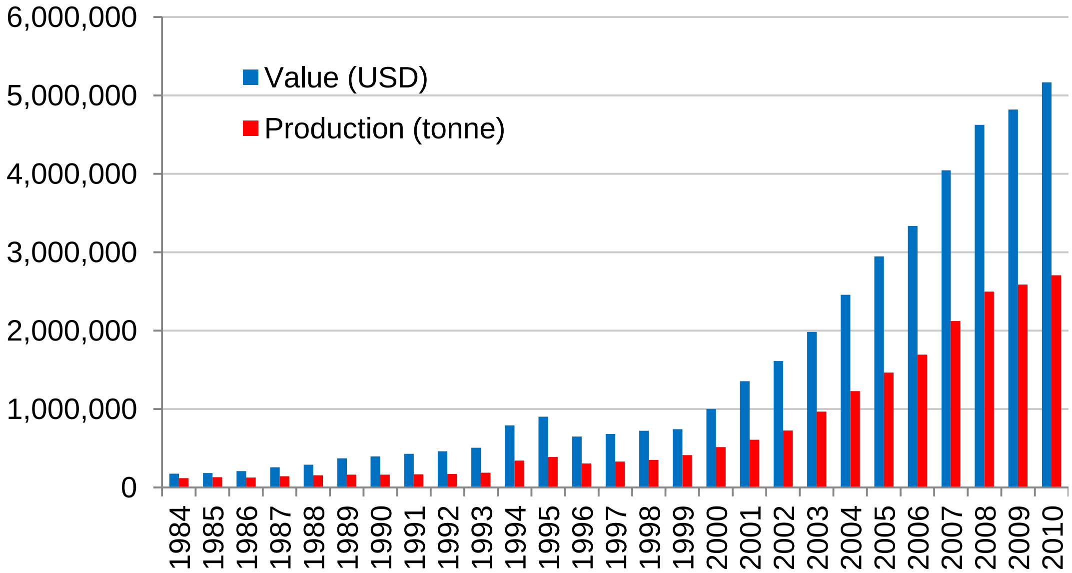


Figure 1. 3. Growth of Vietnamese aquaculture.

Source:(FAO, 2012a; VASEP, 2010)

Culture species

The key aquaculture species in Vietnam are shown in table 1.1. In fresh water, pangasius and catfish (Tra, Basa) dominate, alongside other species including carps, rohu, mrigal, and mono-sex tilapia. Vietnam also produces some high valuable marine species such as lobster, grouper, oyster and *Babylonia* species. Tiger shrimp are produced in southern Vietnam and production has increased sharply in recent years especially in some coastal areas in the north, the middle of Vietnam and in the Mekong delta (FAO, 2011).

Table 1. 1. Main aquaculture species in Vietnam and production.

Country, species		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Viet Nam											
Cyprinus carpio		...	...	...	...	...	...	...	...	75 000 F	109 800 F
Cyprinidae		...	...	...	...	...	...	...	...	340 000 F	497 900 F
Oreochromis(=Tilapia) spp		...	...	...	...	...	...	...	...	50 000 F	73 200 F
Piaractus brachypomus		...	...	...	...	...	...	...	...	6 000 F	8 800 F
Clarias spp		...	...	...	...	...	...	...	...	10 000 F	14 600 F
Pangasius spp		100 000 F	114 000 F	135 000 F	163 000 F	255 000 F	376 000 F	520 000 F	850 000 F	1 250 000 F	1 050 000
Osteichthyes		265 015	269 186	306 827	436 824	506 566	585 100 F	637 045 F	680 300 F	167 300 F	202 300 F
Osteichthyes		...	...	...	...	...	...	...	...	5 000 F	6 000
Macrobrachium rosenbergii		3 513	4 933	5 552	5 961	6 247	5 200	5 482	7 900	7 100	7 700
Panulirus spp		...	...	...	...	...	...	...	...	720	1 003
Penaeus merguiensis		18 002 F	31 107 F	35 397 F	40 000 F	40 000 F	40 000 F	40 000 F	43 000 F	8 100	38 697
Penaeus vannamei		...	...	10 000 F	31 717 F	40 000 F	100 000 F	150 000 F	153 000 F	38 600	36 000
Penaeus monodon		67 486 F	111 095 F	126 416 F	150 000 F	185 569 F	177 200 F	150 000 F	170 000 F	324 600	316 000
Penaeus indicus		4 501 F	7 777 F	8 849 F	10 000 F	10 000 F	10 000 F	9 000 F	10 700 F	10 000	11 000
Metapenaeus spp		...	...	...	...	...	...	...	...	...	9 000
Mollusca		...	...	...	...	...	...	...	...	...	9 200
Mollusca		40 000 F	50 000 F	75 000 F	100 000 F	155 235	143 800 F	146 200 F	170 500 F	170 000 F	165 000
Fish, crustaceans, molluscs, etc.	*Q*	*498 517*	*588 098 F*	*703 041 F*	*937 502*	*1 198 617*	*1 437 300*	*1 657 727*	*2 085 400*	*2 462 420*	*2 556 200 F*
Poissons, crustacés, mollusques, etc.	*V*	*991 318*	*1 345 713 F*	*1 599 449 F*	*1 968 331*	*2 443 589*	*2 930 650*	*3 316 142*	*4 028 050*	*4 605 610*	*4 802 712 F*
Peces, crustáceos, moluscos, etc.											
Gracilaria spp		15 000 F	20 000 F	25 000 F	30 000 F	30 000 F	30 000 F	36 000 F	38 000 F	35 700 F	33 600 F
Aquatic plants	*Q*	*15 000 F*	*20 000 F*	*25 000 F*	*30 000 F*	*30 000 F*	*30 000 F*	*36 000 F*	*38 000 F*	*35 700 F*	*33 600 F*
Plantes aquatiques	*V*	*7 500 F*	*10 000 F*	*12 500 F*	*15 000 F*	*15 000 F*	*15 000 F*	*18 000 F*	*19 000 F*	*17 850 F*	*16 800 F*
Plantas acuáticas											

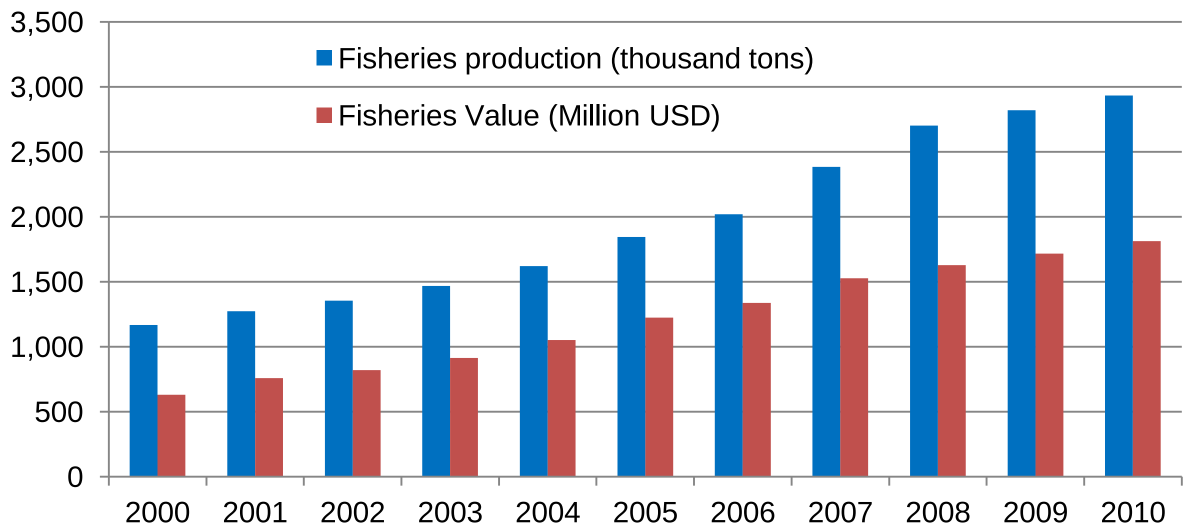
Source: FAO **(2009)**

... : Data not available
Q: quantity (tonne)
V: Value (,000 USD)
F: FAO estimate from available sources of information or calculation based on specific assumptions

1.3 Fisheries and aquaculture in the Mekong delta

The Mekong delta receives fresh water from the Mekong River, as well as strong tidal input from the South China Sea. Consequently, this area is highly suitable for development of fresh and brackish water aquaculture. Aquaculture systems are diverse and range from open to semi-enclosed rearing systems, and this sector is now considered as the main contribution to the regional income, after rice.

Total fisheries and aquaculture production in the Mekong delta approached nearly 3 million tonne in 2010, having almost tripled in the last 10 years. In 2010, seafood from Mekong delta contributed ~US $1.8 billion to the national economy), an increase of more than US $1.2 billion compared with 2000 (~ US $0.6 billion) (figure 1.4). The total area committed to aquaculture was ~ 660,600 ha in 2003 (Ministry of Fisheries, 2005) rising to ~753,300 ha by 2010 (GSO, 2012a).



Source: *General Statistics Office* (GSO, 2012a)

Figure 1. 4. Total aquatic production in Mekong delta

1.4 Environmental impacts from aquaculture

Although aquaculture produces almost half the world's supply of seafood for human consumption, there has been considerable debate about the negative impacts to the environment from effects including polluted water resources, destruction of original habitats, introductions of exotic diseases and loss of bio-diversity (De silva and Davy, 2009; World Bank, 2006; FAO, 2006; Naylor, William, and Strong, 2001; Naylor, Goldburg, Mooney, Beveridge, Clay, Folke, Kautsky, Lubchenco, Primavera, and William, 1998) . Theoretically, waste products from aquaculture which mainly contain nitrogen (N) and phosphorus (P) components are the main factors contributing to environmental pollution (Subasinghe, Soto, and Jia, 2009). A report from FAO (2006) is rather optimistic and cites studies showing that discharges of N and P from aquaculture are usually negligible. By contrast, (De Silva, Ingram, Nguyen, Bui, Gooley, and Turchini, 2010) considered that discharged N and P from aquaculture may be harmful to the aquatic environment.

In the Mekong delta, the catfish industry has become an important source of aquatic wastes resulting in some contamination by nitrate and phosphorus in soil and water which has exceeded the limits of Vietnamese water and soil quality standards (Guong and Hoa, 2012). In fresh water aquaculture, catfish culture is estimated to have released 31,620 tonne nitrate and 9,893 tonne phosphorus in 2007, and 50,364 tonne nitrate and 15,766 tonne phosphorus in 2008 (De Silva et al, 2010) which mainly came from excretion and metabolic products (Nhan, Verdegem, Binh, Duong, Milstein, and Verreth, 2008; De silva and Anderson, 1996). In integrated aquaculture (high input fish with rice cultivation), the surplus waste discharge has been described as one of the most potential sources of environmental pollution (Phong, Stoorvogel, van Mensvoort, and Udo, 2011).

Brackish shrimp culture in the Mekong delta has recently caused impacts to the surrounding environment and ecosystems (Guong et al, 2012; Hoa, Thuy, and Tran, 2010). Intensive shrimp culture in coastal provinces results in high levels of organic waste discharge, sustained over time, with direct impacts on the environment and sustainability of ecosystems (Martin, 2011; Landesman, 1994). In this context, the most detrimental development in coastal areas has been the shifting from rice to shrimp culture, resulting not only in changed ecology but also having social effects such as labour migration and livelihood configuration (Lan, 2011).

1.5 Potential impacts of agrochemicals on aquaculture

There are always potential conflicts between the development of aquaculture and agriculture, especially in the Mekong delta where the government policies aim to promote the increase of both aquatic and agricultural production in the same area. Agrochemicals are widely applied for agriculture with multiple purposes such as controlling pests, insects, diseases or enhancing the product quality. These chemicals have their own capacity to absorb and desorbs between soil and water when introduced to the environment. Their transport through natural hydrology processes such as runoff, flow, dispersion allow them migrate widely and merged into the water environment. Generally, agrochemicals can persist in the water environment, which creates a both direct and indirect risks for aquatic fauna and flora. Accumulated residues of agrochemicals, particularly pesticides, in the soil and water environments may have negative effects on production and quality of seafood.

Pesticides existing in a water body will impact on water quality directly and have toxic effects on plants and animals. Herbicides, for example, activate in water and can target algae and other micro-organisms to cause oxygen fluctuation (Overmyer, Noblet, and Armbrust, 2005; DeLorenzo, Scott, and Ross, 2001; Jayaraman, 1986), which can cause lethal or sub-lethal effects on aquatic organisms. Acute toxicity for pesticides often causes death and low productivity for aquaculture organisms over both short term and long term exposures, and is considered one of the most serious problems in rural aquaculture..

Although pesticides are considered as a dangerous factor for aquaculture activities, aqua-farmers have no information about their potential concentration and spatial distribution in the environment. The pesticide dispersion normally expands from point source inputs to large scale distribution, which causes difficulty in measuring the presence and quantity of pesticide. Environmental modeling of distribution and quantity of pesticides can be used to reduce the risk caused by pesticide impacts to aid aqua-farmers in selection of aquaculture sites to minimize investment losses and increased profitability.

1.6 GIS and its application for fishery resources and environmental management

1.6.1 Definition and principle of GIS

Geographical Information Systems (GIS) are geographical computational systems which enable data acquisition, storage, integration, analysis and display of model results (maps or tabular outputs) (Khongpuang, 2011; Carocci, Bianchi, Eastwood, and Meaden, 2009; Wadsworth and treweek, 1999; Burrough, 1986). GIS has been used in many fields related to urban, rural, environmental planning, natural resource management, health and emergency planning, infrastructure organization, marketing, estate, agriculture and forestry and coastal management (Liao and Tim, 1994). A GIS is usually organized in 5 components including data, hardware, software, procedures and users (figure 1. 5).

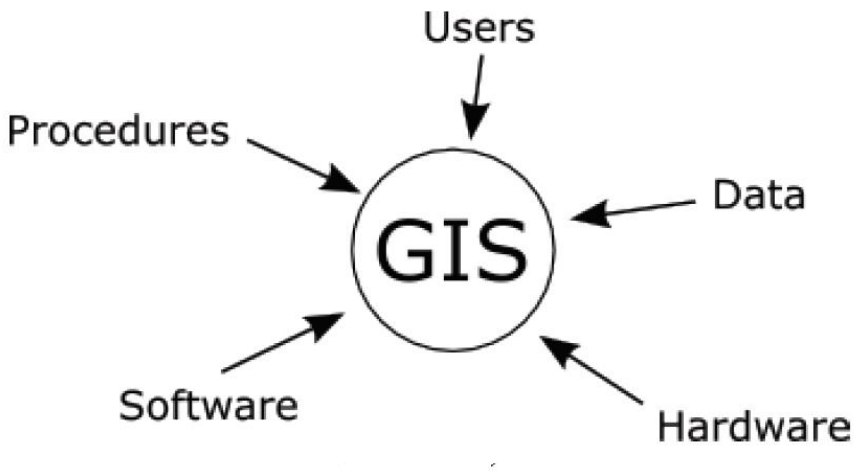


Figure 1. 5. GIS components

The hardware provides the core processing power and input, storage, manipulation and display of results. The GIS software complements this and enables control of all activities in GIS such as capture, storage, database management, manipulation, analysis, modeling and display (Eastman, 1999; Scholten and Lepper, 1994). Data is perhaps the most important component and can be divided into 2 types; spatial and attribute data. The spatial data is represented by raster and vector data structures (Nath, Bolte, Ross, and guilar-Manjarrez, 2000) which describe the shape and geo-position of an object on the earth, whereas attribute data illustrates the qualities of those objects (Khongpuang, 2011; Eastman, 2006; Luc Anselin, 1992). The effectiveness of how GIS is applied depends upon the knowledge and understanding of the users who define the procedures and methodologies to be applied to any spatial problem (Wadsworth et al, 1999; Liao and Tim, 1994; Burrough, 1986).

The working principle of GIS is outlined in (figure 1.6). Input data is the main material which usually comprises a variety of data types originating from maps, tables, databases, data logger files, field instruments, satellite images or the Internet. The system employs these data and process under the control of users. The processing steps in GIS is usually know as capturing, encoding, editing, storing, retrieving, manipulating, analyzing and displaying. After processing step, the system provides the outputs which can be displayed in similar form of input data such as reports, maps, images, tubular, GIS models, data and database.

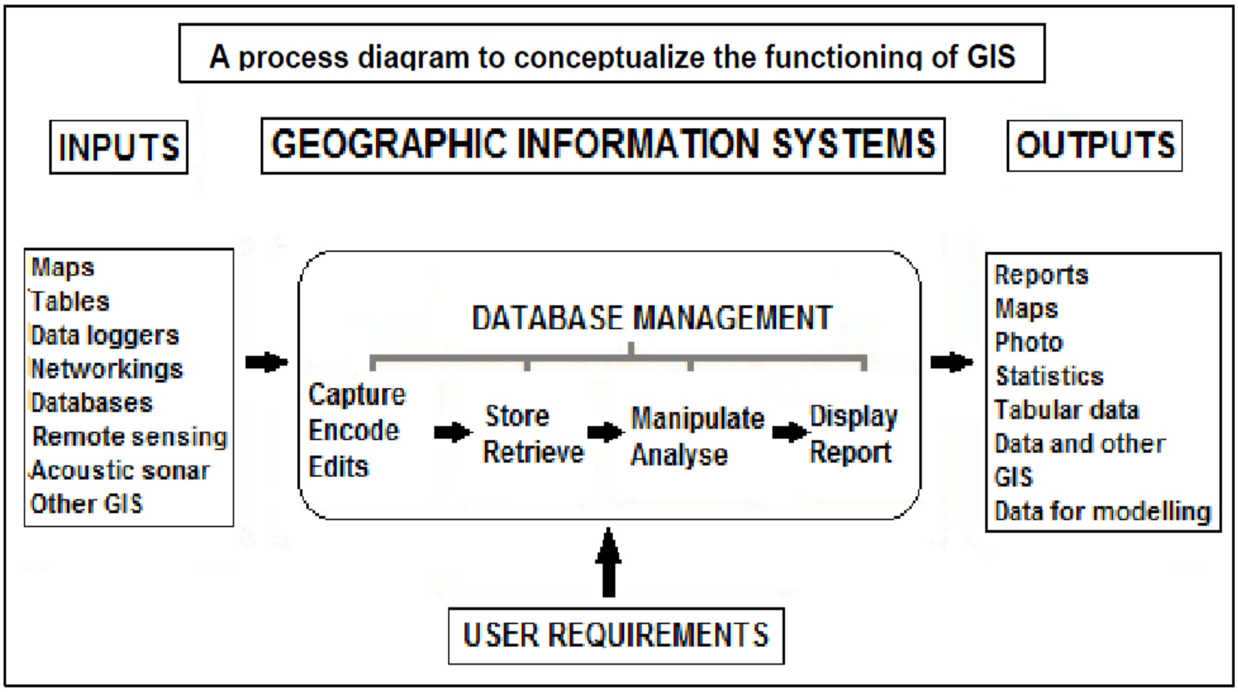


Figure 1. 6. A conceptual diagram of a GIS.

Following the description of *Nath et al (2000c)*

1.6.2 The use of GIS for decision support in aquaculture development

GIS can be used as a powerful facility for assisting decision-makers in many fields. GIS can provide geo-referenced model outcomes and supporting information to entrepreneurs, developers, policy makers and regulators at a variety of spatial scales. When spatial models are developed by skilled end-users, they are of particular value in identifying optimized sites for aquaculture development and zoning. There are many examples of studies applying GIS to aquaculture site selection (Nath et al, 2000; Kapetsky et al, 1990; Kapetsky, 1989), or to contribute to the sustainability of aquaculture (Longdill, Healy, and Black, 2008), and for managing the development of fisheries and aquaculture (De Freitas and Tagliani, 2009; Meaden and Kapetsky, 1991).

GIS models have also been used to identify suitable sites for aquaculture and coastal planning (Latinopoulos, Konstantinou, and Krestenitis, 2012; Luis Alvarez and Perez Roa, 2012), for shrimp site selection in coastal areas (Rajitha, Mukherjee, and Vinu Chandran, 2007; Giap, Yi, and Yakupitiyage, 2005; Salam, Ross, and Beveridge, 2003), and for cage aquaculture (Halide, Stigebrandt, Rehbein, and McKinnon, 2009; Ross, Mendoza, and Beveridge, 1993). GIS has also been used for planning and management of inland aquaculture (Kapetsky, 1997) modeling for carps and native species (Peredo-Alvarez, 2011; Salam, Khatun, and Ali, 2005), giant prawn (Hossain and Das, 2010) and catfish culture (Kapetsky, Hill, and Worthy, 1988). GIS has also been applied to define suitable sites for valuable shellfish culture in several regions including oyster (Cho, Lee, Hong, Kim, and Kim, 2012; Buitrago, Rada, Hernandez, and Buitrago, 2005), scallops (Radiarta and Saitoh, 2009; Radiarta, Saitoh, and Miyazono, 2008) or to evaluate the impacts from environmental issues to aquaculture species (Silva, Ferreira, Bricker, DelValls, Martin-Diaz, and Yanez, 2011) and predicting production for cockle and mussels (Khongpuang, 2011).

1.6.3 Mathematical models for environmental modeling integrated with the GIS framework

GIS can greatly enhance the management and visualization of environmental models as it provides a framework and tools for spatial mathematics, enabling encoding, spatial analysis, manipulation, and presentation of model outputs.

Most applicable utility of GIS in aquaculture and natural resources management is as a Decision Support System (DSS), which is a computerized system based on calculating various alternatives scenarios and their calibrated values which aim to support decision makers, planners, managers and stakeholders in resolving problems. A DSS has the benefit of adaptability, flexibility, economical efficiency, and support for modeling by decision maker. DSS within GIS can be built for carrying a number of functions

1.6.4 Implementation of hydrological models within the GIS environment

GIS has been identified as a suitable framework to integrate with environmental modeling for simulation of hydrological process in a watershed (Sui and Maggio, 1999; Meiner, 1996; Poiani and Bedford, 1995; Tim et al, 1994; Liao et al, 1994; Gilliland and Baxter, 1987). Recent studies have concentrated on implementation of specific models within a GIS framework for hydrological processes, water balance, catchment and small watershed modeling, predicting chemical concentrations and assessing non-point source pollution (Maidment, 1996).

The problem of modeling hydrological processes at a watershed scale is to simulate all activities in a catchment.. Watershed-based models deal with a variety of functions of hydrological activities such as rainfall, run-off, overland flow and water transport to stream networks (Pullar and Springer, 2000). Mathematical modeling of almost all of these functions has been integrated in GIS using published equations to simulate the dynamic processes (Batelan and De Smedt, 2007; Liu, Gebremeskel, De Smedt, Hoffmann, and Pfister, 2003; Olivera and Maidment, 1999; Sui and Maggio, 1999). Modeling the transport and flow of water within GIS was also considered to be essential to optimize the non-point source pollutants or nutrient discharges in a watershed (Kohne, Kohne, and Simunek, 2009; Ng, Wai, Li, Li, and Jiang, 2009; Morari, Lugato, and Borin, 2004).

Runoff is perhaps the most complicated hydrological process in a watershed. Runoff modeling is based on mathematical systems which merge multiple components including rainfall, evaporation and transpiration, interception, land-use treatment, terrain and stream network (Moreda, 1999). Enhanced dynamic runoff modeling has been linked to GIS to manage the complex mathematical equations and large datasets by many authors (Coroza, Evans, and Bishop, 1997; Goodchild, Park, and Steyaert, 1993; Heit and Shorteid, 1991). A range of mathematical models running in a GIS framework can be used not only to stimulate the hydrological phenomenon in a watershed, but also to generate results which act as the input to modelling of nonpoint source pollutants or nutrient discharges. In these studies, the SWAT model (Soil and Water Assessment Tool) (Arnold, Srinivasan, Muttiah, and William, 1998) which uses the theory of HRUs (hydrological response units) was applied in GIS to predict runoff (Pai, Saraswat, and Srinivasan, 2012; Easton, Fuka, Walter, Cowan, Schneiderman, and Steenhuis, 2008a; Kang, Park, Lee, and Yoo, 2006; Zhan and Huang, 2004; Bingner, 1996), nonpoint source pollutant (Yang, Dong, Zheng, Xiao, Gao, and Lang, 2011), erosion (Oeurng, Sauvage, and Sa´nchez Pe´rez, 2011; Kim, Chung, Won, and Arnold, 2008; Chaplot, 2005), water quality management (Ullrich and Volk, 2009). The Agricultural Non-Point Source Pollution Model (AGNPS) (Young, Onstad, Bosch, and Anderson, 1989; Young, Onstad, Bosch, and Anderson, 1987) uses hydrodynamic modelling to evaluate the runoff and fate of agriculture substances at a watershed scale (LIU, Zhang, ZHANG, HONG, and DENG, 2008; Mohammed, Yohannes, and Zeleke, 2004; Lenzi and Di Luzio, 1997) was and is considered as an perfect match with GIS (Pullar et al, 2000). The ANSWER model (Agricultural Nonpoint Source Pollution) (Beasley, Huggins, and Monke, 1980) simulates sediment movement in watersheds which have agricultural pollutant as their primary model and has been successfully integrated with GIS, using FORTRAN code, to evaluate non-point pollution scenarios in the environment (Joao and Walsh, 1992), and applied for modelling soil erosion in watershed (Bhuyan, Kalita, Janssen, and Barnes, 2002; Montas and Madramootoo, 1991; De Roo, Hazelhoff, and Burroh, 1989; Beasley et al, 1980). Other mathematical models have successfully been linked to the GIS environment and are widely applied for hydrodynamic simulation in watersheds, such as DRAINMOD for surface flow modeling of drainage areas (Dayyani, Prasher, Madani, and Madramootoo, 2010), WEPP (Water Erosion Prediction Project) was created for modeling for erosion but specially concentrated on water runoff (Singh, Panda, Satapathy, and Ngachan, 2011; Raclot and Albergel, 2006; de Jong van Lier, Sparovek, Flanagan, Bloem, and Schnug, 2005; Bhuyan et al, 2002; Tiwari, Risse, and Nearing, 2000; Flanagan, Gilley, and Franti, 1995; Flanagan and Livingston, 1995).

1.7. Objective of the study

In the Mekong delta, aquaculture has developed very rapidly in recent years, a phenomenon known locally as “rocket development”. This has contributed massively to the huge production of seafood for internal consumption and international export. However, agricultural production also dominates as the main cultivation activity in the Mekong delta, where development and improvement of rice paddies has been the main target for national economy policies and food security. There is a potential conflict between these production sectors, and this happens specifically when intensive rice fields apply agrochemicals including pesticides which have potential detrimental effects upon the development of sustainable aquaculture in the same delta. This potential conflict is of concern in the Mekong delta.

This study aims to investigate the current pesticide use in agriculture and their fate in the environment within the Mekong delta. Using these results, this study will develop spatial models to identify affected and non-affected aquaculture sites in terms of pesticide risk to some important cultured aquatic species (e.g. tiger shrimp and pangasius).

This study uses Geographic Information Systems (GIS) integrated with mathematical hydrodynamic models to approach the following key objectives and expected outcomes:

(1) Overall assessment of pesticide use in the Mekong delta

(2) Development of the hydrological models for water runoff, erosion and sediment yields

(3) Determination of spatial pesticide accumulation in sediment and water

(4) Classification of risk to aquaculture sites caused by pesticides for some target species

It is expected that these outcomes can provide good decision-making tools for policy makers who are looking for harmonized development between agriculture and aquaculture in Mekong delta. The application of these results will help reduce the risk of losing the long term benefit from aquaculture investments caused by pesticide accumulation. Moreover, these models could help to increase the security of seafood safety by providing information on areas and mechanisms of high accumulation of pesticides in seafood within the Mekong delta.

Chapter 2

Study area: The Mekong Delta, Vietnam

2.1 Geography and topography

2.1.1 Geographical location

The Mekong delta is located in Southeast Asia between $8^0 60'$ to $10^0 00'$ N Longitude and $104^0 50'$ to $106^0 80'$E Latitude (Huan, Mai, Escalada, and Heong, 1999). While the major part of the delta of the Mekong river is situated in Vietnam, it is linked to Cambodia in the north and in the South and East it has a long coastline directly connecting to the South China Sea. In the west it faces the Gulf of Thailand and Ho Chi Minh City in the North-West. The Vietnamese delta covers 13 provinces which occupies 12.93% of the total area of Vietnam (Lap Nguyen, Ta, and Tateishi, 2000).

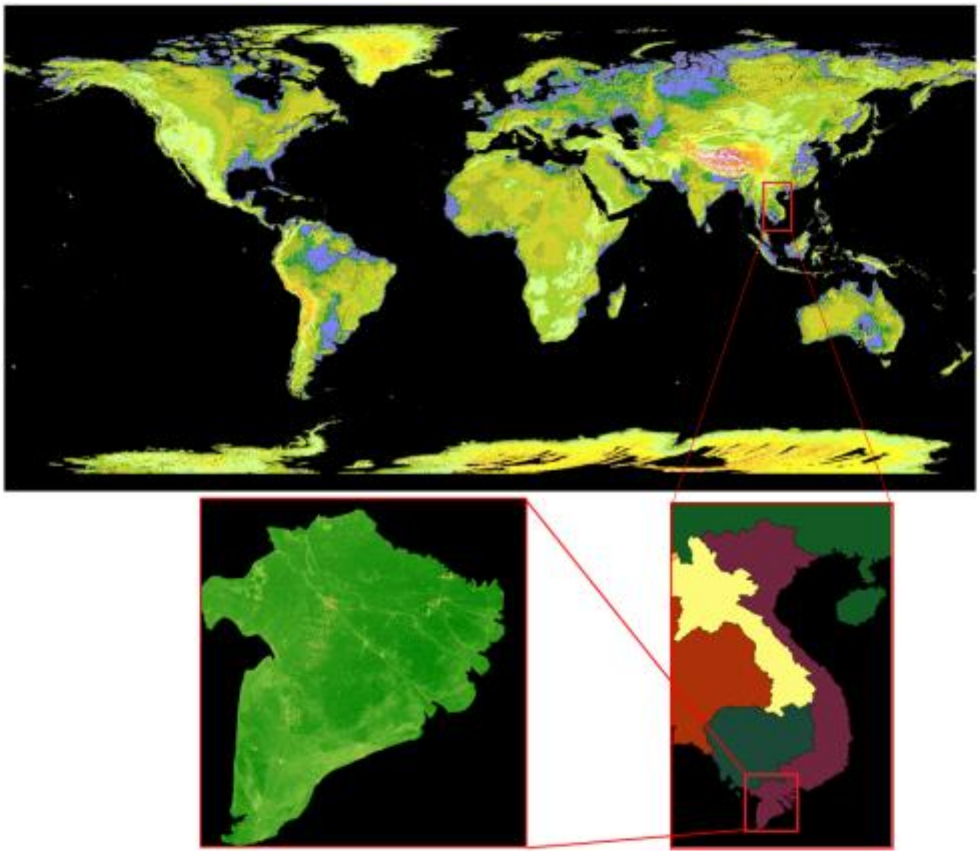


Figure 2. 1 .Geographic location of Mekong delta, Vietnam

The total area of the delta is approximately 40,000 km^2 (275 km from North to South, 260 km from West to East) comprised 13 provinces namely Long An, Tien Giang, Ben

Tre, Vinh Long, Can Thö, Tra Vinh, Dong Thap, An Giang, Kien Giang, Soc Trang, Bac Lieu and Ca Mau and Hau Giang. The delta has a complex of rivers and canal systems, both natural and man-made. Annually, 50 billion m^3 of water are discharged from Mekong river along with ~1 billion m^3 of sediment (Nguyen et al, 2008; Nguyen, Wolanski, Tran, and Haruyama, 2007).

There are nearly 20 million inhabitants in the delta (Dapice and Xuan, 2012) with an average population density of 435 people per square kilometre (Nguyen, 2007). Approximately 80% of the population work in agriculture and have a low rate of education and are unskilled (Dapice and Xuan, 2012; Nguyen, Phuoc, Mai, Bui, and Pham, 2000), especially in rice cultivation and aquaculture activities. Located in the tropical monsoon belt, the Mekong delta supports agricultural production throughout the year, with about 71.6% of the land devoted to agricultural land (in 2007), and contributing ~53% of rice for export (in 2009). In addition, the region has over 700 kilometres of coastline combined with the complex canal network, and so the Mekong delta not only has potential for aquaculture but also able to supplies ~60% of total national fisheries products annually (Nguyen, 2007).

2.1.2 Topography

The Mekong Delta is characterised by low flat terrain with an average elevation from 0.7 to 1.2 m relative to the mean sea level (Akira, 2005). The only exception is some hilly areas located in the Northern delta in An Giang province (VNMDMP, 2011). Towards the North and Northwest to the Cambodia border, the mean elevation increases to 2.0 to 4.0 m above sea level, the central plains range from 1.0 to 1.5 and in the tidal and coastal areas elevation is only 0.3 to 0.7 m (figure 2.2).

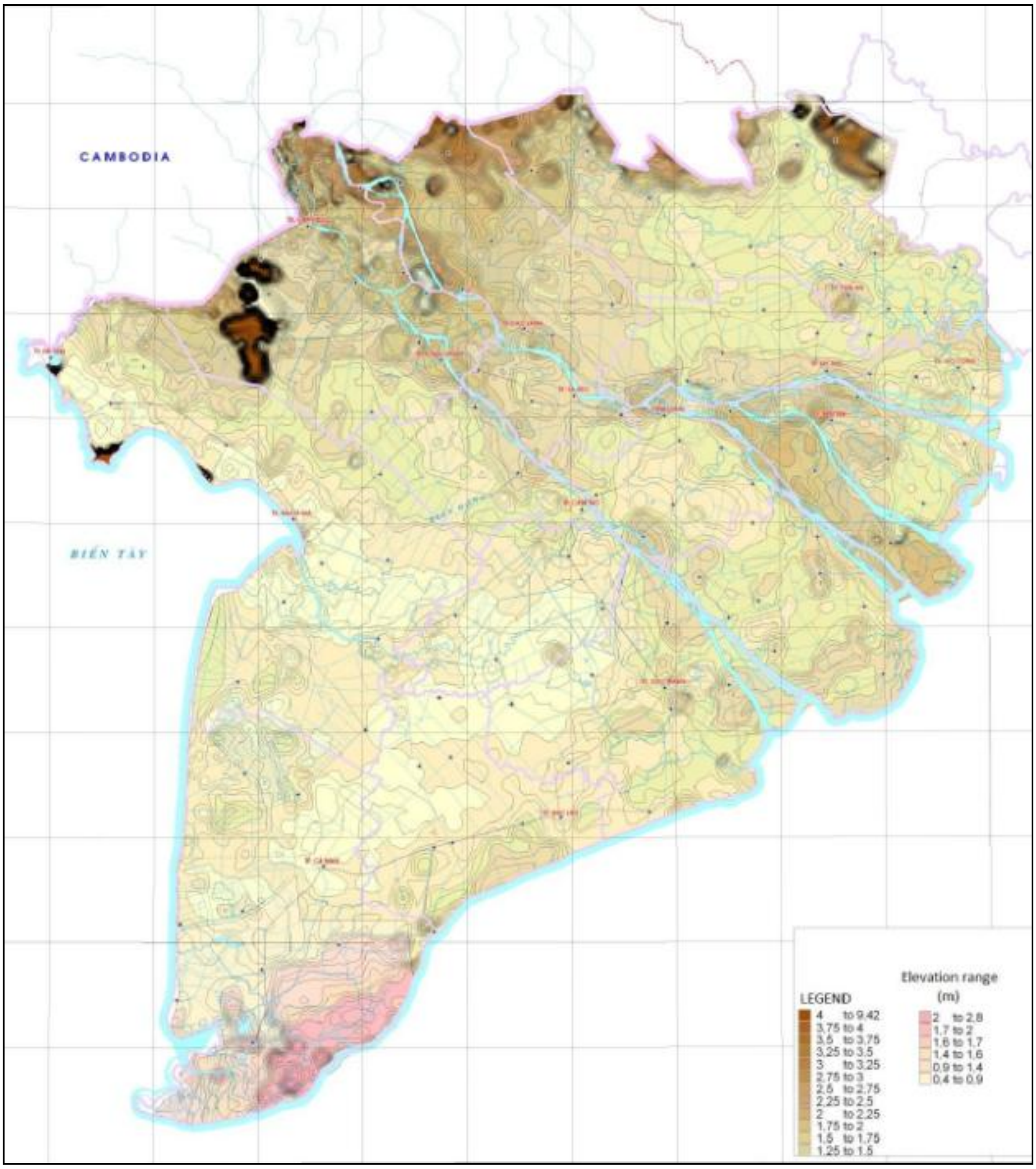


Figure 2. 2. Topography of the Mekong delta

(VNMDMP, 2011)

2.2 Natural Resources

2.2.1 Water resources

Fresh water resources from Mekong River

The Mekong delta receives a huge amount of fresh water annually with discharge estimated from 2100 m^3/s in the dry season to a maximum of 40,000 m^3/s in the rainy season (Wolanski et al, 1996) or up to ~45,000 m^3/s (Kite, 2001). Total annual water flow into the delta is approximately 400 to 500 billion m^3 and is ranked at the 6th largest water discharge delta in the world (Johnston and Kummu, 2012; Nguyen et al, 2008; Kite, 2001). This water resource supplies the entire Mekong delta for almost all agricultural irrigation, aquaculture and living demands of the inhabitants.

River System

The river and canal system of the Mekong delta is considered as one of the most complex in the world and it involves a dense network of both natural and manmade channels (Tamura, Saito, Sieng, Ben, Kong, Sim, Choup, and Akiba, 2009). This network is well established with the purpose of delivering fresh water to anywhere within the delta. The natural river system is formed by 2 main Mekong river branches, the namely Song Tien and Song Hau, which release water to the South China Sea through 9 outlets.

Although receiving an equivalent amount of water from upstream, the water volume flowed by these two river branches is different. Tien river annually transfers 55% of fresh water, whereas only ~45% passes through the Hau river (Nguyen *et al.*,2008). Compared to the upstream sections of the Mekong, both the Tien and Hau rivers are wide and deep. The mean width is from 1000-1500 m with average depth from 10-20 m. Besides these two main rivers, the delta also has more than 1,000 man-made canals which have been constructed for agriculture irrigation, transportation, protection against salinity intrusion, land reclamation and storm protection (Le *et al.*,2007). The total length of primary and secondary manmade channels in Mekong delta is about 40,000 kilometres (figure 2.3)

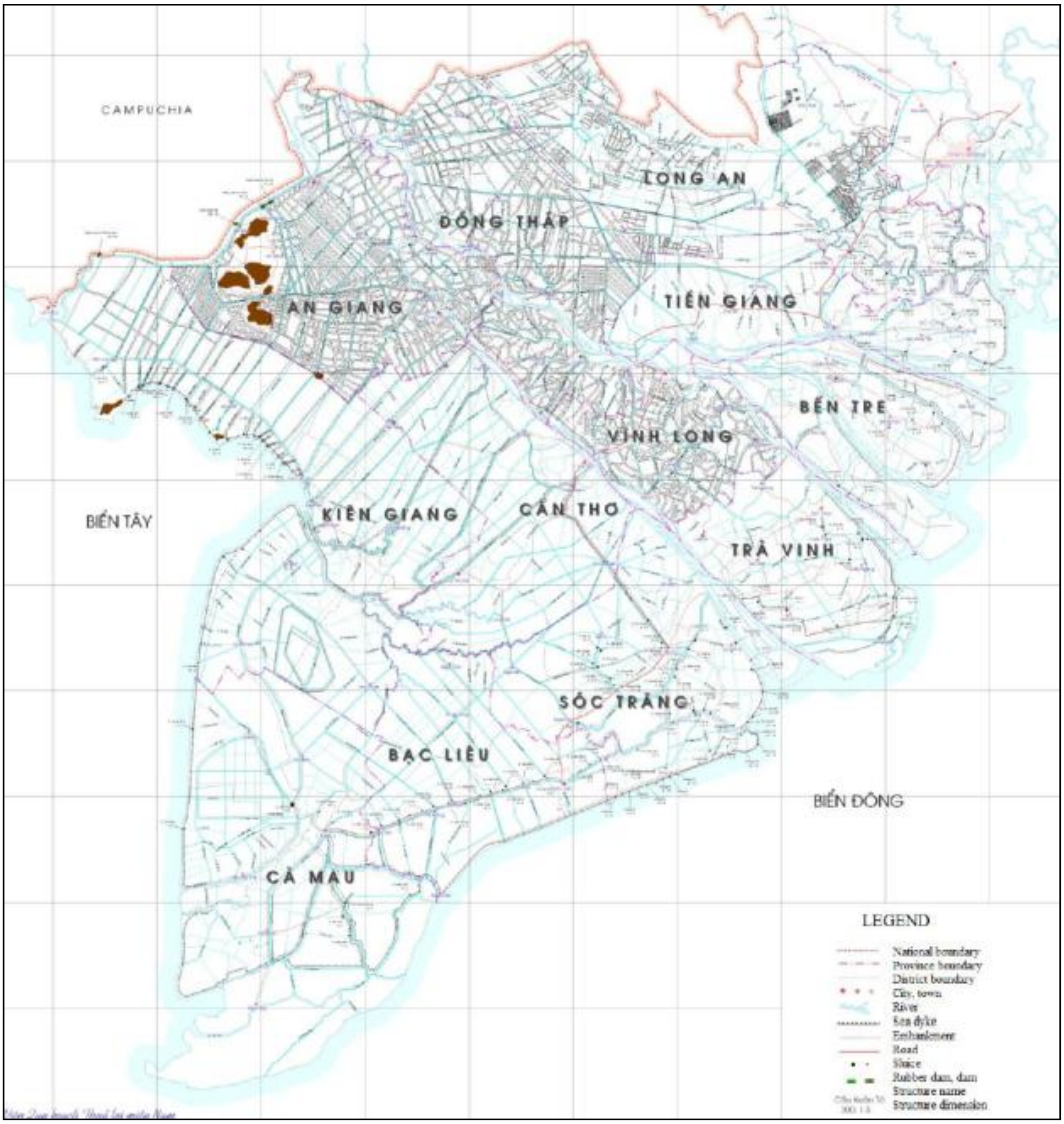


Figure 2. 3. The channel network in the Mekong delta, showing man-made channels and natural rivers and canals

Source: *(VNMDMP, 2011)*

Rainfall

The Mekong delta is affected by the tropical monsoon, having a warm humidity climate and high rainfall (figure 2.4). The delta has an average annual rainfall of approximately 1800 mm, but the distribution varies with geographical and seasonal factors (Akira, 2005). The highest rainfall is in the West with annual average from 2000-2400 mm, while the East has an average of 1600-1800 mm. The central plains stretching from Long Xuyen, Chau Doc-Can Tho to Tra Vinh - Cao Lanh - Go Cong have the lowest rainfall with averages of 1200-1600 mm. Approximately 80% of rainfall occurs during the Southwest monsoon season, the remaining 20% being in the transitional months and the Northeast monsoon period. Rain during the tropical monsoon usually happens with low intensity but large raindrops which occasionally may continue for 3-5 days causing temporary flooding in the delta.

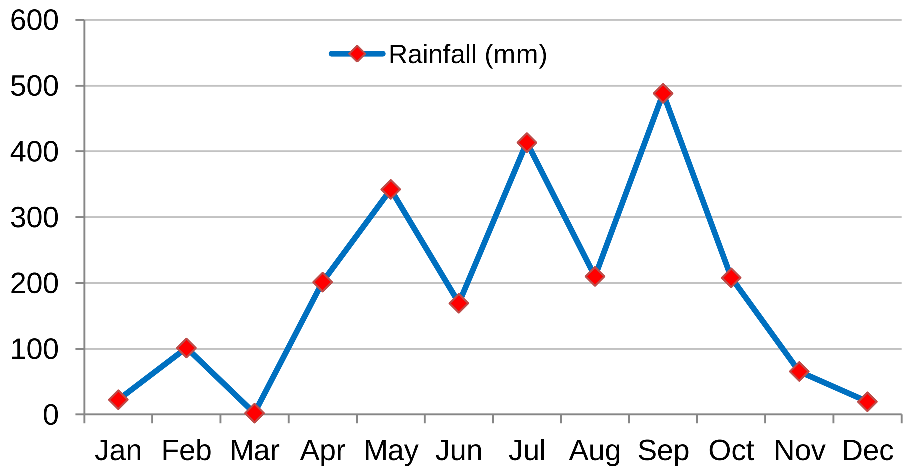


Figure 2. 4. Monthly rainfall measured at Camau Station in Mekong delta in 2010

Source:(GSO, 2012c)

The high annual rainfall contributes mainly to rice culture, vegetable and orchards.

2.2.2 Climate

Dominated by the Southeast Asian monsoon, there are two seasonal divisions; the wet season and dry season. The dry season is hot and occurs between November and April, while the wet season occurs from May to October and is warm and humid.

Air temperature

The average temperature in Mekong delta ranges from 27 to 28 °C. The highest temperature occurs between March to April with max temperature well above 30^{0}C, while the lowest air temperature is in December to January with minima of ~25^{0}C (figure 2.5). With the relatively flat terrain in whole area, air temperature is usually not significantly different between regions.

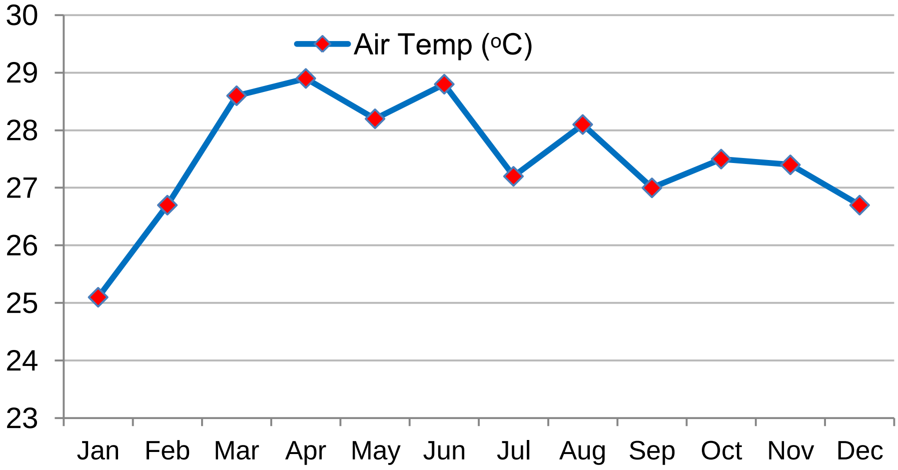


Figure 2. 5. Average air temperature measured at Camau Station in Mekong delta in 2010

Source:(GSO,2012c)

Air humidity

Air ranges from 78% to 90% (figure 2.6) and is relatively high during April to October, decreasing with the decrease in rainfall in October. Generally, humidity is high at around 84% (GSO,2012c).

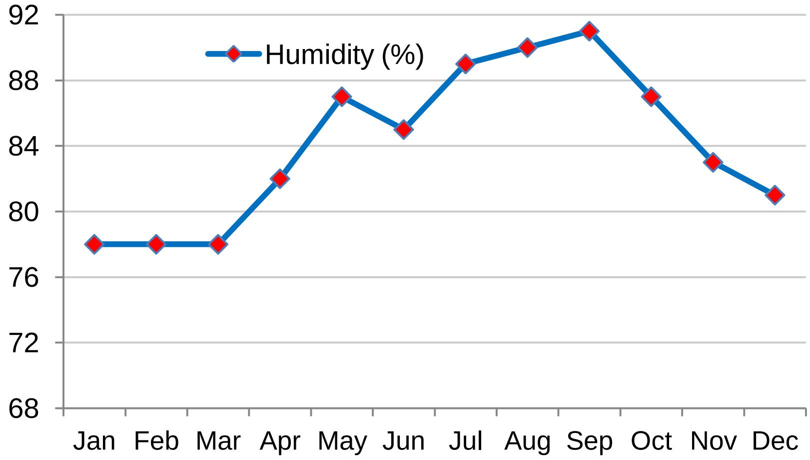


Figure 2. 6. Average air humidity measured at Camau Station in Mekong delta in 2010

Source:(GSO,2012c)

2.2.3 Flooding

Fresh water flooding

Many reports have investigated flooding conditions in the delta (Mekong River Commission, 2009), or different flooding scenarios (Le *et al.*,2007). Annual flooding by fresh water from upstream covers from 1.2 to 1.5 million hectare which can extend to 1.9millon ha (~50% area) when rainfall is high (White, 2002). Landform studies by Chiem (1993) and an SRTM Digital Elevation map have revealed the annual flood patterns. The low elevation in the central and the landform of this area acts like a pan, storing water up to 4 m height (Akira, 2005). The floods occur from July to August and are rich in sediment and nutrients brought from upstream. A second flood period occurs later over 2 or 3 months with the full increase of fresh water. The highest annual flood areas in October can extend as far as the coastal provinces (figure 2.7) and run until the end of November with water receding at the end of December.

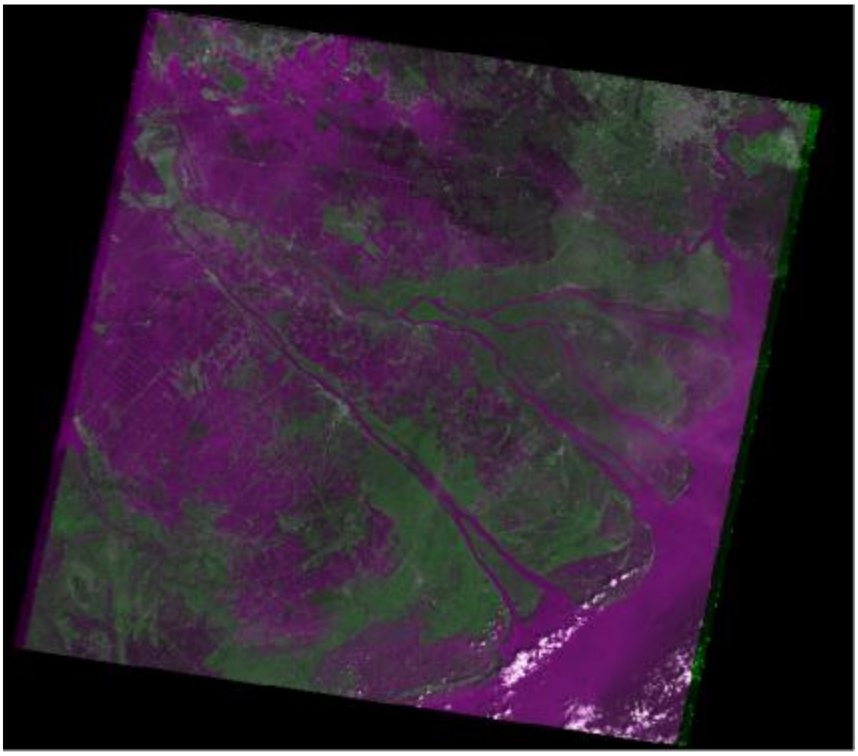


Figure 2. 7. A Landsat ETM+ image taken in Mekong delta in October 2003 showing the flood water (pink colour) spreading out in Mekong delta. In this period, only the coastal areas (in green colour) are not inundated

Source: (NASA Landsat program, 2003)

Flooding in the delta causes most economic and social impacts such as crop damage, infrastructure destruction, livestock loss, epidemic and shortage of clean water resources. On the other hand, during the 5 months flooding, approximately 460 billion m^3 of water flow to Mekong delta directly which bring almost of 200 million tonnes of alluvial soil for recovering the fertility for agricultural cultivation. These huge nutrient resources and minerals are also important for aquaculture development.

Salt intrusion and flooding by tides

Approximately 1 million ha of land in the Mekong delta are affected directly by tidal flooding with up to 1.7 million ha (45% in total area) under salt intrusion. (Reiner, Hien, Hoanh, and Tuong, 2004). This saline intrusion and tidal flooding follows the channel and river network and affects all coastal provinces in both the west and east side. The East Sea semidiurnal tide regime dominates the provinces on the east with a range of 3-3.5m (White, 2002) whereas the tidal range on the West side is only 0.8 to 1.2 m.

Saltwater intrusion occurs over a large part of the Mekong delta mostly in April when fresh water discharge from Mekong river becomes weak (MRC, 2005), this being dependent upon the volume of freshwater supplied from upstream. The saline intrusions measured in dry season in main rivers are found up to 50 km inland and a minimum of 20 km in the wet season. Strong mixing of salt and fresh water was found around 28 km inland during the wet season and 33 km in the dry season (Tateishi, Nguyen, Ta, Tokuoka, Fukita, Nishimura and Matsuda, 2007; Tateishi, Nguyen, Tokuoka, Fukita, Nishimura, Matsuda and Suzaki, 2006).

2.2.4 Soil types

The soils of the Mekong delta were formed by Holocene deposits with alluvial soil being located in the flooded and other lowland areas (Nguyen, 2012). Acid sulphate soils also are widely distributed in the Plain of Reeds (Dong Thap province) and are used for rice cultivation (Husson, Verburg, Phung and Van Mensvoort, 2000).

During the flooding period, huge amounts of alluvial soil and suspended sediments are deposited in low lying areas. Permanent saline soil and saline acid sulphate soils which are not suitable for agriculture are found in coastal areas. Lightly saline and acid sulphate soils are found in all coastal provinces while acid sulphate soils without saline effects represent almost 45% of the southwest side of Kien Giang, Ca Mau, Can Tho and Hau Giang provinces (Sebesvari, Le, Toan, Arnold and Renaud, 2012; Vo, 1995).

2.3 Population and labour resources

Population data for the Mekong delta varies but census data from General statistic office- GSO (2012b) indicates that there were 17.272 million people in Mekong delta in 2010. By provinces, population distribution and density are shown in figure 2.8

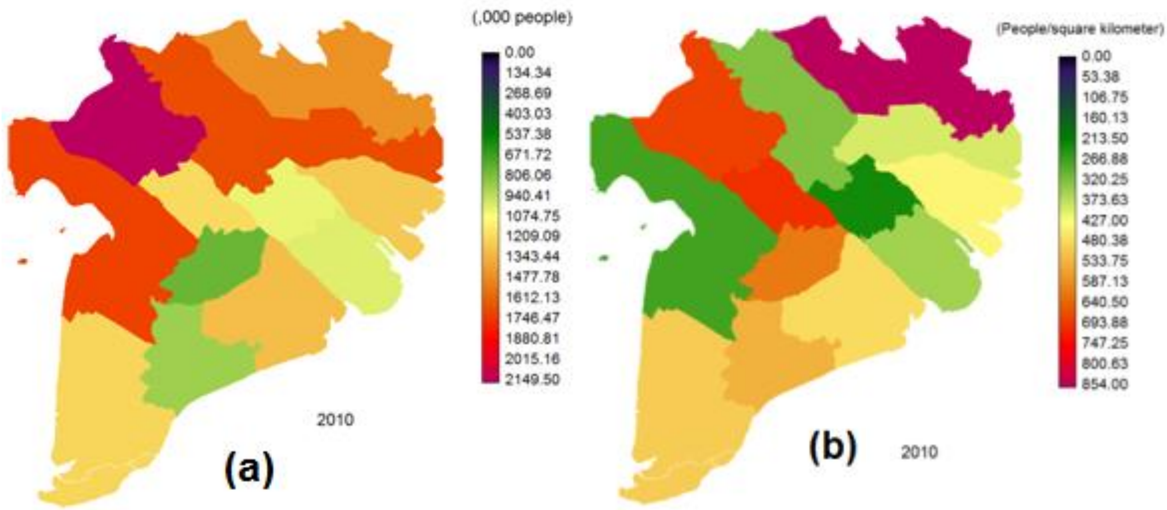


Figure 2. 8. Population distribution (a) and density (b) by provinces in the Mekong delta in 2010

An Giang, Kien Giang and Kien Giang have the highest populations with approximately 1.6 million people, An Giang alone having almost 12.5% of the total population in the region. The population is concentrated in the upper parts of the delta where there are rich fresh water resources and where this population serves the agricultural sectors such as rice cultivation.

2.4 Fishery resources and aquaculture

2.4.1 Inland fisheries

Vietnam has abundant inland fishery resources most of which are native to the Mekong. Catfish and fresh water fish are considered the most popular species in Mekong delta. There are 16 species of pangasiid catfish alone present in Mekong delta, as well as a large number of carps, tilapias, clarias, and snakeheads also found in this area. Despite this variety of fish species, recently recorded data shows a decrease of around 13 to 14% per year from inland capture fishery production. Specifically, An Giang province has seen an annual loss of approximately 40,000 tonnes of natural captured fish. There is no stated reason for this, although clearly it may be related to overfishing and reduction of native species, water pollution, and the impacts of shifting cultivation (Brakel, Hambrey, and Buntin, 2012).

Although a decline has been recorded, no account has been taken of the huge fresh water fish resources which move into the Mekong delta during flooding periods. In fact, the natural captured fish due to the seasonal movement of species has been reported to be up to 430kg per hectare in Can Tho and Kien Giang provinces and this illustrates why captured inland-fish production is always underestimated. This resource plays an important role in supplying protein resources for local people even during the flood period.

2.4.2 Coastal fishery resources

The coastal area of the Mekong delta is an important ecological zone for many aquatic species, having abundant natural feeding created by nutrient discharges through the delta from upstream. This resource of nutrient supplies foods for both plankton and fish fauna. The Mekong delta is also known for the density of mangrove along the almost 700 km coast line which creates locations for aquatic animals to live and reproduce.

The Mekong delta produces about 67% of the total coastal fishery production of Vietnam (White, 2002). The principal species captured include wild shrimps *(Penaeus* sp*.)*, crabs *(Scylla serrata)*, brackish water fish, eels, and large yields of shellfish on the muddy coastline such as blood cockle *(Anadara granosa)* and muddy clam *(Meretrix lyrata).*

In common with other coastal areas, coastal fisheries of the Mekong delta are facing multiple problems including overfishing, natural habitat losses and degradation, conflict on land-use, tourism activities and climate change impacts. Valuable species fish production has decreased and many species are being captured at smaller sizes, leading to decline in their reproduction ability, strongly impacting populations of valuable fish. The most dangerous influences are the changes in ecology (mangrove ecosystems) potentially affecting millions of people whose living depends on coastal fishery resources (Ministry of Fisheries et al, 2005).

2.4.3 Aquaculture in Mekong delta

Vietnamese aquaculture in has grown significantly in recent years and it is ranked in the top ten fishery exporters of the world (FAO, 2012a). Seafood exports have increased by more than 21% annually since 1996, mainly based on aquaculture. Many types of aquaculture system are used in Vietnam. Extensive and intensive farming is usually found in estuarine provinces like Ca Mau, Tra Vinh for shrimp culture whereas intensive farming is more popular in river bank areas such as An Giang, Dong Thap, Can Tho for high density catfish ponds.

The Mekong delta is the largest aquaculture production area in the Mekong river basin. Entering the global market from 1990, tiger shrimp *(Penaeus monodon)* and pangasius (*Pangasianodon hypophthalmus)* play an important role in seafood export. Freshwater aquaculture production in the Vietnamese Mekong delta was 256,708 t in 2001 from a culture area of 116,017 ha (VNMC, 2003) cited by (Brakel et al, 2012). In 2006, Vietnam supplied 2.6% of the global shrimp market with a value of US $1.46 billion, along with US $ 736 million value of pangasius; by 2010 this had reached US $1.62 billion value of shrimp and US $1.45 billion for pangasius (VASEP, 2010). Total aquaculture production in 2010 is approximately 1.92 million tons with the principal production areas concentrated on riverside provinces (figure 2.9a).

In 2008 the aquaculture area in the Mekong delta was 445,000 ha, increasing annually to approach 754,000 ha in 2010 (figure 2.9b) (GSO, 2012a). Coastal provinces generally have larger areas under aquaculture compared with riverside provinces, mainly focused on shrimps and brackish aquaculture where large areas of land are used with low production and high values. By contrast, freshwater culture occupies much less land but is based on high density rearing systems which produce huge quantities of species such as pangasius.

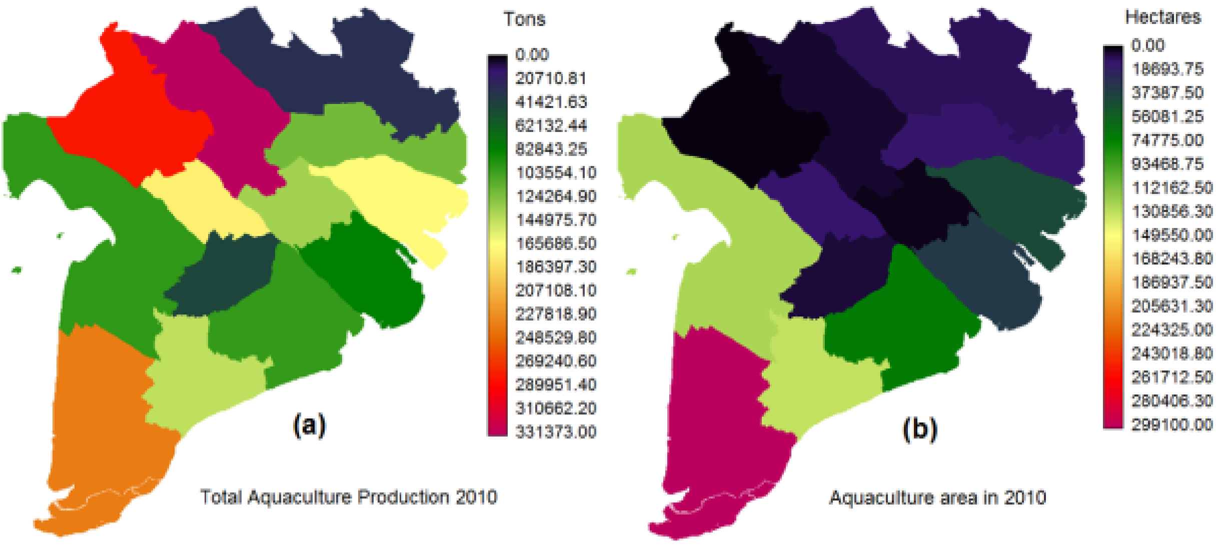


Figure 2. 9. Total Aquaculture production (a) and areas (b) in 2010

Brakel et al (2012), showed that the area of aquaculture changed from 2000 to 2005 with the biggest aquaculture expansion occurring in the coastal provinces of Ca Mau, Kien Giang, Bac Lieu for shrimp culture (tiger shrimp). Other, riverside, provinces have remained relatively stable in terms of aquaculture development (figure 2.10).

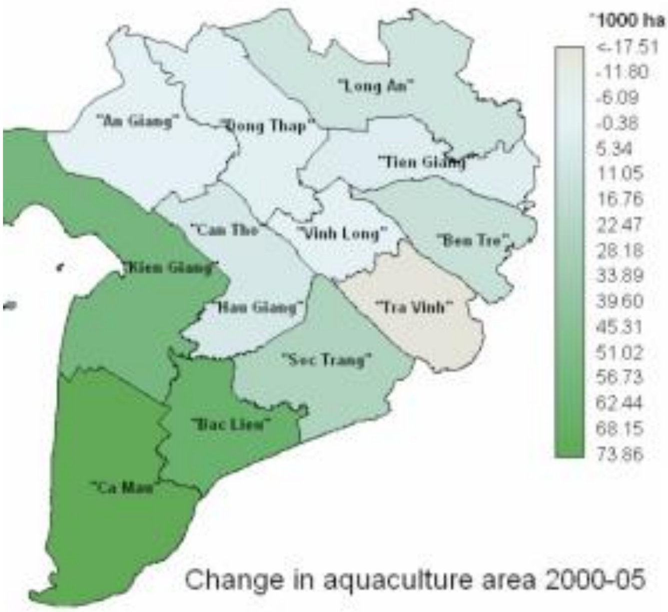


Figure 2. 10. Change in aquaculture areas in Mekong delta

Source:(Brakel et al, 2012)

There is a variety of aquaculture systems used in the Mekong delta. Intensive farming (figure 2.11) of both pangasius and tilapias has tended to replace cage culture in the rivers (figure 2.12) which was strongly successful in the previous decade (Phan, Bui, Nguyen, Gooley, Ingram, Nguyen, Nguyen and De Silva, 2009). Rice-fish or rice-shrimp integrated culture (figure 2.13) is a typical form of sustainable aquaculture in rice fields for a variety of fresh water fish or with tiger shrimp (Phong, van Dam, Udo, Van Mensvoort, Tri, Steenstra and van der Zijpp, 2010; Berg, 2002; Rothuis, Vromant, Xuan, Richter and Ollevier, 1999; Duong, Nhan, Rothius, Quang, Giau, Chi, Thuy, Hoa and Sinh, 1998; Arjo, 1998). During flooding periods, fisherman in these areas relies on incoming fresh water and transported nutrients to develop the fish farm (figure 2.14). This farming system is totally open extensive culture of Mekong native species with low density per surface area.

In the coastal areas, both intensive and extensive shrimp farms have been developed in wet lands along the coastline and in the estuary zone where there is good exchange of fresh and salt water. Extensive and semi-intensive shrimp farms (mainly *Penaeus monodon* and *Penaeus vanamei*) are well constructed and externally resourced (figure 2.15), whereas extensive shrimp farms rely much on the natural ecology and traditional farming technology (Minh, Yakupitiyage and Macintosh, 2001; Johnston, Trong, Tuan and Xuan, 2000). The rice-shrimp and mangrove-shrimp are two typical open extensive farming systems in coastal areas especially in Ca Mau (Nigel and Helena, 2003; Ha and van Dijk, 2000) and Tra Vinh (Thu and Populus, 2007).

Figure 2. 11. Pangasius culture systems and product processing in Mekong delta

Figure 2. 12. Pangasius cage culture in Mekong delta

Figure 2. 13. Rice-fish culture in Mekong delta.

Figure 2. 14. Aquaculture in flooded areas.

A net-pen is used to surround areas to retain the fish during flooding periods. Reared species are usually native to the Mekong.

Figure 2. 15. Open intensive shrimp *(tiger shrimp)* culture

2.5 Water environmental issues in Mekong delta

2.5.1 Catfish industry and water discharges

The pangasius catfish industry in the Mekong delta creates a problem of environmental pollution and waste loading emerging from pangasius farms can exceed environmental standards (TCVN 5942-1995: Vietnamese standard for surface water quality) (Guong *et al.*,2012). Measurements of total discharges from pangasius culture in the Mekong delta in 2008 show that nitrogen, phosphorus approach 50,364 tonnes and 15,766 tons respectively (De Silva *et al.*,2010a). To stabilise pangasius culture, large quantities of drugs (antibiotics), chemicals (pesticides), hormones and additives (vitamins) are inserted into the aquatic environment (Sebesvari *et al.*,2012). A survey by Kestemont (2012) from 2005 to 2006 revealed up to 155 types of drug, 31 types of antibiotics and 49 type of pesticides and 21 other compounds were used for pangasius culture in commercial catfish ponds and in hatcheries.

Catfish farms usually discharge waste water directly into rivers (63%), to canals (19%) and to rice fields or gardens (11%). It has been estimated that only 7.8% of the discharged water was screened prior releasing, and 11.2% of waste water was generally processed using lime or chlorine (Phan *et al.*,2009). Bosma et al (2011), calculated that the total N discharge is equal to almost 2% of total N present in the river. Clean water consumption by catfish culture is relatively high and the total requirement for pangasius culture in the delta reaches up to 2% of the total water in the Mekong rivers. This means that for 1 tonne of Pangasius product, between 700 and 5,970 m^3 of water needs to be exchanged or flow through the fish ponds. Specifically, in 2007, Mekong delta produced ~683,000 tons of pond catfish which consumed ~437.1 million m^3 fresh water and released 275.4 million m^3 waste water in to the rivers. Compared to other species, up to ~1,100 - 4,300 m^3 water exchange is required for one tonne of shrimp and max 25,200 m^3 water for salmon rearing in tank (Beveridge, Phillips and Clarke, 1991).

Feeds and feeding have been identified as the main source of pollutant material. The water discharges from pangasius culture usually causes eutrophication and freshwater ecotoxicity. The pangasius industry in Mekong delta at max waste discharge period was estimated to contribute 2.4% N and 3.7% P to the total in the Mekong rivers (Bosma, Hanh and José, 2012).

2.5.2 Suspended matter

Water resources in the Mekong delta have a naturally high suspended matter load. Recorded data from 2007 at several stations showed the total suspended solid (TSS) in Mekong river to be around 75 mg/L (MRC, 2008). More recently, measurements of TSS in the flood plain areas in Dong Thap province revealed TSS concentrations up to ~100 mg/L (Hung, Güntner, Merz and pel, 2011) which is much higher than the national water quality standards. Despite the high concentration of TSS, there is no report on the effect of high TSS to aquatic species (Sebesvari *et al.*,2012). This is probably due to the full adaption of Mekong native fish which prefers environments with high levels of suspended solids.

2.5.3 Nutrient discharge from agriculture

Farmers in the Mekong delta tend to use high amounts of fertilizer to enhance crop profits. Rich nutrients from agricultural activities will move into ponds, canals and rivers by leaching, runoff, infiltration and aquifer transport and these may become a hazard for aquatic ecosystems (Guong *et al.*,2012). Fertilizers containing nitrogen, phosphorus and potassium (NPK products) are preferred. Hoa et al (2010) showed that up to 93.6% of soil samples analysed contained high concentrations of phosphorus (as cited (Guong et al.,2012).

In rice cultivation, nitrogen fertilizers (URE) dominate the market with average use of nitrogen in 2007 of around 80-100kg N/ha in the dry season and 60-80kg N/ha in the wet season (Huan, Thiet, Chien, and Heong, 2005). Total input of fertilizer for rice cultivation in the Mekong delta is estimated at 400,000 tons of nitrogen, 180,000 tons of phosphorus and 120,000 tons of potassium per year. Due to hydrological activities, these nutrients move into water bodies and accumulate over time (Hach and Tan, 2007).

2.5.4 Pesticides

In the Mekong delta there is still a big conflict between use of pesticides in agriculture and their influences upon the aquatic environment when they enter the water bodies due to hydrological dynamic processes. Organophosphate and Organchlorine are considered the 2 most popular insecticide classes which are able to bio-accumulate and threaten the aquatic ecosystem in the delta (Minh, Minh, Iwata, Takahashi, Viet, Tuyen and Tanabe, 2007b). In practice, farmers not only apply persistent chemicals, but also tend to apply pesticide in excess of the recommended dosage.

Some studies have measured pesticide concentrations in water samples and have shown high concentrations of some very persistent pesticides in water, biota and sediment samples. Specifically, DDT (dichlorodiphenyltrichloroethane) was found in sediments from 0.01 to 110 ng/g of dry weight of samples (Minh, Minh, Kajiwara, Kunisue, Iwata, Viet, Cam Tu, Tuyen and Tanabe, 2007a), and 5.46 to 123.03 ng/g of dry weight of soft tissues of bivalve molluscs (Carvalho, Villeneuve, Cattini, Tolosa, Thuan and Nhan, 2008). When analyzing pesticides concentration in water samples, Pham Van Toan (2010) recorded median concentrations of quantified compounds from 0.01-2.72 µg/L sampled in Long An province and 0.01-0.38 µg/L sampled in Can Tho province. Endosulfan is a typical insecticide which has also been detected in most water samples with the levels of from 1.3% to 9.2% in total samples (Fabrice and Claudia, 2012) are recognized as having exceeded water quality regulations for aquatic safety standards (level B1) (US EPA, 2012)

Chapter 3

Materials and Methods

This study can be broadly divided into two categories: (a) laboratory based data aggregation, processing and model development, and (b) field based data collection.

3.1 Laboratory-based work

3.1.1 Hardware

Computer system

All laboratory-based work was carried out within the facilities of the Geographical Information Systems and Applied Physiology lab of the Sustainable Aquaculture Research Group, Institute of Aquaculture, University of Stirling. The computer system used was a Dell workstation, model T5400, containing a Intel Xeon 3.16Ghz CPU with 8 Gb RAM running 64-bit Windows 7 operating system. Laboratory PCs are connected the Local Area Network (LAN) of the University of Stirling and to other devices such as printers, digitizer, storage systems, etc..

Storage facilities

High resolution spatial data (30 m x 30 m) was used for the whole area of the Mekong delta (40,000 square kilometres). This required large local storage (2Tb + 2 Tb HDD) and access to the research group's network attached storage (NAS) systems (QNAP 16 Tb active and LaCie 4Tb archive).

Output facilities

To enable high quality work, every workstation PC is equipped with twin high resolution 21" monitors supported by a high capacity integrated graphic card with up to 4 Gb display capacity. Printing was done via a networked Epson Aculaser C1900 device.

3.1.2 Software

The main spatial modelling software (Geographic Information System – GIS) used in the study was IDRISI Taiga version (Clark Labs, Clark University, USA, 2011). The software is specifically is designed for both GIS and remote sensing operations and is particularly suitable for environmental modelling, natural resources management, multi criteria and multi objective decision support, risk analysis, spatial or surface interpolation, and statistical characterization. The software comprises almost 300 program modules to allow users to input, display and analyse the spatial information (Eastman, 2011)

Besides the main software, use was made of Google Earth (Google Corp, USA, 2012) which is one of the most popular programs for visualising topographic and land-use data and to support land cover classification. Subject to checking image date and quality, this data portal is widely used to verify ground-truth user data against current satellite information.

3.2. Acquisition and processing of satellite data

Satellite images used in this study were the gap-filled Landsat 7 ETM+ products. The products were downloaded free of charge from the USGS website (*United States Geological Survey: http://earthexplorer.usgs.gov/)* through the Land Global Survey section. The downloaded products were chosen from the period of 2000 to 2005 and covering the entire Mekong delta area. For work with the latest products, images from 2004 to 2005 were downloaded as a priority. Unfortunately, the Landsat 7 scan line corrector (SLC) had a mechanical failure in 2003 (Pat, Esad, and Gyanesh, 2012) which has resulted in all subsequent images having missing data, shown as gaps, away from the central track of the image. While the products released since 2003 are more up to date they need to be processed to fill the gaps. This was achieved by using the local linear histogram matching techniques and set of algorithms provided by USGS technical paper (James, Pasquale, and Gail, 2012). The downloaded post-2003 Landsat images from USGS- GLS (USGS-Land Global Survey) were already completed using above method.

Landsat 7 ETM+ SLC-off products comprise 7 discrete spectral bands (electromagnetic spectrum of an image) 1 panchromatic band. The maximum resolution of the 7-band product is 30x30 meters per pixel, and the panchromatic band (band 8) has a resolution of 15 m x 15 m per pixel (table 3.1). For the purposes of this study, four LANDSAT satellite images were required to cover the selected area. Therefore, four Landsat 7 images were chosen for download with product codes LE71250542005324EDC00, LE71250532005020EDC00, LE71260532004329EDC00, and P126R054_7X20010116 (table 3.2).

Table 3. 1. Lansat 7 ETM+ product information

Band Number	Wavelength (μm)	Resolution (meters)	Data lines Per Scan	Spectral response	Bits per Sample
1	.450–.515	30	16	Blue-green	8
2	.525–.605	30	16	Green	8
3	.630–.690	30	16	Red	8
4	.775–.900	30	16	Near-IR	8
5	1.550–1.750	30	16	Mid-IR	8
6L	10.40–12.50	30	16	Thermal-IR	8
6H	10.40–12.50	30	8	Thermal-IR	8
7	2.090–2.35	30	16	Mid-IR	8
8	.520–.900	15	32	Panchromatic	8

Source: (USGS, 2007) and (Lillesand and Kiefer, 1994)

Table 3. 2. Landsat 7 images were downloaded and used in this study

Image Number	Satellite type	Path	Row	Position	Date of Acquisition	Spectral Band
0207	Landsat7 ETM+	126	053	N-W	Mar-2004	1,2,3,4,5,6,7,Pan
0120	Landsat7 ETM+	125	053	N-E	Jan-2005	1,2,3,4,5,6,7,Pan
0116	Landsat7 ETM+	126	054	S-W	Jul-2001	1,2,3,4,5,6,7,Pan
0324	Landsat7 ETM+	125	054	S-E	May-2005	1,2,3,4,5,6,7,Pan

N-W: North - West; N-E: North-East; S-W: South-West; S-E: South-East; Pan: Panchromatic

3.3 Study area creation

Firstly, for each iteration or date, the four satellite images were concatenated together by the module CONCAT in IDRISI. The order for the overlap process will be priority from left to right and from the top to bottom. In the CONCAT module, the order for 4 images will be 0207, 0120, 0116 and 0324. The concatenation is then completed for every image band (figure 3.1).

Secondly, the study area needs to be more narrowed to cover only the targeted area and to reduce the number of rows and columns. The concatenated images were cut using the WINDOW module with min X, max X, min Y and max Y UTM-48N coordinates of 452625, 714255, 945915 and 1225575 respectively.

To improve the resolution of the imagery the PANSHARPEN method was used to enhance the resolution from 30 meters to 15 meters per pixel. This approach uses satellite images band 3, 4, 5 as image components and the panchromatic band 8 is used for the enhancement.

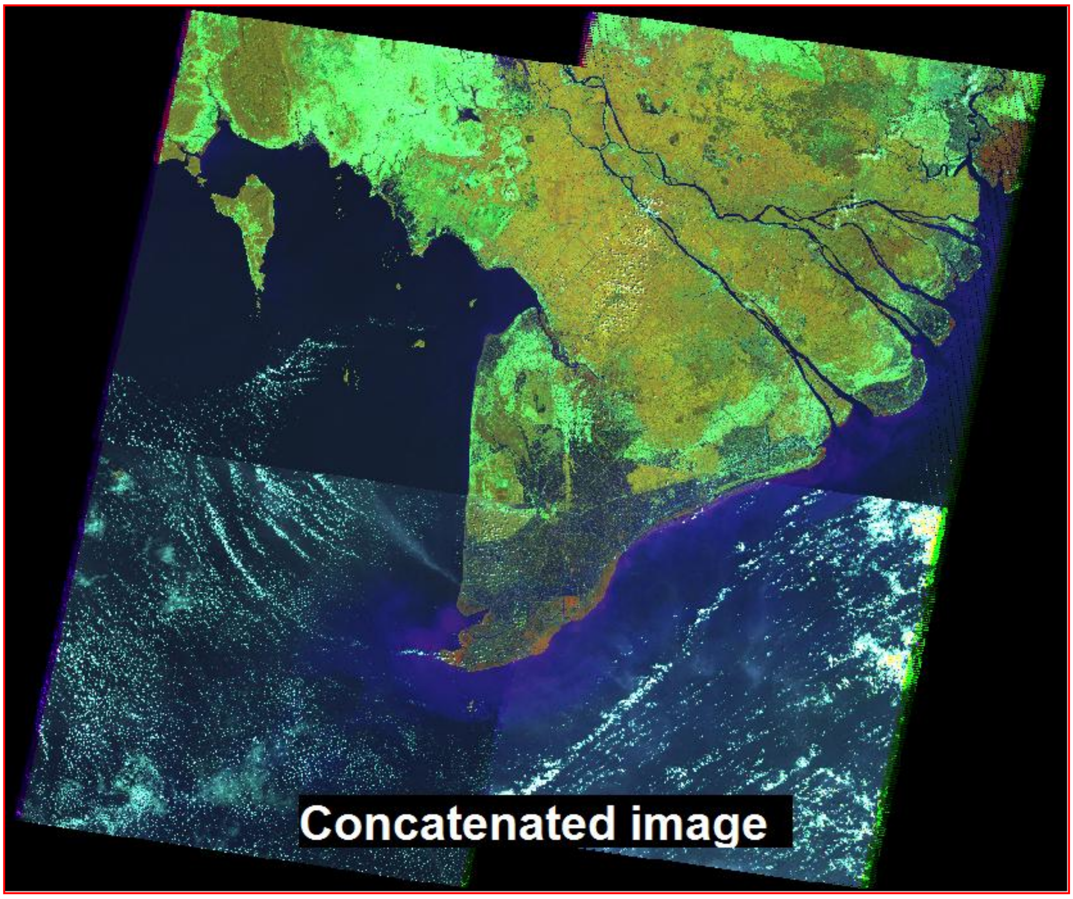


Figure 3. 1. Result from module CONCAT.

The most important section of the Mekong delta for aquaculture production is the area around and including the two principal river channels. This section was identified for detailed analysis in this study by digitizing function. Figure 3.2 shows the BOOLEAN boundary where "0" is background and "1" is study area.

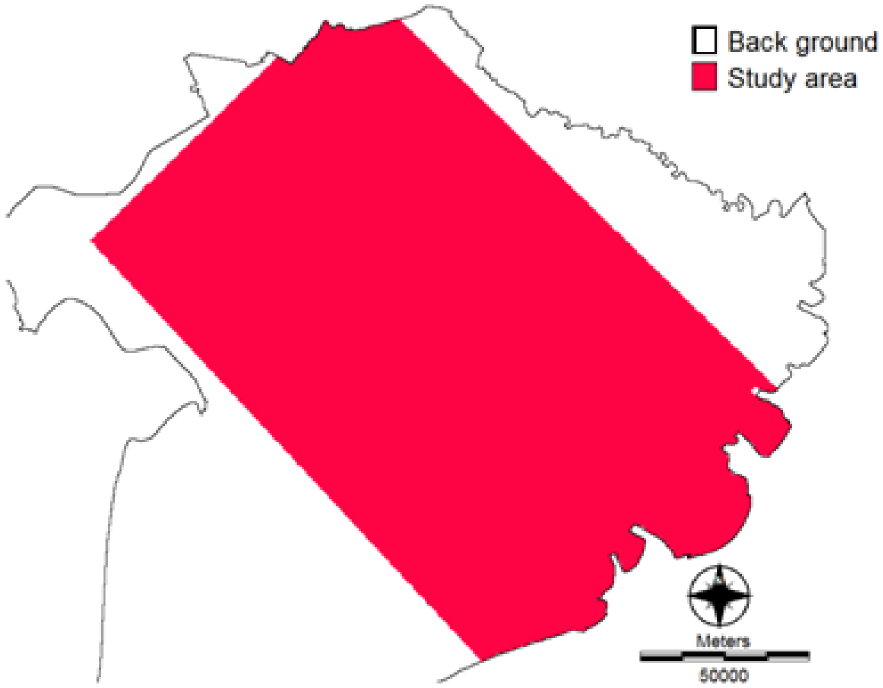


Figure 3. 2. Study area

3.4 Other data

Rainfall data source

Rainfall in this study is the core input data because it related to all hydrology models such as runoff, soil erosion which will be applied to calculate sediment yields and pesticide losses. Rainfall data was provided by the National Meteorology and Hydrology Centre of Vietnam. Annual rainfall data for 2008 were collected daily from 39 stations over the study area under electronic format (.xls format). A rainfall raster layer was constructed following the flowchart in figure 3.3. Firstly, a vector point file was created to show the geo-location of every rainfall station ID (figure 3.4). In DATABASE WORKSHOP function in IDRISI, the rainfall data in for rain event has been linked to the ID in vector point file. Secondly, it needs to export these data to X, Y reference system in sector UTM-48N. The vector point files for rainfall data show value of rainfall in millimetres at a specific station (figure 3.5). Finally, the module INTERPOL was called to interpolate rainfall vector point layer to expand surface value on a raster file system based on surface interpolation with using 6 points search radius. The function will automatically calculate the new rainfall value nearby stations by the distance weighted the interaction among values of stations surround (Eastman,2006). Rainfall data layer after defining the boundary was shown in figure 3.6.

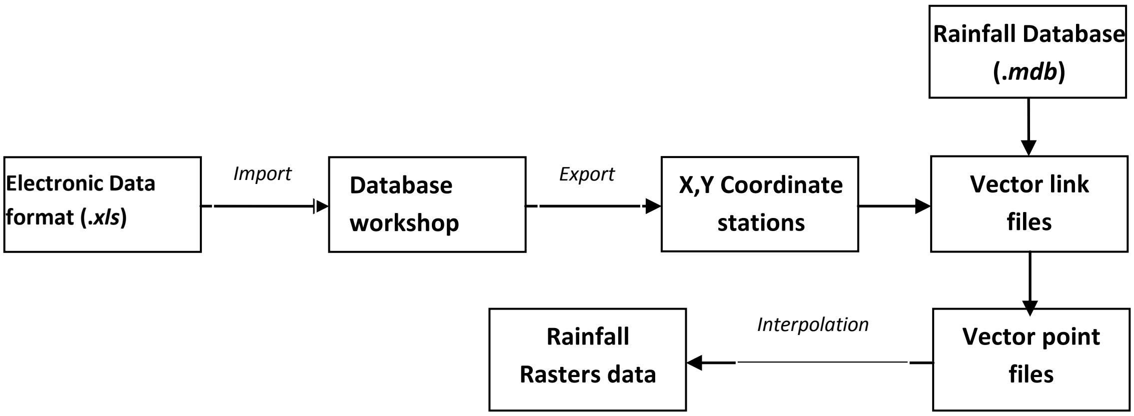


Figure 3. 3. Rainfall data layer construction chart

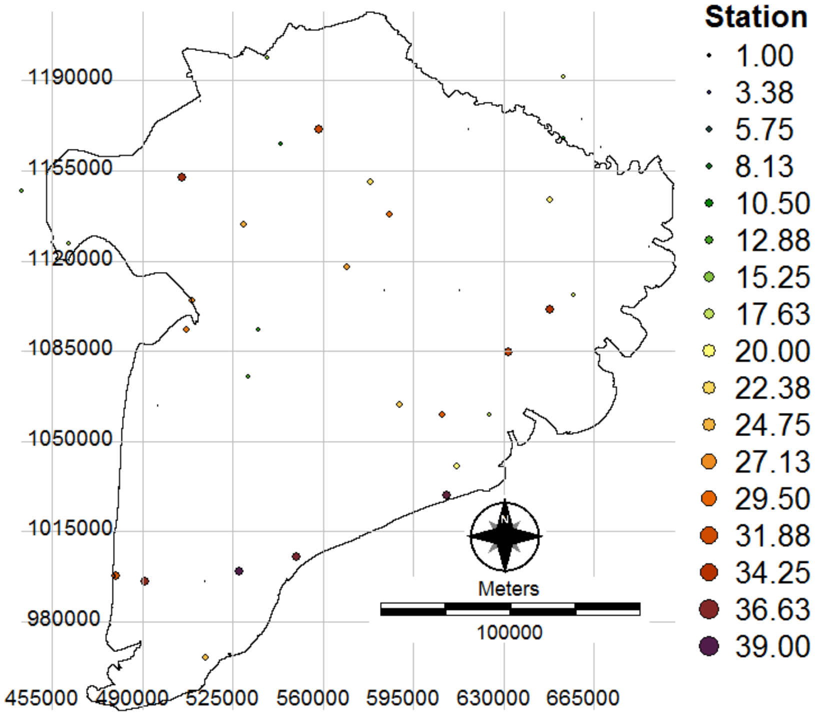


Figure 3. 4. Geo-location (UTM-48N) of 39 rainfall stations

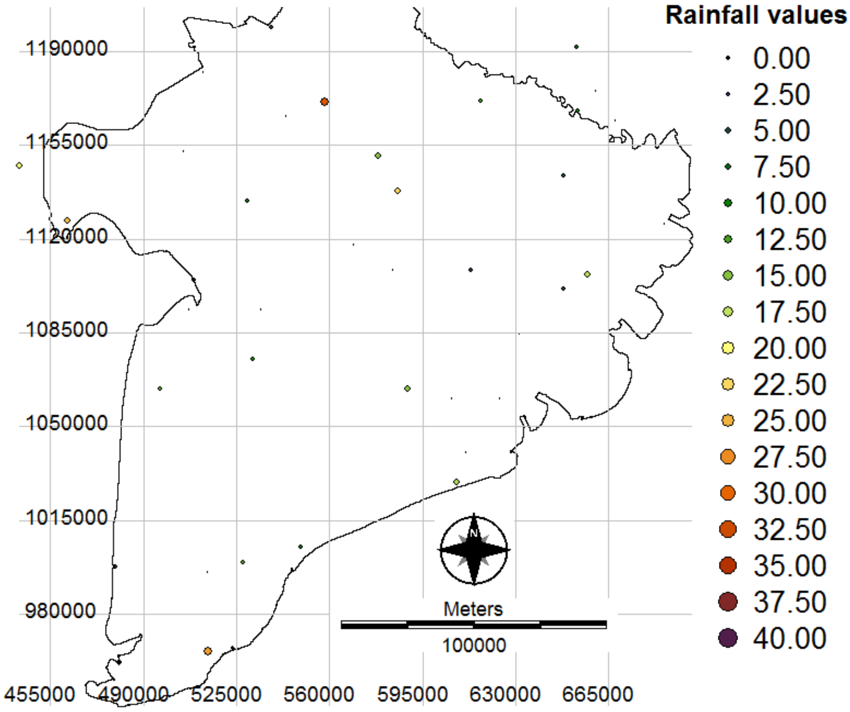


Figure 3. 5. Vector to show linked rainfall values to ID station

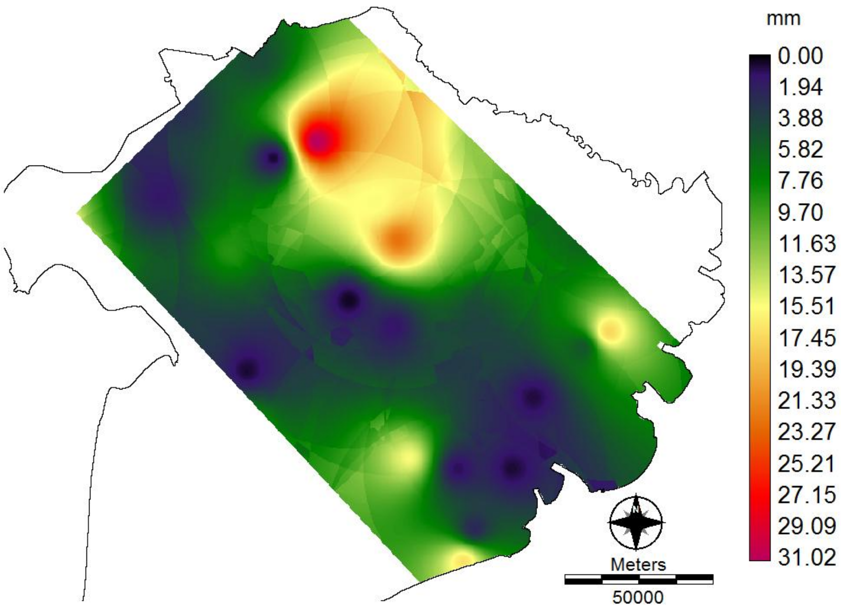


Figure 3. 6. Rainfall data raster layer for 21st of June, 2008

Soil types data

Soil type in the Mekong delta is mostly formed by the deposition of Alluvium soil which comprises sand, mud, gravel, and shell debris. In the upper part of soil column, soil type was found as a mixture of Jarosite and Geothite which is very fertile. The lower part of the soli column is mainly sulphuric Jarosite which contains acid sulphate soil and a lot of organic matter (Husson *et al.*,2000). As described by Chiem (1993), horizontal distribution of soil type throughout the delta was divided into 6 groups. The alluvium soil is the result of yearly deposition by the two main branches of the river and occupies an area of around 28% of the total Mekong delta area. Saline soil is located along the coastal area and occupies 21% of the delta area.

Soil type database was supported from GeoNetwork on FAO (Food and Agricultural Organization of the UN: *www.fao.org/geonetwork/srv/en/metadata.show?id=14116*). The product is vector polygon file data which is formatted in shape file with Lat/Long coordinate. This vector data was imported to IDRISI. Using PROJECT module combined with study area image (Figure 3.2) to registed the imported product to UTM coordinate system. Almost imagery processing in IDRISI only accepts the inputs as raster file, a small step need to carry out to convert vector files to raster. The module WINDOW was used to cut the image by defining the exact coordinate values at 4 corners to fit into the study area. To make sure the soil type map having similar coordinate with study area after window, the further module PROJECT was called to register the final product to the UTM-48N (Figure 3.7).

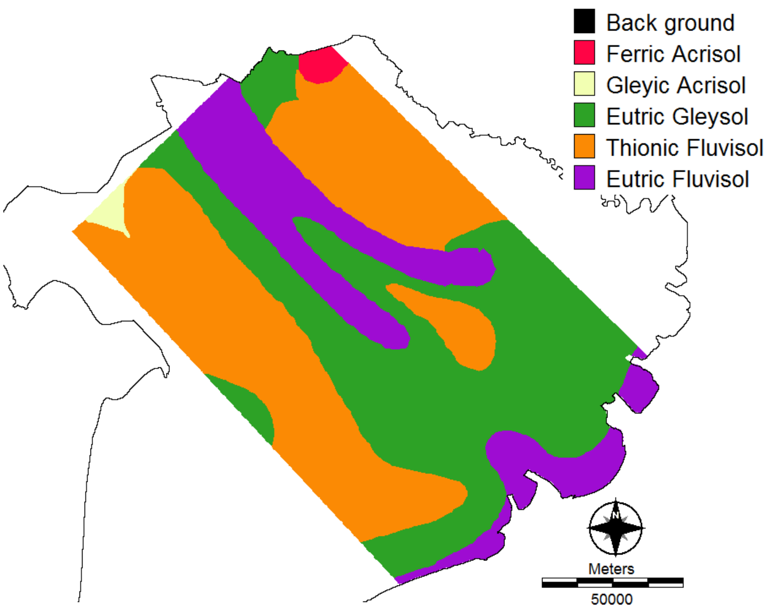


Figure 3. 7. Soil type in Mekong delta

Topology feature data

SRTM data with 90 meters resolution and Lat-long coordinate (SRTM_57_10; SRTM_57_11; SRTM_58_10; SRTM_58_11) were downloaded from the USGS website, and imported to IDRISI. Using the PROJECT module, it was converted into a 30 m resolution raster image and project them into a UTM-48N registered Geo-referenced system. The study area was covered by 4 SRTM images which were concatenated into a single images using the CONCAT module in IDRISI, and geo-referenced. This image was extracted again to narrow the frame to the actual study area (figure 3.8). The original background value is minus 32,768 as the value assigned for elevation of mean sea level. This value was created unintentionally by mathematical processing of the creation process. The final step is to re-class all minus values to zero. This also means the elevation data of water body was considered as zero (figure 3.8).

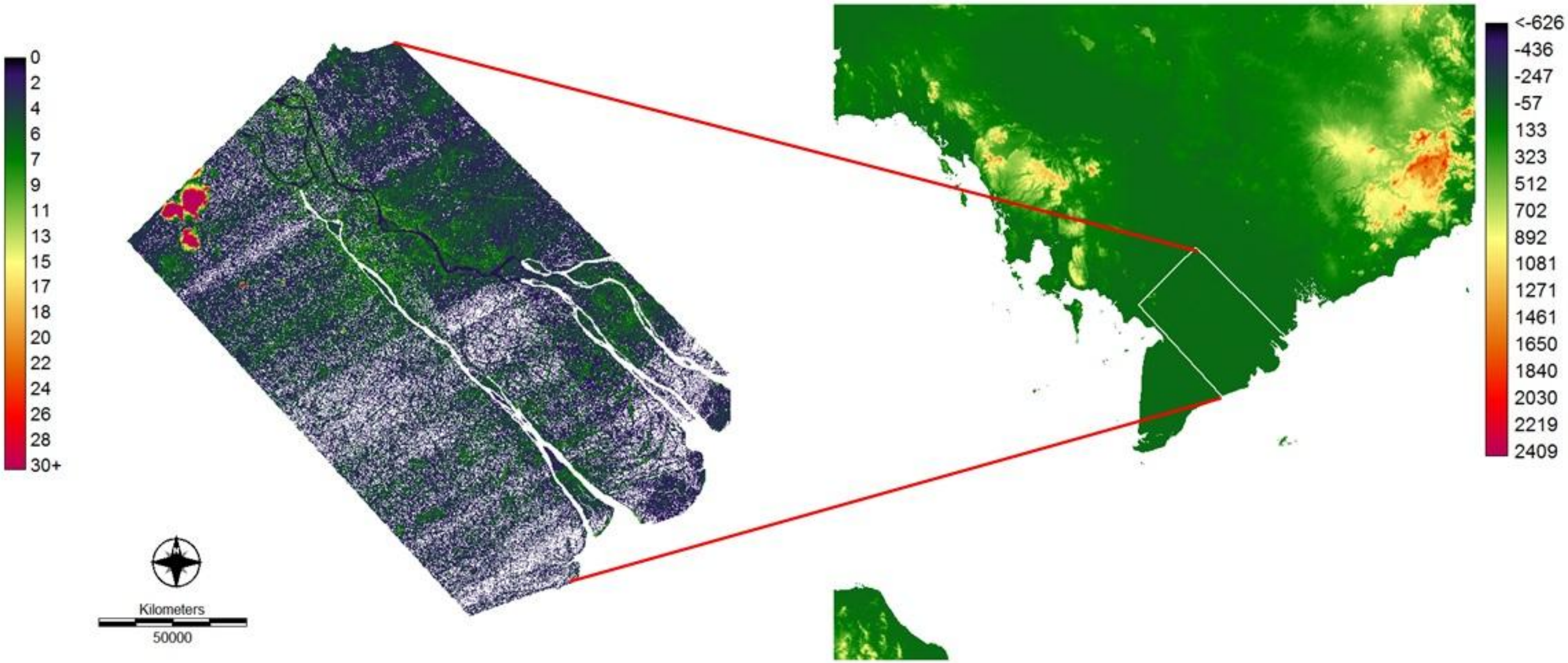


Figure 3. 8. Digital Elevation Model (DEM) data for the study area. The scale is in m above mean sea level.

3.5 Field data collection

The field data collection was carried out only to generate data of pesticide use. The data collection concentrated on pesticide types and usage in the field, farm location with X, Y coordinates, crop types, soil types, date and frequency of application and stocking of pesticides.

3.5.1 Sampling sites

Sampling station locations were selected by using the SAMPLE module within IDRISI using the stratified random option within the study area. The stratified random function establishes the locations of points in the whole frame, including background and study area zones. The number of 2010 was chosen to run the module resulting in 435 sampling locations with full geographical information inside the study area (figure 3.9). However, this number was further narrowed by eliminating some points which fell in the Mekong River and the final number of sample points to be approached for interview was finally at 343.

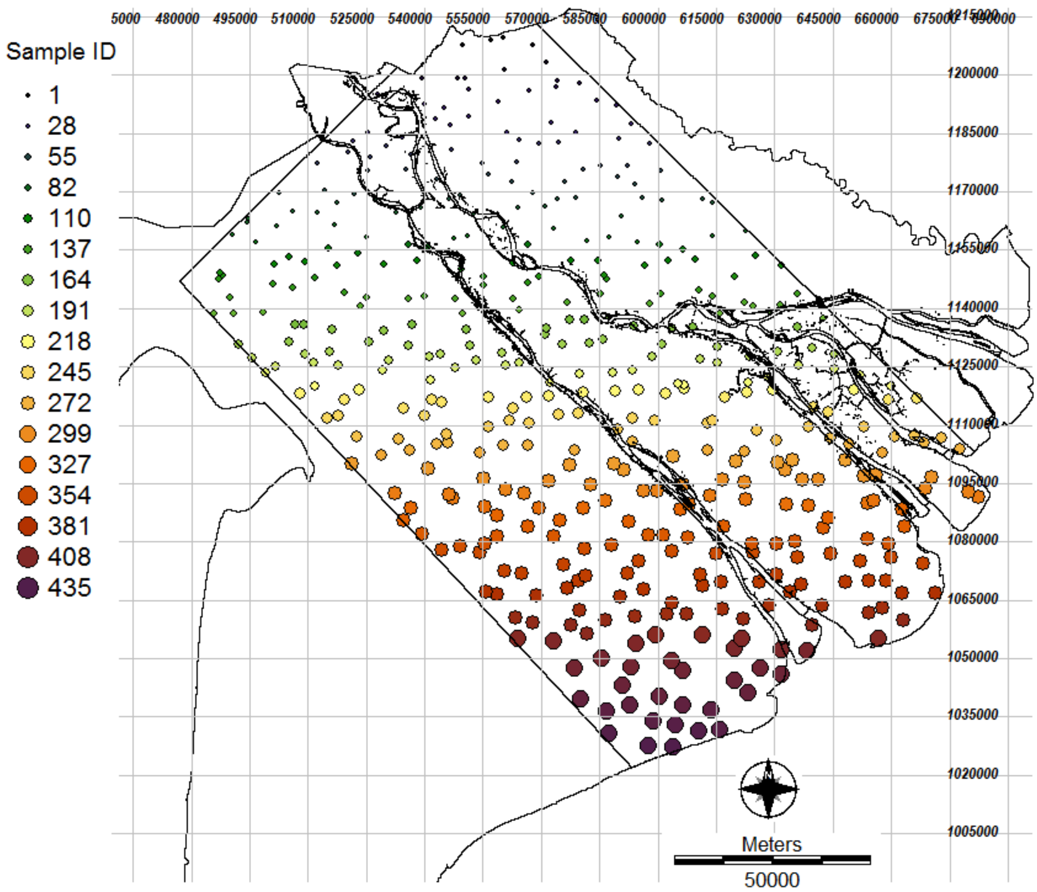


Figure 3. 9. Sampling sites including points located in the Mekong river.

In practice, there were many points located in channels, on bare lands or in residential areas. To ensure that data was collected for such points, the shifting sampling concept was used in which samples were taken from those farm locations nearest to the original point. These new points were called shifting points. In cases where the distance from the shifting point to original point was more than 1km, this point was ignored. However, during the survey, no shifting point was further than 1km from the original one.

3.5.2. The questionnaire

A questionnaire was designed to obtain relevant data including farm information (ID, name of farm, size, coordinate X and Y, crop types, integrated farm with fish or monoculture, soil type, soil texture) and pesticide data (including name and type of pesticide, dosage, number of application, total pesticide expenses per hectare); See text box 1. Each questionnaire contained geographical data which was imported to a handheld GPS device used to find the location for each sample. The field survey was carried out over 4 months (from 10th March to 10th July 2009).

Text Box 1: QUESTIONNAIRE FOR PESTICIDE AND LAND-USE IN SOUTHERN VIETNAM

Name of owner :……………………………………………………………………………………………………….

Name of farm:…….

Reference no: …………………………………… GPS coordinate ………………………………….

Location/address : ………………………………………………………………………………….

Size of farm (ring) ……………………. ha IPM farmer Y N

Crops: ……………………………………………. ………………………………………………..

Where did you learn to use pesticides: ……………………………………………………………………

Chemical name	Rainy season			Dry season			Reason for use
	No. app	g/ha/mth	H/L	No. app	g/ha/mth	H/L	

3.5.3 GPS support

To locate a sample point in the field, a hand held GPS (Global Positioning System) device was used. The Garmin Etrex HCX 60 used was able to receive signals from up to 12 satellites to calculate the position and planning the route to approach a target. The road map system in the Mekong delta was not updated within the GPS and therefore approaching a target mainly relied upon compass and distance calculation functions generated from GPS.

Due to the complexity of the river and canal systems in the Mekong delta, it was not easy to approach more than a few sample points each day. Although 2 points may appear to be close together they can in reality be separated by a small canal, for example. Consequently, a paper map of the Mekong delta (scale 1:500,000) with channel system information was used to plan a set of target points (usually 5 to 8 points) which were not separated by river or canals.

3.6 Pre-processing of data

3.6.1 Spatial data sets

Not all spatial data downloaded from different resources was in a similar projection system and so the geo-referencing of data sets needed to be unified prior to use in the spatial database and models. The PROJECT module was used to transform all raster and vector layers from their current referencing system to the UTM-48N system (Universal Transverse Mercator- Zone 48). The process uses a re-sampling procedure with the options of bilinear analysis. The computation process adopts a value based on the distance-weighted average of the values of the four nearest cells in the input image. This option was chosen because the input image was quantitative (Eastman, 2011). In some cases, low resolution images after re-projection will be distorted and do not match the reference image template (usually the study area image). To correct them, the RESAMPLE module was called to correct the geo-coordinates by matching the ground control points (GCPs) between the template image and the distorted one (Salam *et al.*,2003; Maria, 2002).

3.6.2 Pesticide data unit conversion

Pesticides used in Mekong delta exist in solid and liquid forms. Farmers apply pesticides in the field based on the manufacturer's instructions regarding the amount of gross product per unit area. Some chemicals are mixed with additives to make them easier to handle during application. Consequently, it was necessary to allow for these additives when calculating the quantity of active ingredient used. Each substance was re-calculated based on the percentage concentration of the active ingredient, based on data from the Vietnamese Ministry of agriculture and Rural Development and additional databases from the Agriculture Department of the Philippines (MARD, 2009; FPA, 2008). With this data, it is simple to convert the gross product volume into pure weight of pesticide. There are two cases for converting pesticide as used in Vietnam:

- With the pesticide in solid form, the label on pesticide products will show the concentration in g/L or g/kg. The pure chemical in g was determined by the percentage of the original chemical in the total weight of gross products (container is not included).
- With the pesticide in liquid form, the label on the trading product will show the information on ml/L (meaning volume per volume). The conversion relies upon specific weight data supplied to the users via the product label or in the

pesticide registration list (FPA, 2012). If the concentration shown on the label is concentration (%) per volume, the pure pesticide in g can be estimated by multiplying the percentage concentration and specific weight (equation 3.1).

$$\boldsymbol{M_{gr}} = \boldsymbol{Concentration}(\%) * \boldsymbol{Specific\ Weight} \qquad \text{Equation 3. 1}$$

Where M_{gr} is pesticide in g, and specific weight is measured in g/L chemical

3.7 Modelling orientation

3.7.1 The runoff model

A runoff model simulates the water runoff from a watershed or grid cell or a hydrological response unit. The grid-cell used in this study was the same size as the original pixels in the Landsat images. This study applies the curve number method for predicting runoff which followed the methodology of USDA (United States Department of Agriculture) developed in 1980s by USDA (1986). The key point in this method presents a methodology to identify the CN number (Mishra, Tyagi, Singh and Singh, 2006; Chow, Maidmen and Mays, 1988) based on several factors which are closely related to land-use and land treatment, soil type, rainfall, and topography condition. The model detail description and database requirements will be mentioned in further chapters.

Runoff volume results from a rainfall event and locates a specific amount of water in a watershed. After a particular time, the amount of rainfall will be affected by a variety of factors such as infiltration, absorption, vegetation cover, plant intake, which reduces the rainfall volume. The remaining amount of water will then be affected by topographical conditions which determine how it moves to other places. This is called the runoff route.

The runoff accumulation is determined by estimating the peak discharges. This was estimated by using the graphical peak discharge method (USDA-SCS, 1986) which is based on the estimation of unit peak discharge, the size of the drainage area and the undulating conditions in that area.

3.7.2 The Soil erosion and sediment accumulation model

The soil erosion model basically relies upon implementation of the mathematical model USLE developed by Wischmeier and Smith (1978). The model is an equation which multiplies 5 calibrated factors related to rainfall, soil types, slope and steepness, land-use and land treatment, and farming practice. This equation was improved and developed to adapt many conditions and with variety purposes of users. In the present study the MUSLE (Modified Universal Soil Loss Equation) by Renard and Stone (1982) was applied to calculate soil erosion and sediment yield based on runoff volume. The advantage of this version is that the model can be applied for a single rainfall event whereas the USLE must be applied over a long time period and simulating the total average soil loss for whole a year. Further detail will be discussed in chapter 5.

3.7.3 Pesticide runoff and accumulation model

Pesticide runoff and accumulation can be calculated based on the type of sediment and water runoff model. The pesticide losses were calculated over 2 periods. In the first period, pesticide losses are computed taking account of the preventive action of foliage cover, direct plant uptake and direct merging into the water body using the equation of Huber et al (1998). The second period of pesticide loss takes rainfall into account. Pesticide volume was calculated based on the concentration of pesticide in water and the concentration in sediments when runoff takes place. The gross accumulated pesticides were estimated by the runoff route and the amount of water and sediment load after a particular time. This gross accumulation is based on a simple concept: the total pesticide accumulation at a plot of land after a time will equal the already existing amount plus the amount received from other plots when runoff, and deducting the amount runoff to other plots. The equation to describe this concept will be presented in Chapter 6.

3.7.4 Pesticide risk assessment on aquaculture

The pesticide runoff and accumulation models generate results on current pesticide spatial distribution in a particular place at a specific time. These results can be used to reclassify the affected and unaffected areas relevant to any aquaculture development or existing farming system. Some of toxicity parameters such as LC_{50} (Half- population loss lethal concentration), LD_{50} (Half- population loss lethal dose) or EC_{50} (Half-population effect concentration) (PPDB, 2012; EPA, 2012; EPA, 2000) was used as a criteria for classification. The reclassified criteria were then imported to the system as a fuzzy dataset (Bosma, van den Berg, Kaymak, Udo and Verreth, 2012; José, Sánchez-Fernández, Carrasco-Ochoa and Martínez-Trinidad, 2012).

Chapter 4

Pesticide use in the Mekong delta: Current use status and GIS pesticide mapping

4.1. Global pesticide use

Pesticide use worldwide has become matter of concern. Farmers use many pesticides to protect their investments in which comprise land, seed, labour, fertilizer and other expenses. Use of pesticides is considered as a final step which aims to protect crops and realise profits from agricultural operations. However, as well as being beneficial they may also be the source of ecological, economic, social and health problems.

United states Environmental Protection Agency reports (EPA, 1997) have shown that in 1995, the values of pesticides purchased was over US $37.5 billion. Herbicides and insecticides were the most popular products with a value of US $16 and US $12 billion respectively. Fungicides and other agricultural chemicals were used less (figure 4.1). From 1997, total world expenditure decreased slightly, but re-established at US $39 million in 2007, with the proportional distribution among pesticides remaining more or less constant.

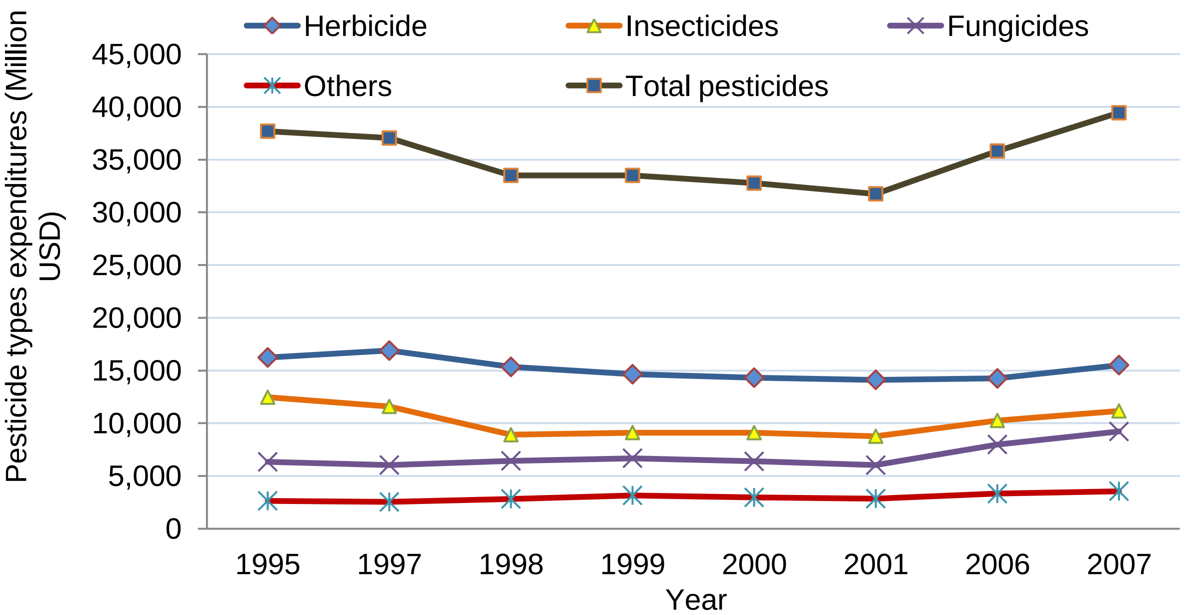


Figure 4. 1. Global pesticide type expenditure by years

Source: (Arthur, David, Timothy, and La, 2011; Timothy, David, and Arthur, 2004; David, Timothy, and Arthur, 2002; Arnold and Arthur, 1999; Arnold, 1997)

Insecticide use decreased slightly, possibly due to the perception that they are harmful but remained at 28% of total purchases in 2007 (figure 4.2). Herbicides, are used widely in developed countries and represented 38% of the pesticide market in 2007. By contrast, purchase of fungicides and other chemicals in the other hand increased slightly, representing 23% and ~10% respectively of the total in 2007.

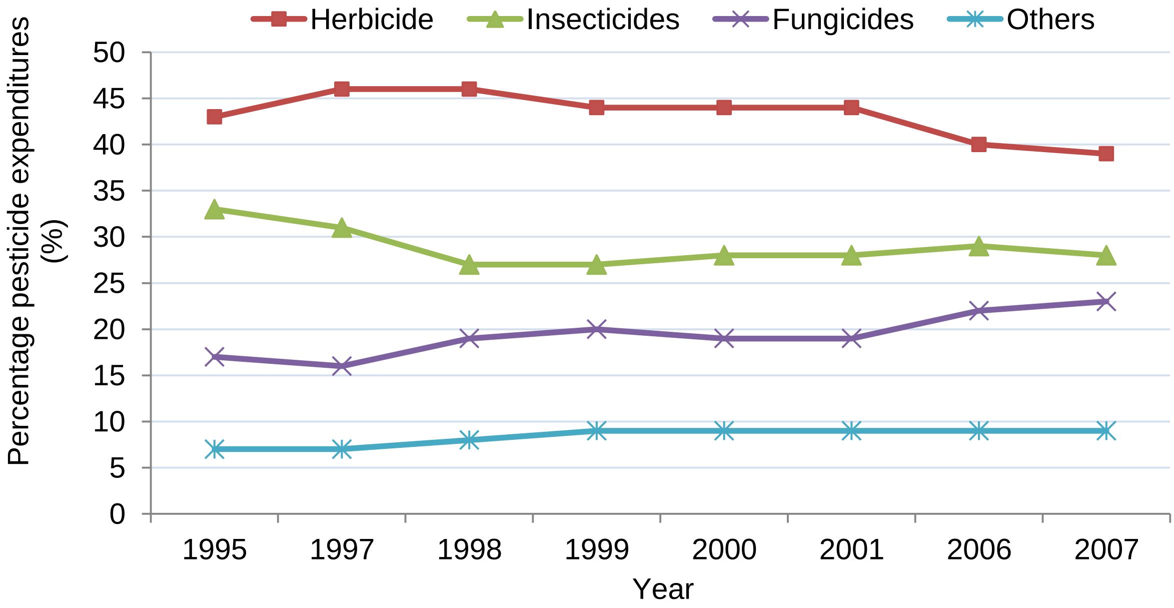


Figure 4. 2. Global percentage pesticide expenditures by years

Source: Pesticides Industry Sales and Usage, EPA reports,1995 to 2007

The total active ingredient in pesticides was greater than 28 million tonne per year from beginning of the 1990s (table 4.1). Total active ingredient in 1995 was 28.55 million tonne, decreasing to 25.23 million tonne in 2001. Herbicides are the most commonly used and the total active herbicide ingredient was 11.27 million tonne in 1997. Compared with other pesticide types, the active ingredient volume of herbicides was 1/3 higher than insecticides and over 3 times than that of fungicides. Insecticide usage was 7.5 million tonne in 1995; 26% of the total active ingredient volume. Other agriculture chemicals occupied 25% of usage. Although the weather and environmental conditions differ from year to year, the use of fungicide to control agricultural diseases has not changed greatly, ranging between a maximum of 2.78 million tonne in 1999 and a minimum of 2.36 million tonne in 2001.

Table 4. 1. Volume of Active Ingredient (Millions of tonne)

Pesticide types	1995	1997	1998	1999	2000	2001	2006	2007
Herbicide	11.05	11.27	10.74	10.2	9.72	9.35	10.09	10.48
(%)	*(39%)*	*(40%)*	*(38%)*	*(36%)*	*(36%)*	*(37%)*	*(39%)*	*(40%)*
Insecticides	7.5	7.35	7.13	7.08	6.77	6.16	4.775	4.46
(%)	*(26%)*	*(26%)*	*(25%)*	*(25%)*	*(25%)*	*(24%)*	*(18%)*	*(17%)*
Fungicides	2.75	2.69	2.76	2.78	2.58	2.37	2.595	2.59
(%)	*(10%)*	*(9%)*	*(10%)*	*(10%)*	*(10%)*	*(9%)*	*(10%)*	*(10%)*
Others	7.25	7.105	7.61	8.33	7.68	7.345	8.525	8.525
(%)	*(25%)*	*(25%)*	*(27%)*	*(29%)*	*(29%)*	*(29%)*	*(33%)*	*(33%)*
Total pesticides	28.55	28.42	28.25	28.39	26.75	25.23	25.98	26.06
(%)	*(100%)*	*(100%)*	*(100%)*	*(100%)*	*(100%)*	*(100%)*	*(100%)*	*(100%)*

Source: Pesticides Industry Sales and Usage, EPA reports,1995 to 2007

Table 4.1 shows that of all pesticides only insecticides have decreased in use since 1995, and particularly between 2001 and 2007. Insecticide use in future is likely to decrease further due to persistence and harm to the environment and agricultural product (Forget, Goodman, and de Villiers, 1993).

Approximately 85 % of total pesticides use are for agricultural activities (WRI-World Resources Institute, 2012) and about three quarters of this occurs in developed countries where herbicides were employed mostly. By contrast, the remaining pesticide use is in developing countries, where insecticides dominate. Although pesticides use in developing countries was less than developed countries (figure 4.3), it has been predicted that the usage of developing countries will grow more quickly than elsewhere in the future (WRI-World Resources Institute, 2012).

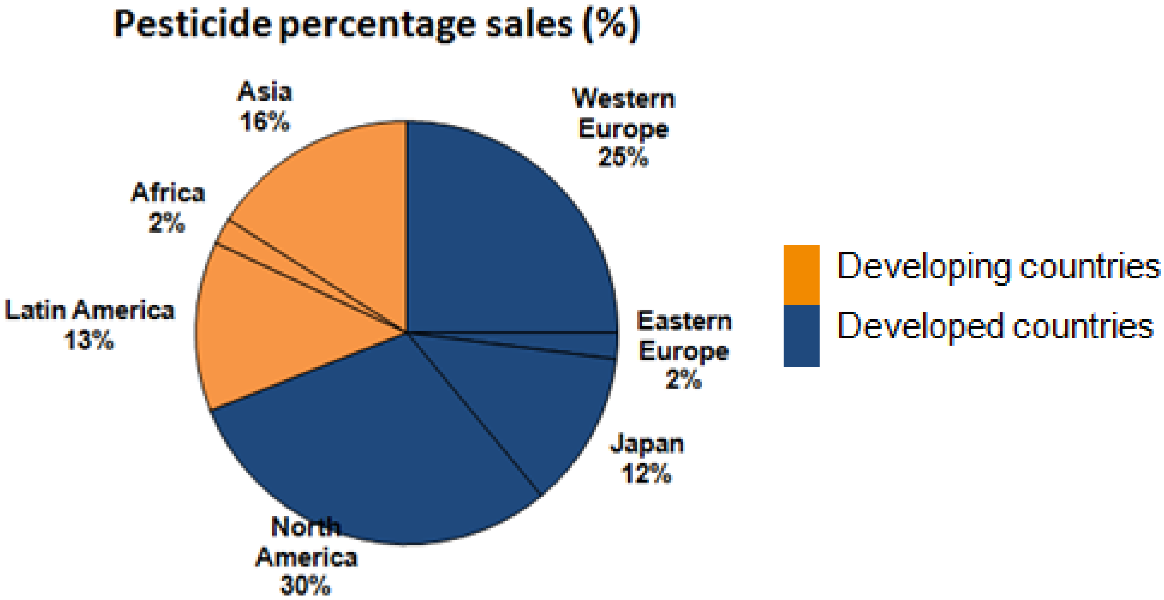


Figure 4. 3. Pesticide percentage market sale in the world in 1994

Source: As cited from (WRI-World Resources Institute, 2012)

4.2. Pesticide used in Asia

Agricultural production in Asia was significantly increased by the "Green Revolution" which occurred from the late 1960s. As reported by the International Rice Research Institute (1985), the principal factors contributing to the increase of agricultural products were a 32% expansion of cultivated areas, 25% improvement of irrigation systems, 22% increase in use of fertilizer, and 21% increase in use of modern disease resistant seed. In addition, an increased use of pesticides has been one of the most important factors to secure the crops against the failures caused by pests.

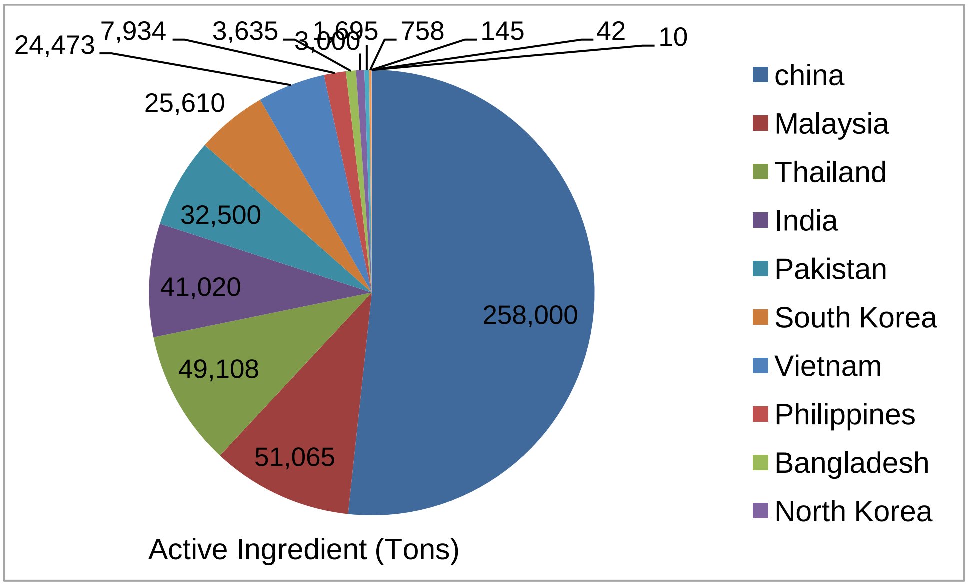
In most developing countries agricultural activities dominate the national economy, so there is a great need to use pesticides to support this and to produce off-season fruit and vegetables for export to other countries, or to increase the number of crops for profit in the year (Forget et al, 1993).

Prior to the 1960s, pesticides were not commonly used in Asia and had been applied mainly to control grass (herbicides). After the "Green Revolution" in Asia, pesticide production quickly became a major business in developed countries. During the 1970s, USA, Britain, Germany, France, Switzerland, Italy and Japan controlled over 75% of world chemicals and supported over 85% of the pesticide demand for Asian agricultural activities (Pingali and Gerpacio, 1997). In 1997, the FAO (1997) revealed that the increased use of pesticide throughout the world was 2 million tonne, compared with the previous decade tonne of which approximately 25% was applied in Asia. The International Food Policy Research Institute (IFPRI, 1996) reported that use of pesticide use was 23% of global use for rice and maize production and approximately 26% in fruit and vegetable production. Global value of pesticides used in rice production alone was US $3.2 billion, with up to US $2.6 billion of this used in Asia.

Although pesticides were produced intensively in developed countries, control of pesticide use and environmental risk assessment in those countries of use was not a priority. Ironically, around 25% of pesticides produced by USA in the 1970's were banned chemicals, either restricted or not registered for use in the USA (Weir and Shapiro, 1981). Moreover, the pesticides used in Asia were criticized as almost all belonged to high risk categories I and II (following the classification of WHO) (Warburton, Palis, and Pingali, 1995; Weir et al, 1981).

Data from IRRI (1995), revealed that Japan was the highest consumer of pesticide, using 61% of the total pesticide in Asia, of which approximately 71% was herbicides, 72% fungicides and 45% insecticides. In Vietnam, 80% of agricultural products produced were dependent upon insecticide application (Tennenbaum, 1996).

In 2004, the annual active ingredient usage of Asia was roughly 500 thousand tonne with a value of US $8.3 billion (figure 4.4), although these reported levels could be much less than the actually used. Pesticides use has tended to increase in Asia while in other continents it has remained static since the 1990s. tonne. Fig 4.4 illustrates recent usage of pesticides in Asia (FAO, 2005) in terms of tonnage used and cost.



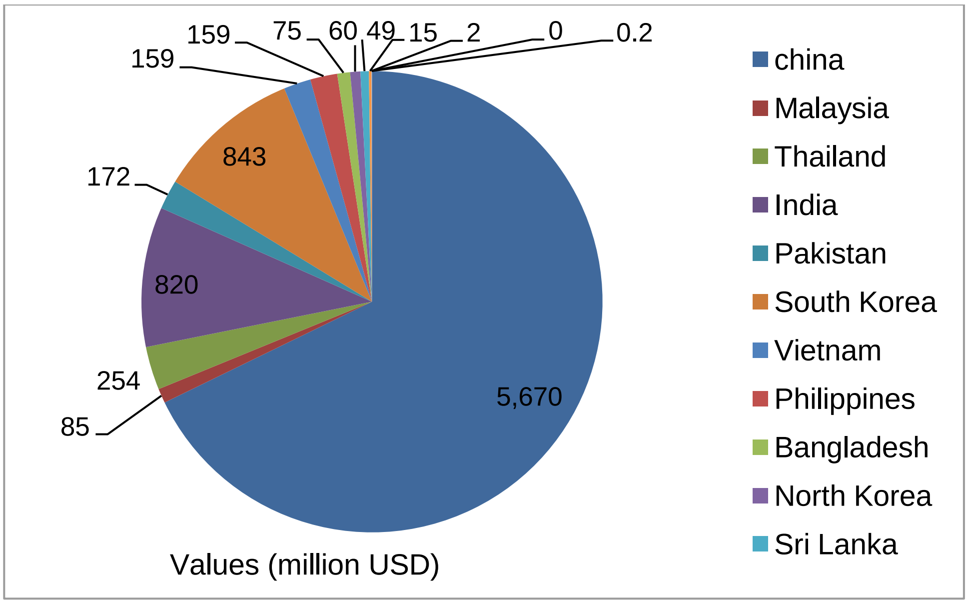


Figure 4. 4. Active ingredient volumes and market values in Asian countries in 2004

More recent information on pesticide use given in figure 4.5 (FAO, 2012b) indicates of the countries investigated the Republic of Korea and Thailand use pesticides most intensively for agriculture production.

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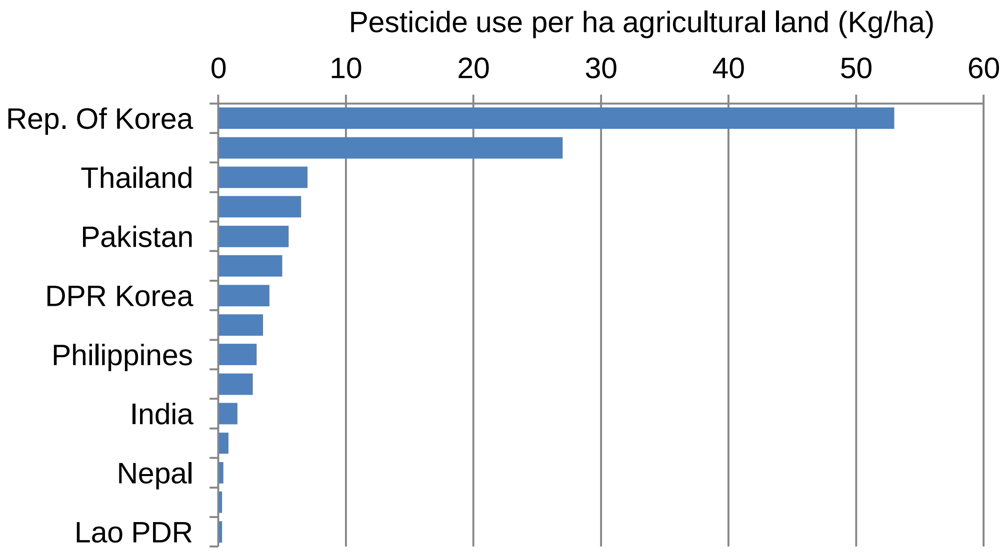


Figure 4. 5. Pesticide applied per hectare

(FAO, 2012b)

Proportional use of insecticide, herbicide and fungicide was dissimilar across the region (figure 4.6) with a trend of less developed countries using more insecticide

(FAO, 2012b). In Thailand and Malaysia, total percentage herbicide and fungicides dominated the pesticide use (at ~80 %)

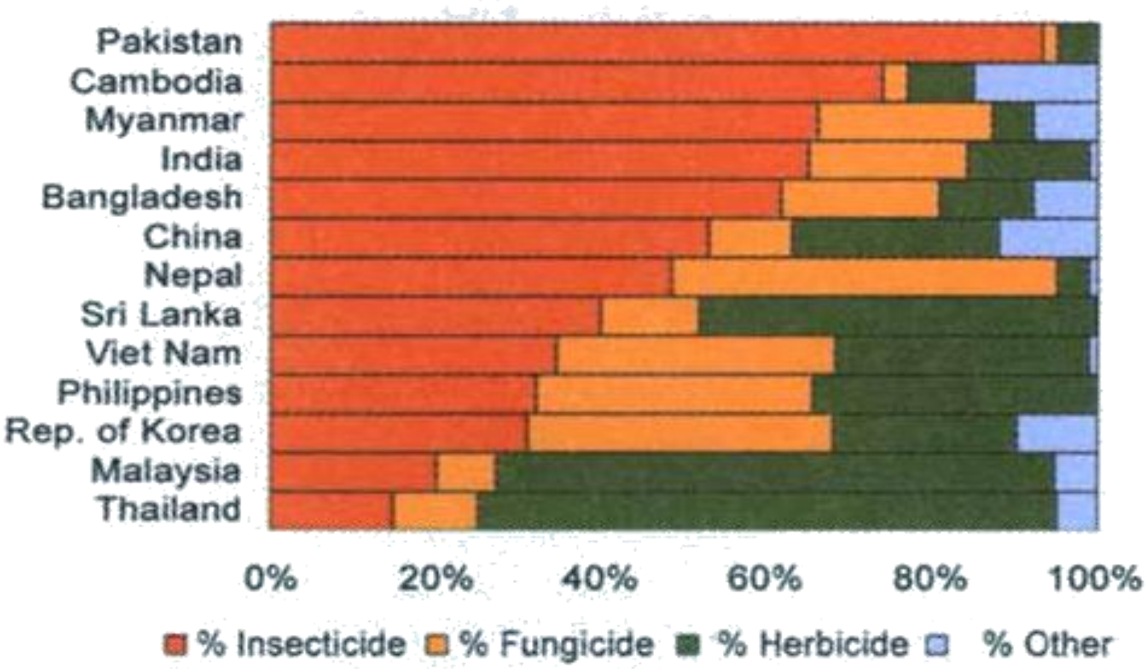


Figure 4. 6. Proportional distribution of pesticide use in Asian countries.

(FAO, 2012b)

4.3 The current status of pesticide use in Vietnam and the Mekong delta

Vietnam is a developing country with an economy dominated by agriculture. The Red River delta in the north of Vietnam and the Mekong delta in the south are both very famous for rice cultivation which employs intensive pesticide use. Especially in the south, pesticides are also used in fruit cultivation which is the second most important product, after rice.

4.3.1 Pesticide use in Vietnam, a review.

In Vietnam, pesticides are considered as a powerful tool to control and secure crops. Before 1992 in Vietnam, 77 active ingredients were registered, with 96 formulated product names and 25 overseas companies were permitted. In the following ten years, there was a rapid increase to having up to 400 active ingredients, over 1000 formulated named products and more than 100 companies working in Vietnam (Quyen, Dan, and Nguyen, 1995). Latest records in 207-2008 show that ~75 thousand tonne of pesticides (equivalent ~$480 million) were legally imported to Vietnam (Vinachem, 2009)

Vietnam began to encourage pesticide use in agriculture activities to enhance rice production during the 1950s in the north of Vietnam (Dasgupta, Meisner, Wheeler, Xuyen and Thi Lam, 2007). At that time pesticides were applied freely without comprehension or regulation by government (Huan and Thiet, 2000; Pincus, 1995). From 1986, the pesticide market was formed by the private sector with some formulated factories granted licenses to formulate chemicals from imported active ingredients for agricultural uses. In the next decade, pesticides became extremely marketable products (Dasgupta *et al.*,2007).

The Asia regional workshop on the implementation, monitoring and observance of the international code of conduct on the distribution and use of pesticides noted that 99% of the important pesticides in Vietnam were bought from developed countries (Hoe, 2004). In 2004, imported pesticides reached ~48,000 tonne of formulated product (containing ~24,000 tonne of active ingredient tonne) with the equivalent values of US $~160 million. From only around 20,000 tonne imported in 1991, pesticide imports into Vietnam have increased significantly (figure 4.7) reaching 50,000 tonne by 2004.

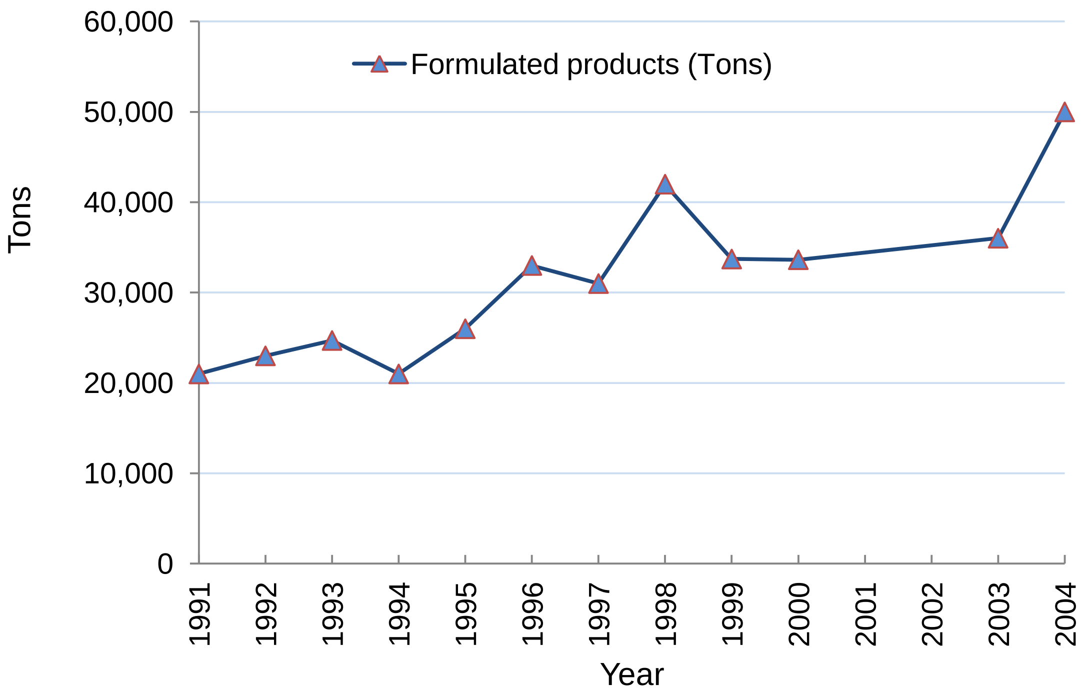


Figure 4. 7. Imported annual pesticide (tones) in Vietnam between 1991 and 2004.

Of the total pesticides used in Vietnam, fungicides and herbicides tended to increase from 1991 to 2004 whereas insecticides decreased significantly (figure 4.8), especially between 1991 and 1999. Use of other types of agro-chemicals was very consistent at a maximum of 3% in 2003.

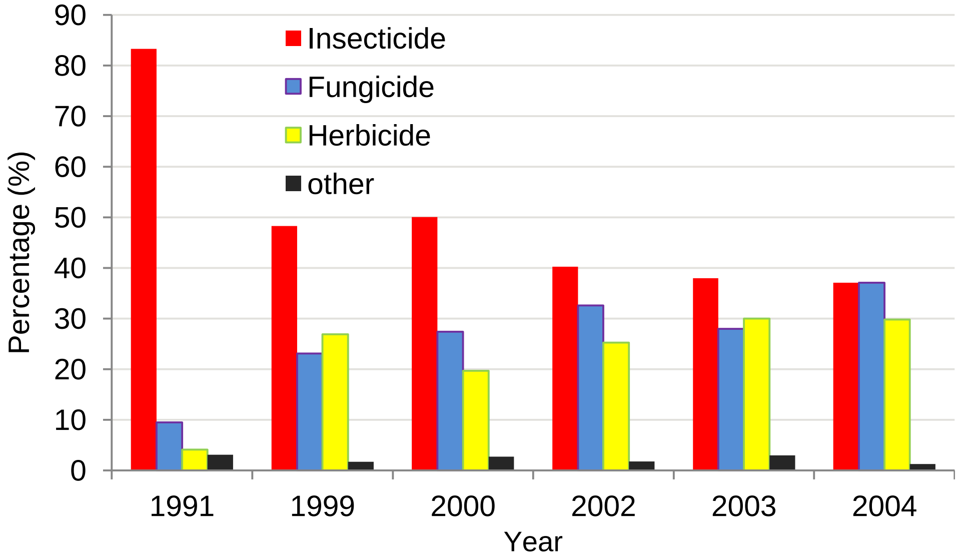


Figure 4. 8. Proportion use of pesticide types in Vietnam from 1991 to 2004

4.3.2 Pesticide use in the Mekong delta

The Vietnamese Mekong delta covers approximately 2 million hectares of fertile land and employs about 24 million labourers to produce ~20 million tonne of rice yearly representing 64% of national rice production (GSO, 2012c). Rice production has rapidly increased from 10.3 million tonne in 1975 to 22 million tonne in 2010 (GSO, 2012c), greatly assisted by use of higher seeding rates and use of fertilizers. This, in turn, resulted in unexpected pest and disease infections and the use of more (Huan *et al.*,2005)

A pesticide survey in 1999 in two intensive rice cultivation provinces showed a mean dosage of 1.8 kg active ingredient (a.i) per hectare per year, distributed between insecticide ~50%, , herbicide ~25% of and fungicide~25%, with small quantities of molluscicide (Berg,2002; Berg, 2001). 64 pesticides were found in the survey the most common being Valydamycin, Propiconazole, Hexaconazole, Fenobucarb, Cartap, Fenoxapro-p-ethyl, Pretilachlor and Fenclorim and there were seasonal differences in application rate.

A further survey between 2001 and 2002 showed that insecticide and fungicide applications in winter-spring period and summer-autumn season had decreased (Huan *et al.*,2005) with the most popular insecticides at that time being Endosulfan, Lindane, Chlorpyrifos, Diazinon, Fenobucarb, and Fenvalerate. Long persistence pesticides like organochlorines were cheaply available and were still be the preferred insecticides for control of pests and malarial vectors (Carvalho, 2011)

Analysis of pesticide residues in the aquatic environment have detected some polar herbicides, fungicides and insecticides such as Diazinon, Fenotrothion and cyclic Endosulfan sulphate. The most commonly detected was Diazinon at levels up to 42.8 ng/L, and Organochlorines at 0.01 ng/g sediments. DDT-the most persistent Organochlorine compound - was found throughout the delta (Carvalho *et al.*,2008; Dang, Nguyen, Nguyen, Luu, Carvalho and Cattini, 1998)

(Nguyen Huu Dung and Tran Thi Thanh Dung, 1999) showed that pesticide usage in 1996 and 1997 was just over 1 kg/ha/yr, with. insecticide being the most common at ~400 g/ha/yr (39%) and fungicides and herbicides at around 300 g/ha/yr (~30%) (table 4.2). According to Berg (2002), pesticide usage in 1999 was considerably higher at around 1.8 kg/ha/yr although this was averaged over a range of different farming practices (table 4.3).

Table 4. 2. Mean usage (g a.i./ha/yr) (Survey 1996-1997)

	Insecticide	Herbicide	Fungicide	Total Pesticide
1996-1997	394.2	323.1	300.0	1017.3
Percentage (%)	39	32	29	100

Source: (Nguyen Huu Dung et al, 1999)

Table 4. 3. Mean usage (kg a.i/ha.yr) in different rice farm types (survey 1999)

	Rice application		Rice-Fish Application		Rice-Fish IPM application		Rice IPM Application	
	(Kg)	(%)	(Kg)	(%)	(Kg)	(%)	(Kg)	(%)
Insecticide	0.93	52	0.52	51	0.13	23	0.2	33
Herbicide	0.31	17	0.2	20	0.17	30	0.14	23
Fungicide	0.55	31	0.29	29	0.27	47	0.26	43
Total pesticide	1.8	100	1.01	100	0.57	100	0.6	100

Source: (Berg, 2002)

The most comprehensive survey on pesticide use was conducted by the World Bank (2004), based on 900 samples from over 3,000 hectares, recording a mean annual use rate of 2.16 kg/ha/yr (figure 4.9). Insecticides and fungicides had the highest usage at 43% and 29% of total pesticides used respectively, but herbicides have been used less recently in rice cultivation. The amount of fungicides used increased significantly from ~300 g/ha/yr in 1996 up to ~923 g/ha/yr in 2004.

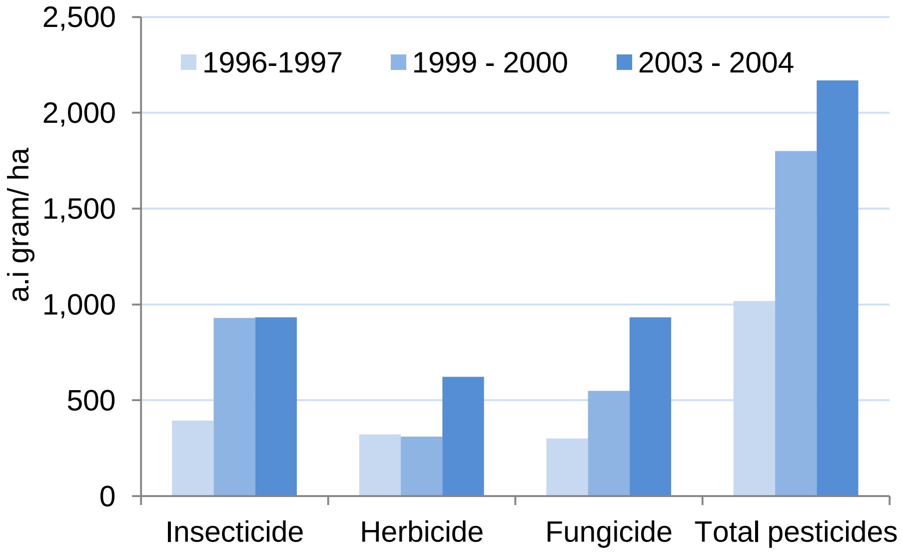


Figure 4. 9. Mean annual use of pesticide per hectare in 1996- 2004.

Source: World Bank (2012).

4.4 Pesticide residues reported in fish

In 1980s, pesticides were shown to have marked effects in several cultured aquatic species (Valmonte-Gerpacio, 1995). The data revealed high herbicide and fungicide residues, which decreased fish survival and affected physiology (Abdullah, Bajet, Matin, Nham and Sulaiman, 1997; Cagauan, 1990); (Bottrell and Weil, 1995). Tilapia was the most commonly fish tested to determine the acute toxicity and the residues and physiological condition for a range of toxic substances (Jayaraman, Celino, Lee, Mohamad, Sun, Tayaputch and Zhang, 1989; Isensee and Tayaputch, 1986; Jayaraman,1986; Mohamad, Juru and Ismail, 1986; Argente, Seiber and Magallona, 1977). Cagauan (1990) and Dela (1981) tested the acute toxicity with the toxic parameter of LC_{50} (in different time of 24,48,72,96 hours) on tilapia with Cypermethrin (insecticide) and Organostannous (molluscicide) to find the relationship of toxicity and the of physiology of hematological and histopathological changes. Lyndane (Reyes and dela, 1983; Medina-Lucero, 1980; Kok and Pathak, 1966)

Current studies have focused on the measurement of persistent Organochlorine by Gas Chromatography method, and found the Organochlorine presented in all samples of fish tissues or fish oil of Nile tilapias (Botaro, Torres, Malm, Rebelo, Henkelmann and Schramm, 2011; Sarkar, Bhattacharya, Bhattacharya, Chatterjee, Alam, Satpathy and Jonathan, 2008; Jacobs, Santillo, Johnston, Wyatt and French, 1998), and the discovery the ranking of residue amount of DDT>Heptachlor>Lindane>Aldrin in catfish tissues sampled in the south of Bangladesh (Das, Khan, Das and Shaheen, 2002). The residues of Andrin, Heptachlor and HCH (Hexachlorocyclohexane) easily found in tissues of in samples collected from worldwide sampling from 15 countries on the species *Sparus aurata* (Kalyoncu, Agca, and Aktumsek, 2009).

Although pesticide residues have been detected in fish, water samples, sediments, the data from gas chromatography has shown that the residue concentration still meets the food safety requirements (Carvalho et al, 2008). The analyses from studies show that the amount residue of pesticides on aquaculture was not enough to affect to the quality of aquaculture products (Carvalho *et al.*,2008; Klemick and Lichtenberg, 2008; Nguyen, Nguyen and Bayley, 2008)

4.5. Field survey of current pesticide use in the Mekong delta, 2008-2009

A field survey of current pesticide use in the delta was carried out as part of this PhD research in March-2009 with the objective of identifying pesticides used, the quantities applied and their geographical distribution. Data was generated through questionnaires at 343 rice farms within the area of ~19,000 km^2. The methodology for sampling has been presented in chapter 3 (see 3.5)

Pesticide usage was expressed as the quantity of formulated product and as quantity of active ingredient. The formulated product is a combination between the active ingredient and other additive substances or water. Active ingredient was calculated using product data from the registered pesticide list of the Philippines Agriculture Department (FPA, 2012).

The survey revealed that 96 pesticides belonging to 23 pesticide groups are currently used in the delta (table 4.4). Many pesticides (34) belonged to Group II, defined as moderately hazardous (WHO, 2006), while highly hazardous (Group I) pesticides were rarely used. The remainder were in the less toxic Groups III and IV.

Table 4. 4. Pesticides used in the Mekong delta from the 2009 field survey.

Pesticide Group	Chemical names	Sample rates	Gram/ha	Toxicity class (WHO, 2006)
Dicarboximide	*Isoprothiolane, Iprodione*	251	3000	II,III
Carbamate	*Fenobucarb, Carbosulfan, Mancozeb, Carbaryl, Propineb*	313	2030	II, II, IV,II, IV
Conazole	*Hexaconazole, Tricyclazole, Difenoconazole, Propiconazole, Prochloraz, Flusilazole*	334	2030	III, II, II, II, II, II
Chitin synthesis inhibitor	*Buprofezin*	272	1065	III
Organophosphate	*Methidathion,Diazinon, Profenofos, Lyphosate, Quinalphos, Phenthoate Dimethoate, Acephate, Chlorpyrifos ethyl, Trichlorfon*	232	1041	Ib, II, II, III, II, II, II, II, III, II
Others	*Pymetrozine, Thiosultap, Metalaxyl, Nitrobenzen, Paraquat, Penoxsulam, Bispyribac sodium, Carbendazim, Flusilazole, Fenclorim*	99	1014	III, II, II, II, IV, III, III, II, IV
Molluscicide	*Niclosamide, Metaldehyde*	220	949	II, II
Phenoxy compound	*Fenoxaprop ethyl, Dichlorophenoxy, Cyhalofop-butyl*	182	924	III, II, II
Anilide	*Pretilachlor, S-metolachlor, Butachlor, Propanil, Thifluzamide*	277	490	No data
Sulfonylurea	*Pyrazosulfuron, Ethoxysulfuron*	84	386	No data
Antibiotic fungicide	*Thiophanate-methyl, Validamycin A, Carbendazim, Albendazole, Diafenthiuron, Kasugamycin*	204	344	IV, No data, IV, IV, III, IV
Aromatic acid	*Bispyribac-sodium, Quinclorac*	94	337	III, III
Abamectin	*Avermectin b1b, Avermectin b1a, Amamectin benzoate*	204	323	Ib
Neonicotinoid	*Acetamiprid, Thiamethoxam, Imidacloprid, Dinotefuran*	294	321	Ib, II, No data, II
Triazine	*Pymetrozin*	203	229	III
Strobilurin	*Azoxystrobin, Trifloxystrobin*	94	213	U, U
Pyrethroid	*Deltamethrin, Cypermethrin, Lambda-cyhalothrin, Gamma-cyhalothrin*	187	148	II, II, II, III
Pyrazole fungicide	*Fipronil, Pyrazosulforon ethyl*	179	135	II, U
Safener	*Fenclorim*	217	79	U
Benzimidazole	*Paraquat, Nitro benzen, Metalaxyl*	23	78	II, II, II
Organochlorin	*Chlorfluazuron, Endosulfan*	83	68	U, II
Oxadiazine	*Indoxacarb,*	71	64	II

The highest usage was found in three types of pesticide Dicarboximide, Carbamate and Conazole. which were applied at rates of 3 kg/ha/y, 2 kg/ha/y and 2 kg/ha/y, respectively (figure 4.10). Organophosphates and Chitin synthesis inhibitors which are considered as some of the longest persistent types of pesticides to the environment (Minh et al, 2007) were applied at over 1kg/ha/y. Perhaps the most dangerous type of chemical in use was Organochlorine (Capkin, Altinok, and Karahan, 2006) which is not only highly toxic but has long persistence in environment, sediment and biota, and was applied at ~68g/ha. Even though Organochlorine (Chlorfluazuron and Endosulfan) are applied in small quantities, they were found in use in 83 of the 343 stations sampled. Although these pesticides are banned for use worldwide, including in Vietnam, by illegally produced and imported, they may still be found in any retailer in Mekong delta where they are preferred because of their strong effects and long persistence after application. Moreover, these pesticides are much cheaper compared to the others and can be stocked for a long time without degradation of their effects.

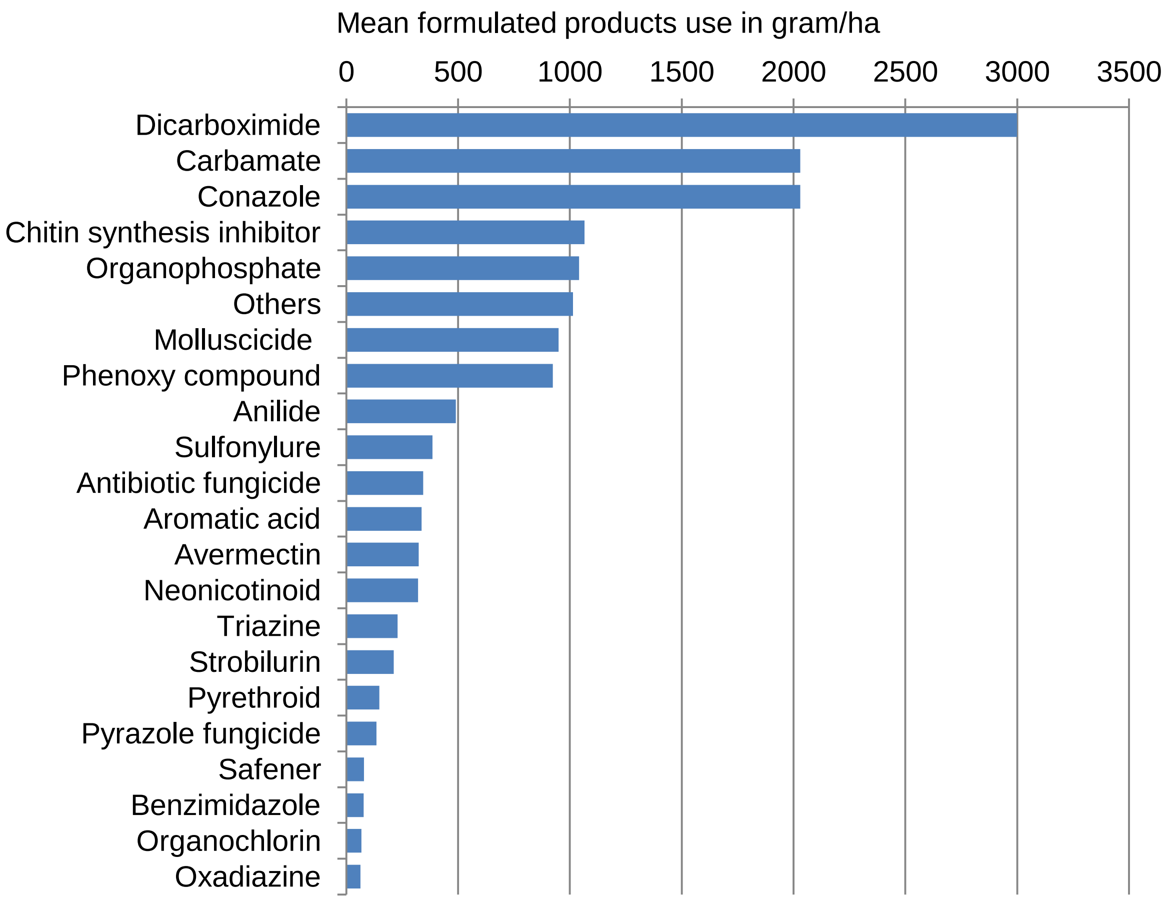


Figure 4. 10. Mean annual application of formulated pesticides (g/ha) in the Mekong delta. Based on 2009 survey data (this study).

The total formulated pesticide applied in the Mekong delta calculated from this survey was at ~14.12 kg/ha/y. This is much greater than the 1999 data from FAO which was less than 10 kg/ha/y (see figure 4.6) (FAO, 2012b). Overall, fungicides dominated in the farms with usage up to 5.82 kg/ha/y formulated products, at 41% of the total pesticides (figure 4.11). As in other Asian countries, insecticides were still widely used at ~5.3 kg/ha/y (~38% of total pesticides). While herbicides and other chemicals represented only ~20% of the total pesticides used.

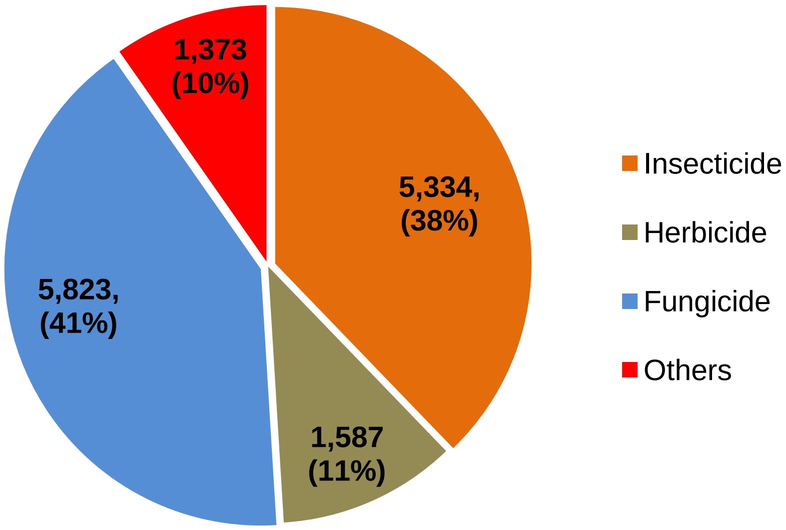


Figure 4. 11. Mean annual application of pesticide product types (g/ha/y) in the Mekong delta. Based on 2009 survey data (this study).

Substances from the Conazole group were found in 334 of the 343 stations sampled (figure 4.12). These chemicals are indispensable in the fight against fungal diseases of rice crops. The next highest rate was Carbamate found at 313 stations, followed by Neonicotinoid, Anilide, Chitin synthesis inhibitor, Dicarboximide, Organophosphate, Molluscicide and Safener found at 294, 272, 251, 232, 220 and 217 stations, respectively. Although molluscicide was applied only once per crop, the application rate was very high at more than 1 kg/ha.

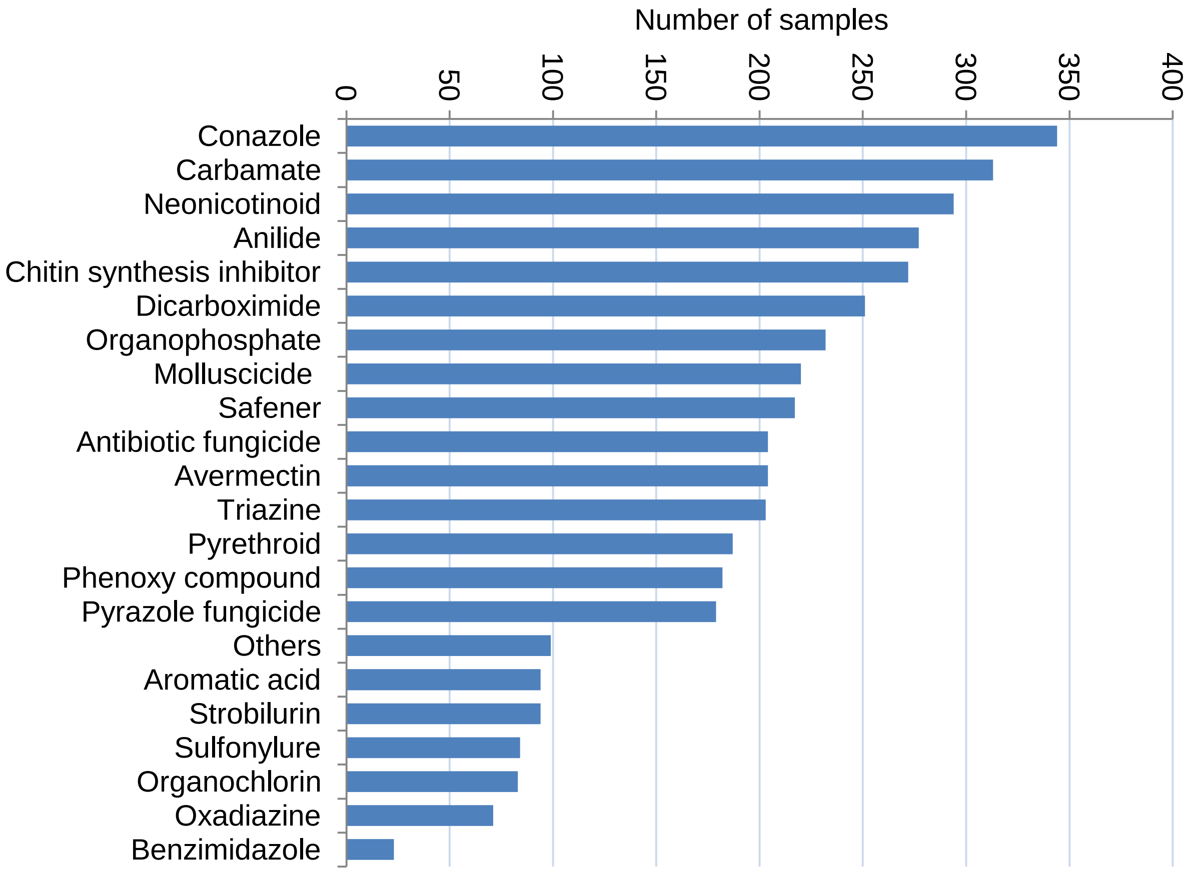


Figure 4. 12. Detection frequency of pesticide group in the Mekong delta.

Based on 2009 survey data (this study).

Pesticide (a.i) use differed between seasons with 975 g a.i/ha over the dry season increasing to 1,537 g a.i /ha over the wet season (table 4.5). There was a notable change in application rate of fungicides from 874 g a.i /ha over the wet season to 359 g a.i /ha over the dry season and a reduction in herbicide dosages from ~197g a.i /ha over the wet season to ~140 g a.i /ha over the dry season.

Table 4. 5. Active ingredient pesticides usage in g a.i./ha over the wet and dry seasons

	Insecticide	Herbicide	Fungicide	Total pesticides
Wet season	466	197.5	874	1537.5
Dry season	478	139.5	359	976.5
Total	944	337.5	1233	2514.

The total quantity of active ingredients applied was calculated to be ~2,514 g a.i./ha which is considerably higher than in previous years (figure 4.13) representing ~45% of the total pesticides used.

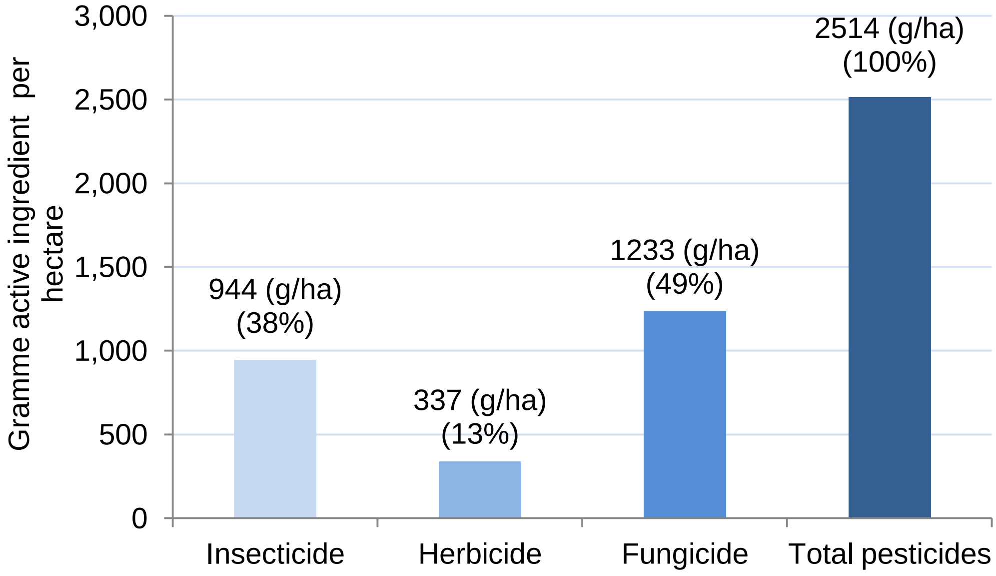


Figure 4. 13. Total use of active ingredients of pesticides in the Mekong delta. Based on 2009 survey data this study.

Comparing pesticide use from previous surveys it is clear that use in the delta has increased sharply from ~1 kg/ha/y to ~2.5 kg/ha/y (figure 4.14) a rate of over 115 g/ha/y. Fungicide use in rice paddies has increase markedly in recent years to a current rate of 1,200g/ha/y from ~300g/ha/y. By contrast, insecticide use has remained relatively stable in accordance with worldwide trends after a step increase from ~394g/ha/y in 1996.

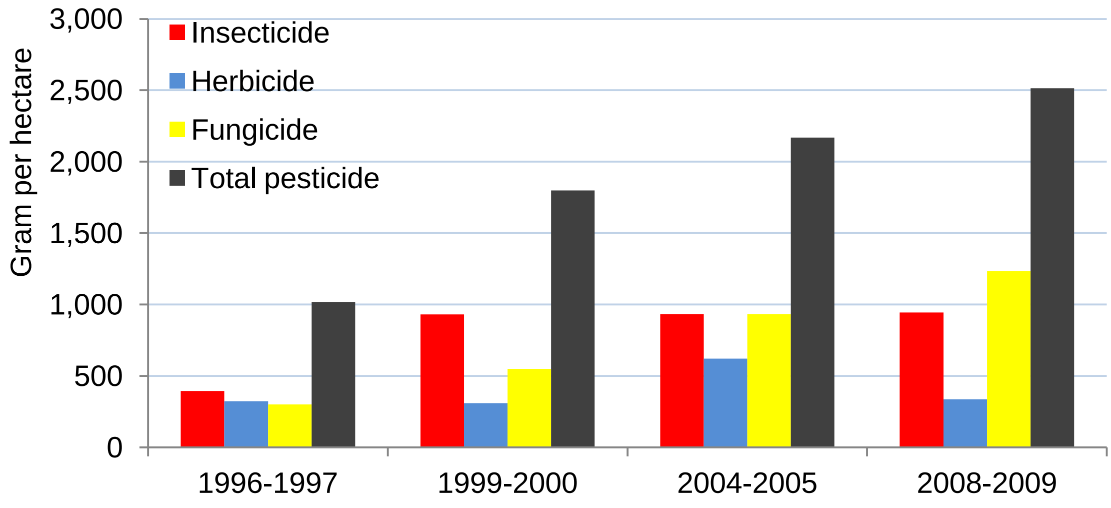


Figure 4. 14. Mean use of active ingredient of pesticides (g/ha/y) from 1996 to 2009. (World Bank, 2012a; Berg, 2001b; Nguyen Huu Dung et al, 1999)

4.6 GIS-based analysis of the spatial distribution and use of pesticides in the Mekong delta.

4.6.1 Databases and data layers construction

During field data collection the x and y coordinates were recorded for every station visited using a handheld GPS. Every instance of pesticide use could then be mapped to show the active ingredient usage in all 343 points on the ground. To enable this, a GIS database was linked to the attribute data (in DIRISI) and geo-locations so that spatial models could be developed to show the show the distribution of every type of pesticide in the Mekong delta.

The data collected in the questionnaire survey comprised ID, X and Y coordinates, current land-use, pesticide trade name, active ingredient, chemical family, dosage, percentage active ingredient, percentage of concentration, actual active ingredient use per hectare, recommend dosage, days of application and number of crops per year.

a. Land-use data

Land-use was the main factor affecting the use of pesticides and their distribution. A land-use data layer was constructed from 2 resources; satellite images and field survey data.

The concept of land-use classification is well known and has been widely used for the purposes of supporting policy makers for development. Land-use data was traditionally collected by field surveys and direct observation but remote sensing techniques allow up to date land-use and land cover classification (Campell, 2007; NASA Landsat program,2003; NASA, 2000; Lillesand *et al.*,1994).

Land-use data was derived by unsupervised classification of Landsat 7 ETM+ images, with a resolution of 30meters, in which the spectral values of every image pixel are ranked and placed into clusters (Thomas, Ralph, and Jonathan, 2008). Bands 1, 2 and 3 (Blue, Green, Red), 4 (Near Infrared), 5 (Middle Infrared) and 7 (Short Wave Infrared) were used in this analysis, the thermal infrared band (band 6) being ignored due to its lower spatial resolution and incompatibility with other bands. The isocluster technique was used within the IDRISI system to create an unsupervised set of clusters based on the 3 sub-modules CLUSTER, MAXLIKE and MAKESIG (Eastman, 1999). CLUSTER uses a histogram peak technique in which peaks are detected in a one-dimensional histogram. Once the peaks have been identified, all values which are not peaks will be assigned to the nearest peak, new assigned values are grouped into a class, and the division of classes is decided as the midpoint between the peaks. In the broad classification, a class must contain a frequency higher than all of its non-diagonal neighbours. In the fine classification, this is relaxed, permitting one non-diagonal neighbour to have a higher frequency. This accommodates true peaks which are otherwise missed because a nearby peak of greater magnitude obscures the usual dip between the peaks.

The overall process, in which 20 clusters were used in the initial classification, is shown in figure 4.15.

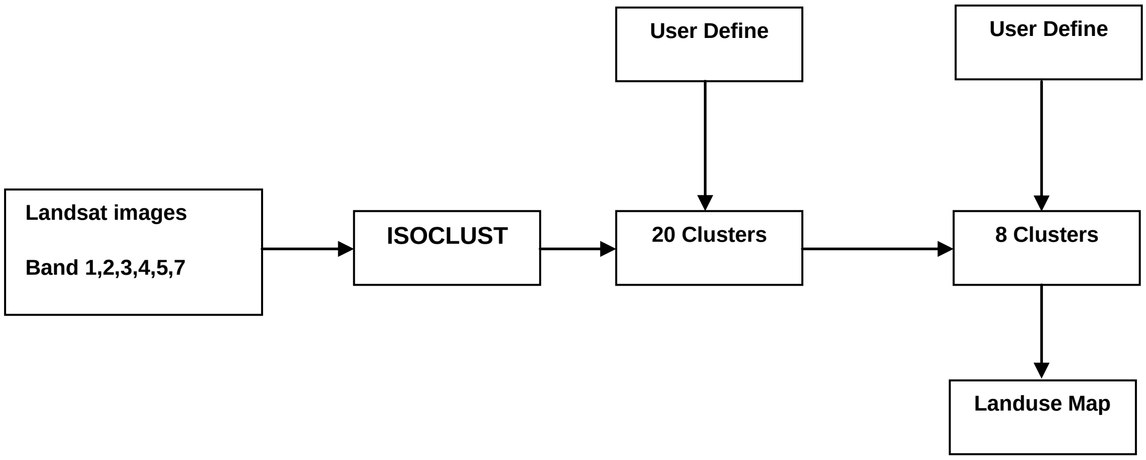


Figure 4. 15. Schematic representation of the land-use classification process.

Unsupervised classification may not be fully accurate, for example mis-identifying as terrestrial features water bodies which have high turbidity or chlorophyll levels. To correct this problem, a further step was carried out to re-classify the 20 clusters into 8 land-use categories. This was based upon the visual results from the unsupervised classification combined with regional knowledge of the author and land-use data recorded during the survey. Each crop type was matched into a specific category derived from the unsupervised classification of the Landsat images. Five important land-use categories were found in the survey including paddies, cash crops, garden and orchards, forest and industrial crops. This data was compiled into an attribute file with the pesticide database. The final result (figure. 4.16) shows more accurate land-use data and removes duplicated clusters (table 4.6).

Table 4. 6 . Expert reclassification of initial unsupervised land-use classes.

New clusters	Landuse Categories	Clusters reclassified
0	Background	1
1	Rivers and canals	14, 17
2	Intensive paddy (2 crops)	3, 6, 11, 19
3	Dry paddy (3 crops)	2, 12, 18
4	Paddy fields mix orchards	4, 9
5	Cash crops areas, vegetable zone	5, 15
6	Coconuts, sugar cane zones	7
7	Brackish aquaculture, mangrove, shrimp farms	16, 20, 13
8	Mangrove forest, Clouds and cloud shadow	10

b. Pesticides database construction

The Excel spreadsheet of field data was imported into the IDRISI system using the DATABASE WORKSHOP procedure to generate a database file (.mdb) in IDRISI. Database construction, vector and raster layer creation will be described in the following sections. These subsequent works is an example study which uses Abamectin as an example. This methodology can be used for any other pesticides found.

4.6.2 Pesticide spatial distribution

a. Pesticide vector layer construction

The 343 point location data for pesticide use had and was extracted from the database as a vector point file with UTM-48N geo-coordinates. Parameters of pesticide use in the wet and dry seasons were respectively linked to the ID points so that any value could be displayed (figure 4.17).

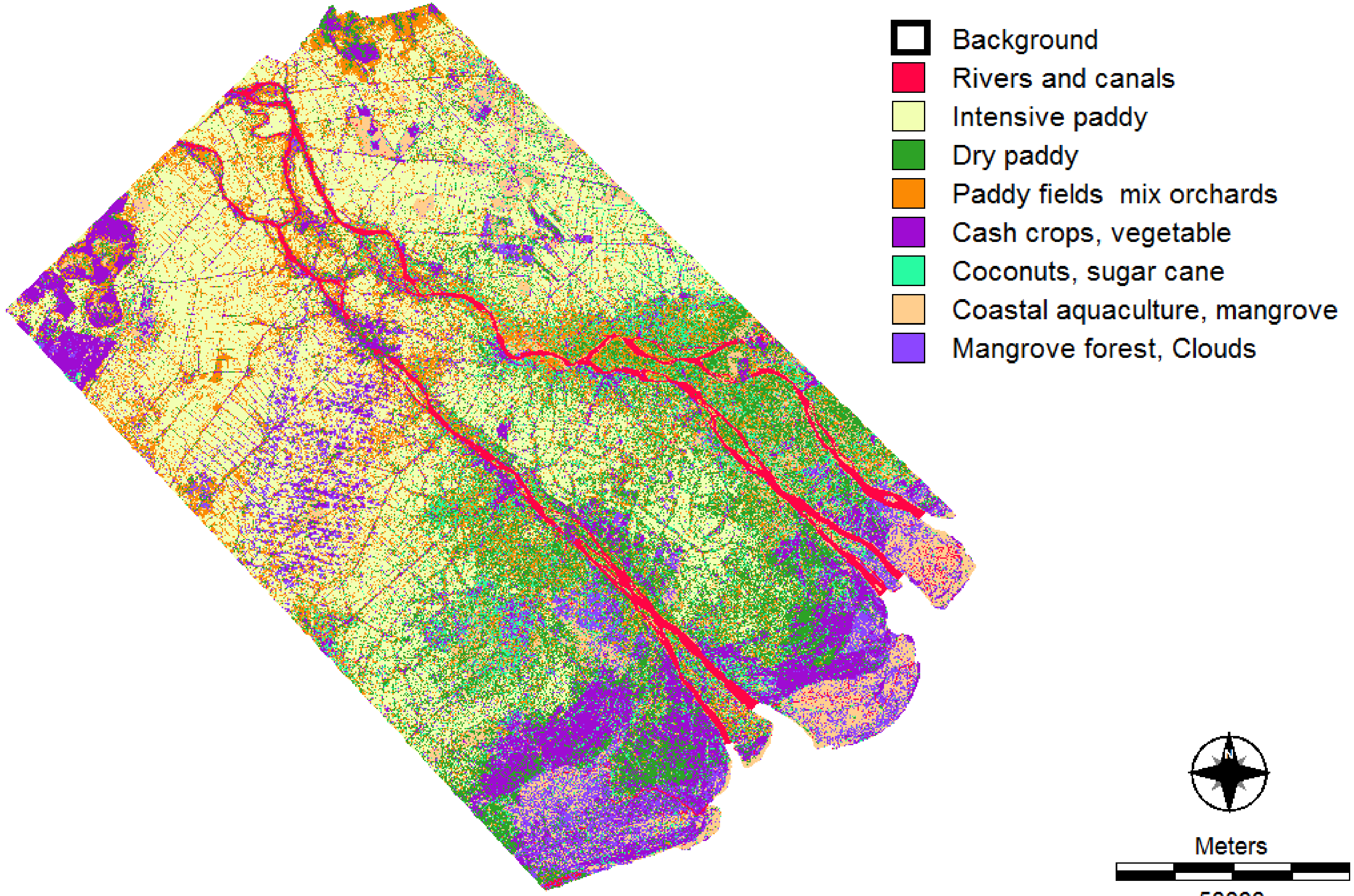


Figure 4. 16. Unsupervised classification of land use in the Mekong delta into 8 land use types.

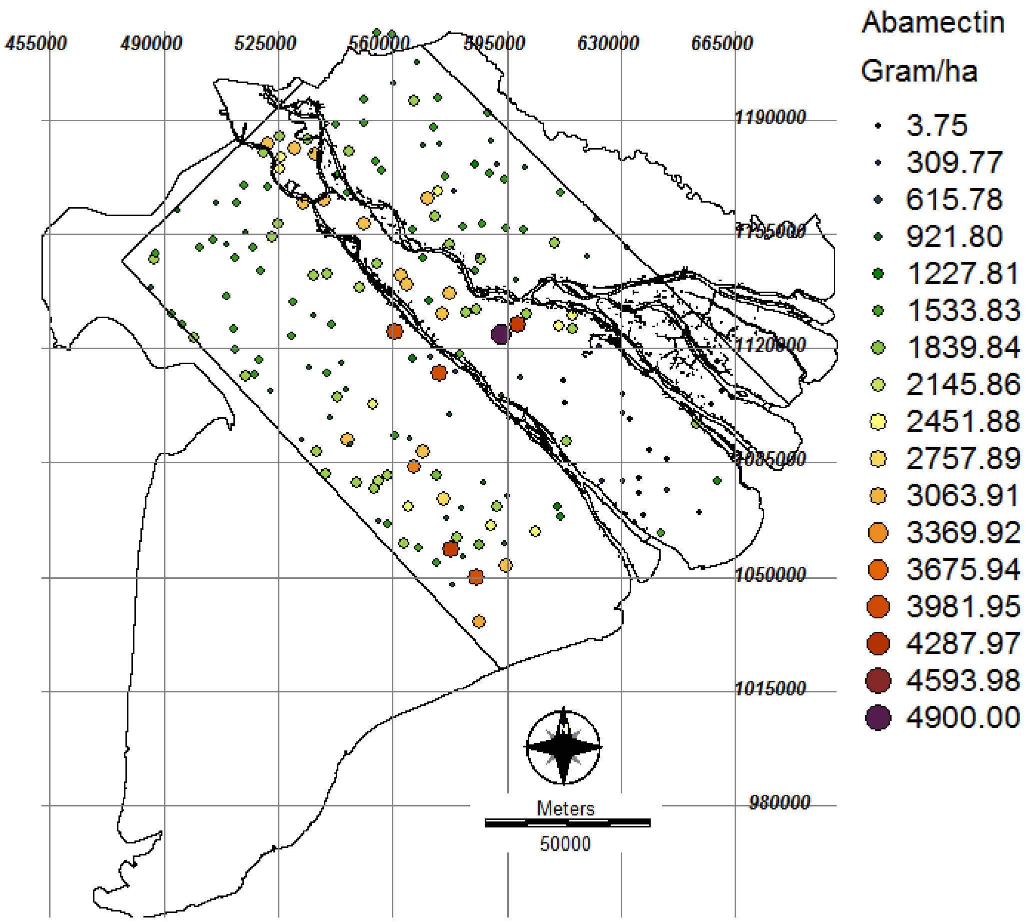


Figure 4. 17. Vector point file showing application rate of Abamectin (gross formulated product)

b. Pesticide raster layer construction

Raster data layers were developed based on interpolation of the vector point files with a distance weight exponent of 2.0 and a six point search radius. The interpolation process produced raster images at 30 x 30m resolution. For each chemical, there were found some locations with a very low rate of use and these values were rounded down during data processing and may be show the value zero. This was in contrast to stations where there was either no use of this chemical or no information available at the time of the survey. When processing the database, these points left blank. The interpolation process deals with points without data, by assigning a new interpolated value estimated by the distance weight exponent function among adjacent data points. Where data points are almost zero or zero, these values will be included in the process, along with adjacent points.

The interpolated product was limited to the study area by multiplication with a Boolean mask image so that values outside the study are multiplied by "0" to become zero value, and the rest with "1" to retain the original values (Thomas et al, 2008). Due to the interaction between 2 data source points, a curve may appear distant from the 2 points. To avoid this effect, a 7*7 pixel filter window was applied to convert all values to the mean values. Figure 4.18 showed an example of raster layer construction for Abamectin mean use in dry season.

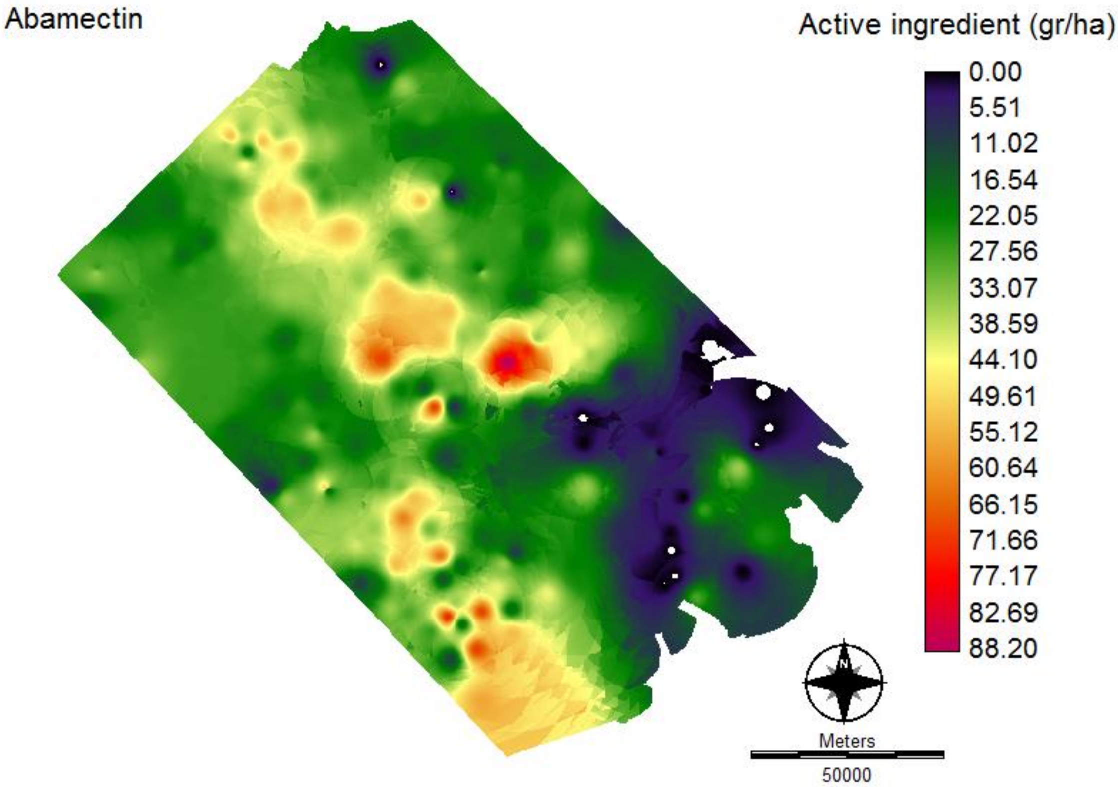


Figure 4. 18. An example of the initial interpolation product: Raster image of Abamectin application (g/ha) in April (2008)

The interpolation process calculated new values for all pixels including some in the rivers and canals. To avoid this, all pixels in rivers were eliminated using a Boolean mask where the river and canal systems have the value “0” and the reminder has the value “1” (figure 4.19). An example of the corrected image is shown in figure 4.20.

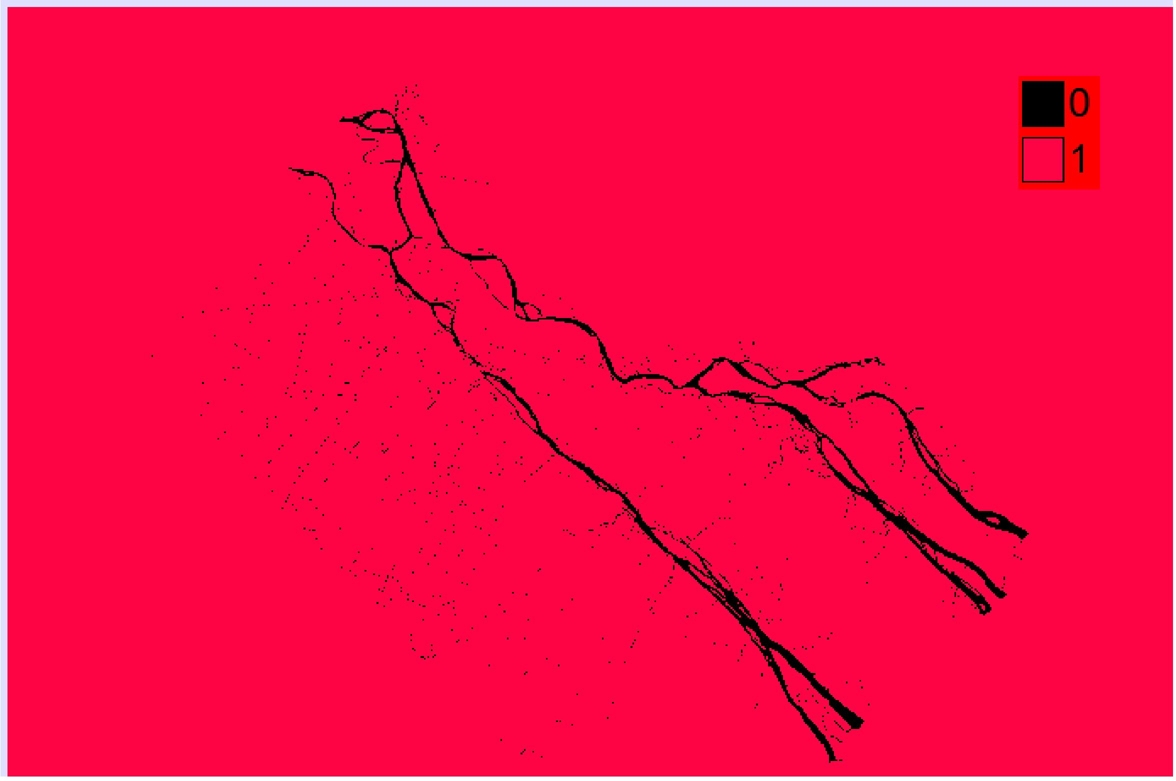


Figure 4. 19. River layer Boolean mask with "zero" values for pixels allocated to the river.

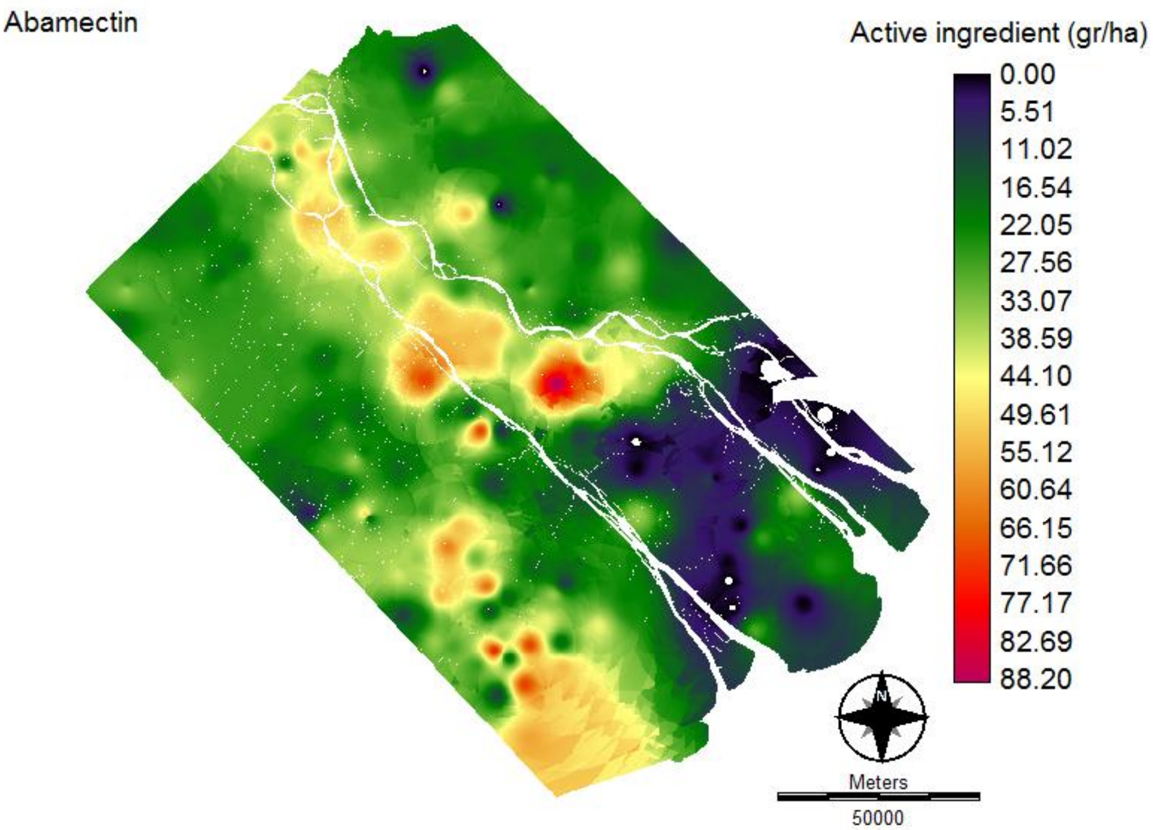


Figure 4. 20. Spatial distribution of Abamectin use in the Mekong delta.

c. Pesticide spatial distribution adjusted for land-use

While the interpolation process calculates values of pesticide use for all pixels in the study area the actual application rate is dependent upon land-use category and so the initial results require correction for this factor. For example, figure 4.20 shows the interpolated use of Abamectin in all areas except pixels in rivers. However, the model predicts use of Abamectin in coastal areas where aquaculture and mangrove and this requires correction by using the land-use image to enhance the accuracy of pesticide spatial distribution.

To achieve this, the interpolation processes needs to be carried out for every pesticide in every land use category (figure 4.21). The spatial database contains information about each pesticide and the land-use categories where these types of pesticides were applied. For example, Abamectin database actually comprised land-use categories 2, 4 and 5 which represent rice paddies, cash crops and industrial crops respectively. Raster point layers were firstly created for each land-use category by using the interpolation function. Water body and mangroves were not taken into account as there was no pesticide application at these areas. For the Abamectin database, 3 vector point files were generated based on Abamectin data points in three land-use categories 2, 3 and 5 (figure 4.22).

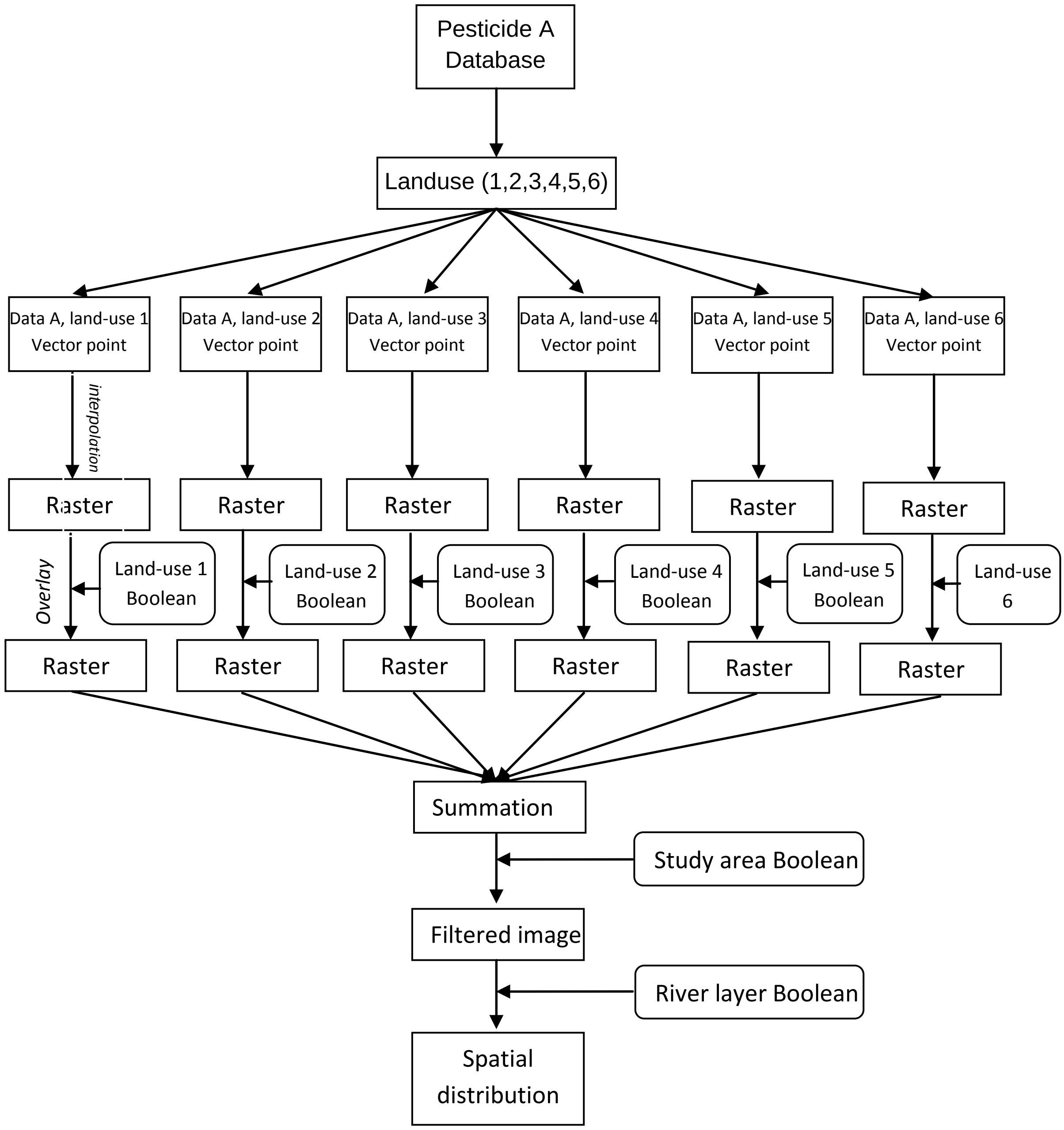
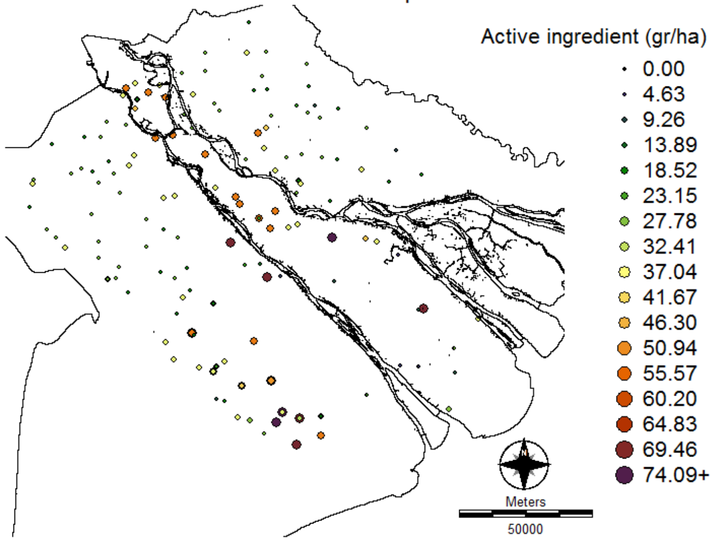
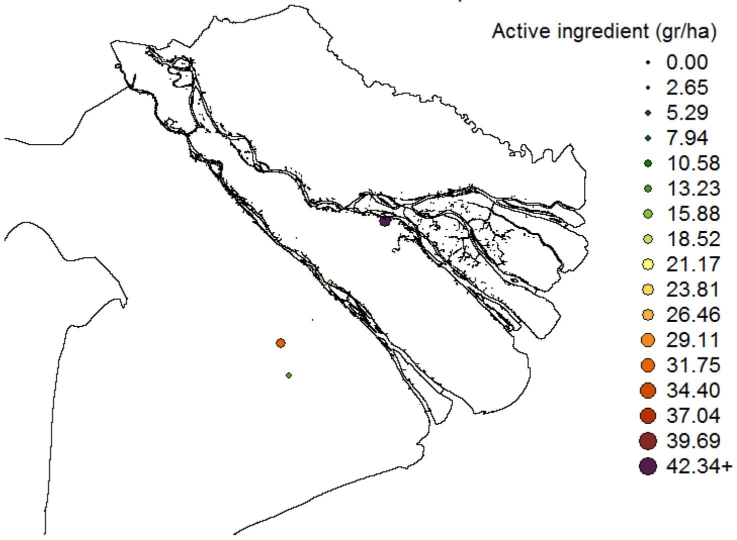


Figure 4. 21. Schematic diagram of the overall process for adjusting the spatial distribution of pesticides based on land use.

Detected Abamectin location in paddies



Detected Abamectin location in cash crops



Detected Abamectin location in industrial crop

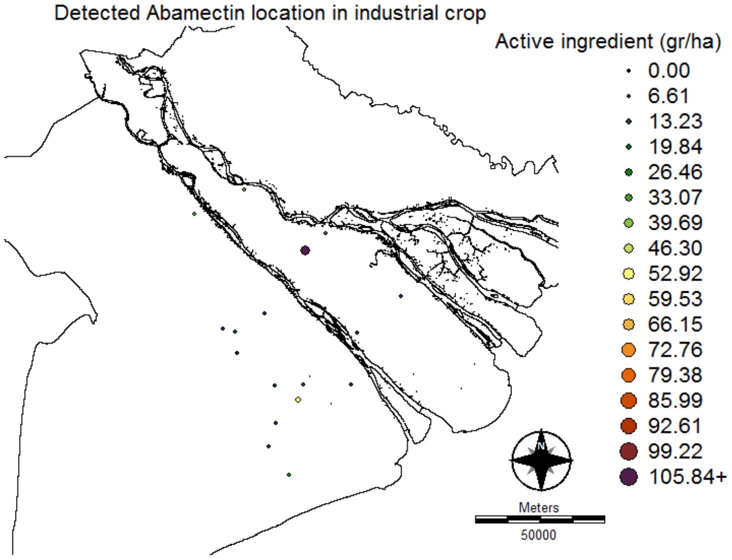
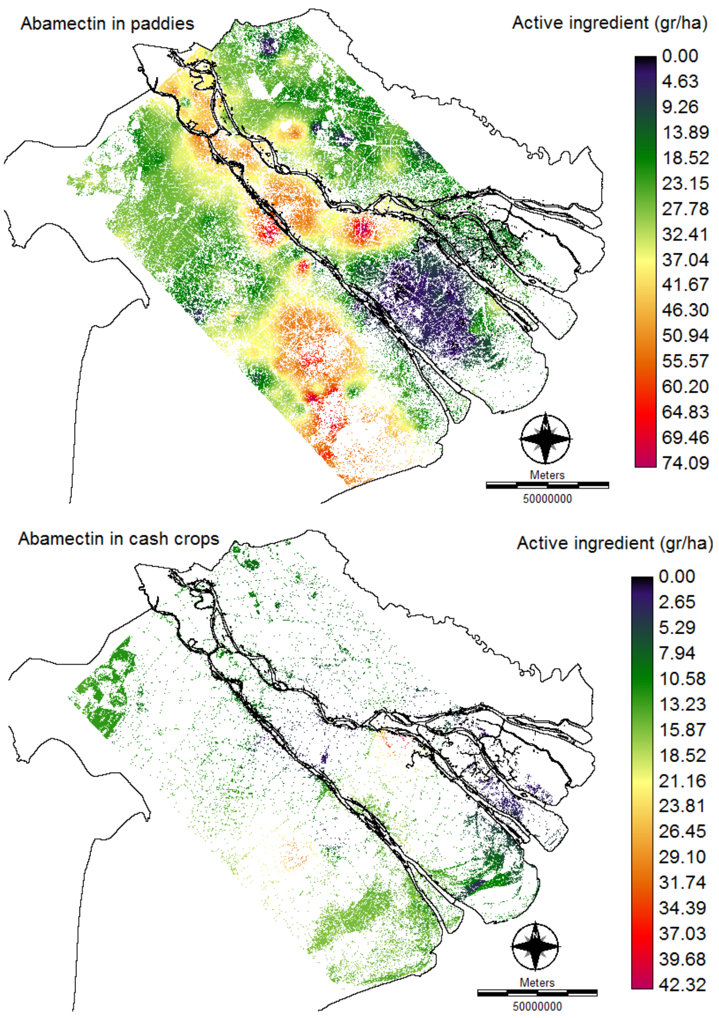


Figure 4. 22. Abamectin vector point files for land-use categories 2, 4, 5 in the Mekong delta.

After interpolating these vector point layers, they were modified by multiplying the raster images with the corresponding Boolean land use image (for Abamectin, they were multiplied with Boolean images of land use 2, 4 and 5, respectively). The raster file outputs from this processing reveal the distribution of each in the context of a specific land-use type (Figure 4.23). After correction, the total number of layers representing use of any chemical was summed either by OVERLAY module or use of the IDRISI IMAGE CALCULATOR to overlay all individual images under the option of first image covers the second one. The process will be continued to overlay until the last image. So, for example, if a specific chemical was applied in 6 land use categories, there would be 6 raster layers generated and then overlaid together. The final step was to apply the Boolean mask to eliminate pixels occurring in rivers and canals. The final output after all adjustments is shown in figure 4.24



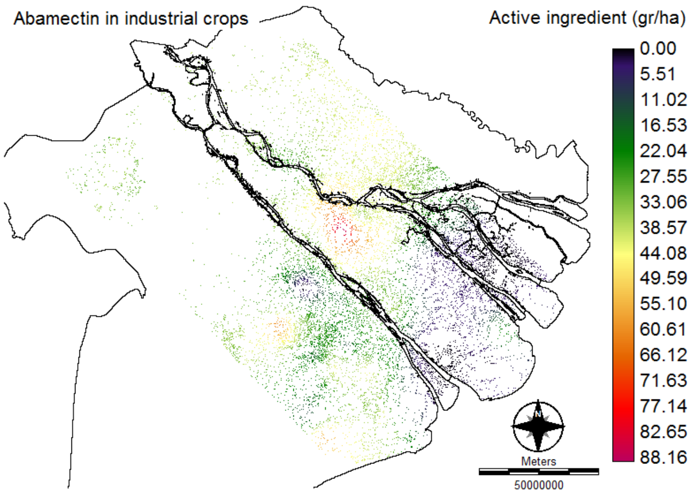


Figure 4. 23. Raster layers showing Abamectin use in the Mekong delta in April (2008), corrected for each relevant land use category.

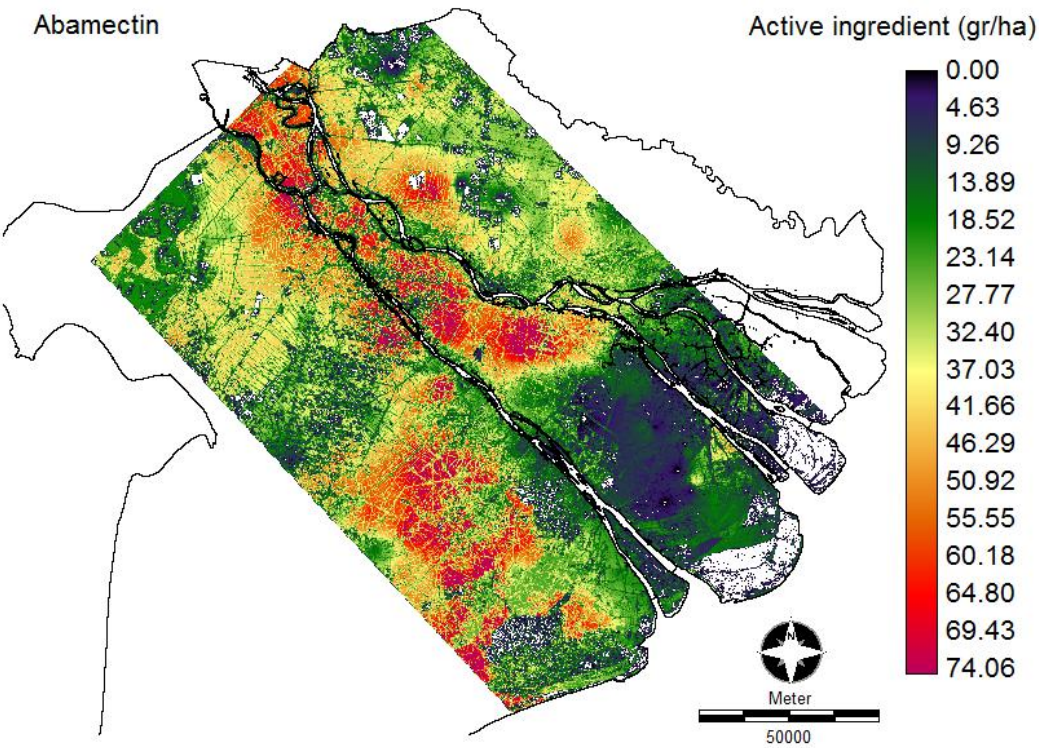


Figure 4. 24. Summary image showing spatial distribution of Abamectin use adjusted for all land use categories.

This process and resulting images show a more acceptable pattern of distribution with less artificial curves than the initial product without adjustment. A specific area contain multiple landuse will show various volume of pesticide distribution, that shows different levels of pesticide volume at garden, road, rice fields, water body and others. A zoomed section of an image in figure 4.25 and figure 4.26 illustrates this significant improvement. The high values (red colour) show Abamectin usage in paddies which are mixed with residential areas, gardens, orchards and other cash crops. This separation is only clearly revealed in the land use-adjusted image.

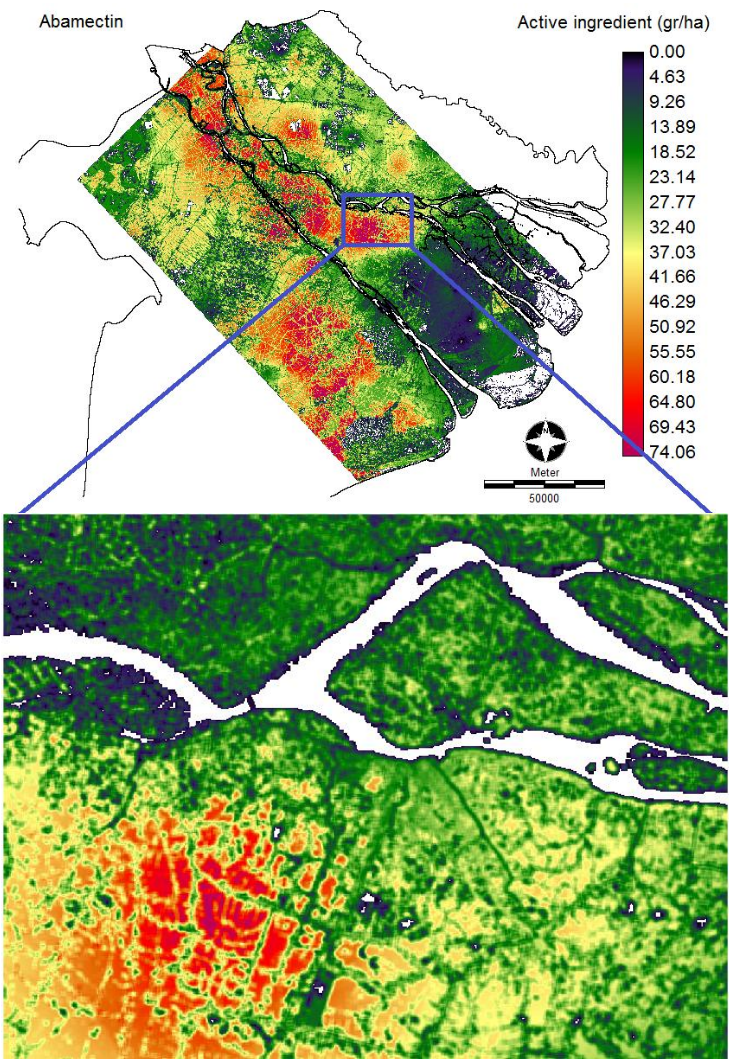


Figure 4. 25. A zoomed section from the Abamectin distribution image adjusted for land use category.

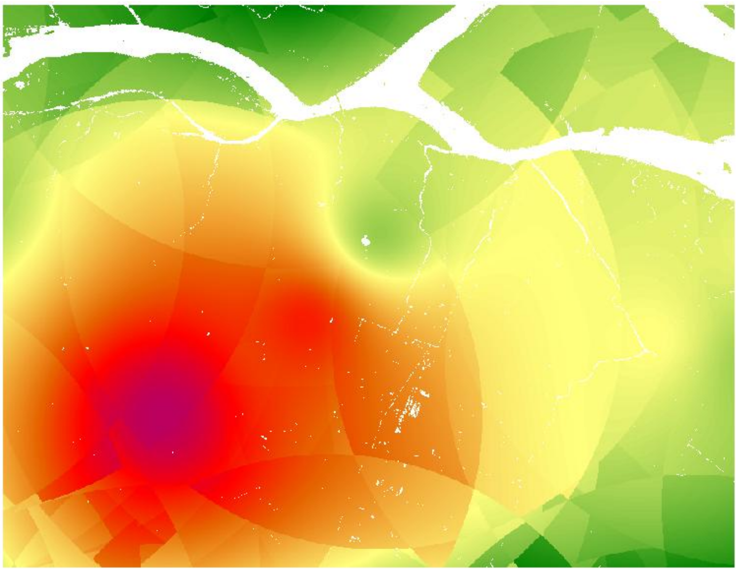


Figure 4. 26. A zoomed section from the Abamectin distribution image without adjustment for land use category.

d. Estimating the date of application based on crop types

Information on the date of pesticide application was rarely available during the data collection and almost no farmer could identify the dates of spraying and also kept no records. As this data is an important parameter for calculating the pesticide loss and accumulation, for modelling purposes the time of application for a chemical was estimated from knowledge of the crop seasons. Although farmers did not know the exact date for application, all interviewees remembered the period for each type of pesticide applied. This information was combined with local knowledge of the author who is resident in this area.

In the Mekong delta, rice cultivation occupies 80% of the available space and occurs in both the wet and dry seasons. Pesticides are used at every stage of the rice cropping system. At the beginning, molluscicides are used to clear out the golden egg snail which has strongly expanded in recent years (figure 4.27). This is followed by use of herbicides to kill all unexpected grasses and this may continue throughout the first month, stopping when the rice foliages is sufficiently strong to dominate the paddies. After the first month, rice stems are soft and are attractive items for insect consumption which develops strongly during this period up to the end of second month. Consequently, insecticides are intensively applied from the beginning of the second month crop, application rates being strong initially but gradually decreasing in both dosage and the number of applications.

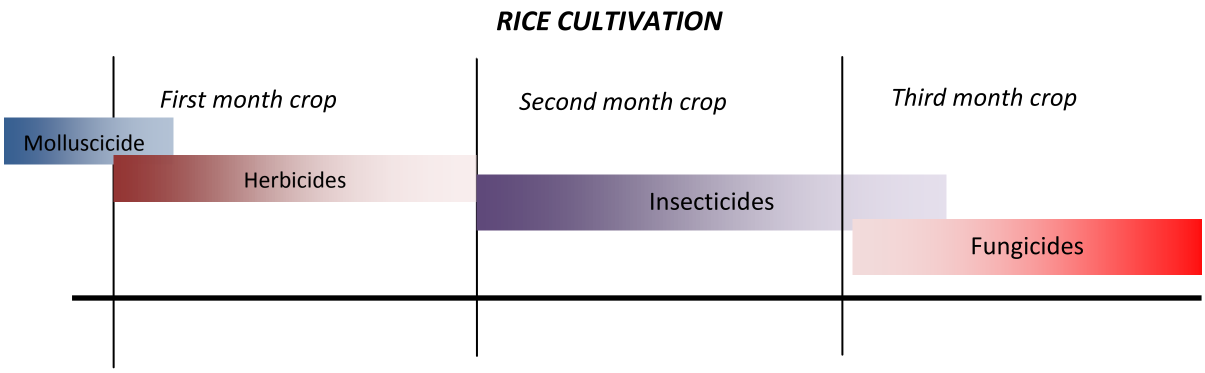


Figure 4. 27. Diagram of temporal pesticide use in a rice crop

In some cases, insecticides may be applied beyond the second month into the third month crop. Most commonly, farmers use high dose rates of herbicides and insecticides at the beginning of the month, then gradually reduced use in preparation for a change to other types of pesticide in the sequence. Conversely, fungicides are applied at very low initial rates which are then increased so that the highest amount of fungicides is used in the last few weeks before harvest.

In general, there are two main rice crops in Mekong delta. The wet season crop which is known as the HE THU starts from the beginning of April to the end of August. This is followed by the dry season crop, or DONG XUAN in which land preparation begins in September, seeding occurs at the beginning of October and the cycle ends in the following February (Sakamoto, Van Nguyen, Ohno, Ishitsuka and Yokozawa, 2006). In some other areas 3 crops can be produced per year but these areas are very few (Chen, Son, Chang and Chen, 2011).

The pesticide application data was grouped into 3 pesticide types, insecticides, herbicides and fungicides respectively and the spatial distribution for each pesticide was modelled depending upon its group and season, the latter being assigned by the author (table 4.7).In general, insecticides and herbicides were assigned to dates at the beginning of the month, whereas fungicide applications were allocated to the end of the third month.

Table 4. 7. Estimation date of application of pesticides in the Mekong delta.

RICE CULTIVATION					
HERBICIDES		INSECTICIDES		FUNGICIDES	
HE THU	DONG XUAN	HE THU	DONG XUAN	HE THU	DONG XUAN
01-April	01-October	01-May	01-November	30-Jun	30-December

4.7. Summary

In conclusion, this chapter presents an overview of pesticide use worldwide and in the Mekong delta. The recent data collection, combined with a GIS-based methodology for spatial modelling of use, reveals the current use and the trends within the study area for each type of pesticide used.

At the global scale, pesticide use is still increasing and world pesticide expenditure hit ~40 billion USD in 2007. Although insecticides and herbicides were most popularly used, the recent trend has been for a gradual reduction. The percentage applied per unit area has clearly dropped off from ~45% to under ~40% for insecticides, and from ~33% to ~27% for herbicides, respectively. Fungicide use on the other hand has sharply increased from ~17% of total pesticide used in 1990s, to ~23% in total pesticide use in 2000, with further increase in recent years.

At a more regional scale, there is still strong demand for use of chemicals in agricultural activities in Asia. Annually, rice industries in Asia consumed large amounts of pesticide with an approximate a value of US $2.6 billion per year. Insecticides dominate the pesticide market in Asian countries occupying about 55% of the applications per unit area. Some very dangerous insecticides which have been banned elsewhere due to their high toxic and long persistence are still widely found in Asian pesticide markets.

Although Vietnam is not remarkable in comparison with other Asian pesticide usages, it still consumes huge amounts of pesticides for rice cultivation, almost all of which are imported. 50,000 tonne were imported in 2000, up from 20,000 in 1991. In the last 20 years, insecticide use has dramatically decreased while fungicide usage has markedly increased.

This study represents the most recent survey to investigate pesticide usage in the Mekong delta. The 2009 survey identified 96 types of popular pesticides in 23 groups most of which are in the WHO groups II and III. Under this classification system, pesticides in Mekong delta could be considered as moderately hazardous although small quantities in the highly toxic and persistent (Ib group) also were found such as Methidathion or Acetamiprid. The survey revealed current total application rates of formulated product of around 14.12kg/ha/y, equivalent to ~2,514g/ha/yr active ingredient. Fungicides and insecticides represent ~49% and ~38% of the total, while herbicide use is relatively low at only ~13% of the total. Organochlorine was found in use at almost 90 stations, but at a low application rate.

The distribution models developed within the GIS were adjusted by using the land use categories to improve their agreement with actual pesticide application conditions. Each type of pesticide was recalibrated based on land and the resulting corrected spatial distributions show the current use and distribution of all of the agrochemical identified in the survey.

The method in this chapter could be applied to mapping the distribution of all pesticide pesticides not only in the Mekong delta but also in other places in the world. The raster layers in this chapter will provide the pesticide input data for pesticide component in the main model. All database constructed in this chapter are able to link to other module as an input of running as a sub-model. The method to connect the results in this chapter to the main target model will be present in chapter 6.

Chapter 5

GIS modeling sediment loss and net sediment accumulation in the Mekong Delta

5.1. Introduction

Soil erosion is a natural activity which varies with rainfall and soil type. A light and stable rainfall creates a steady vegetation layer which protects the top soil layer and avoids erosion. Conversely, a strong and unstable rainfall will postpone the development of the vegetation layer, allowing large rain drops to break down the soil particles and cause the top soil layer to erode (Morgan, 2005). In recent years, soil erosion has been recognized as being a significant problem throughout the world. Globally, over 24 billion tonnes of soil is eroded every year (Lal, 2003), leading to a loss of approximately 2000 million hectares annually (United Nation Environmental Program, 1991). Due to the complexity of the physical hydrological processes involved the economic and environmental impacts of erosion by water are difficult to evaluate. However, it has been estimated that ~55% (~1094 million hectares of soil) are eroded by water annually (Lal, 2003) leading directly to a decrease in cropland area. The products of erosion create massive sediment loading in the aquatic environment and become incorporated into ponds, channel systems, rivers and reservoirs which can lead to considerable economic losses (Kort, Collins, and Ditsch, 1998).

Soil erosion can be estimated using an equation early developed by (Zingg, 1940). The equation simply calculates the soil loss based on the slope of a specific location such as a farm field. In later developments, crop factor, slope and land management were included in the soil erosion calculation by researchers in Soil Conservation Service (SCS) (Wischmeier and Smith, 1978)

Before 1990, several projects had tried to investigate global soil loss though erosion and how it affected agriculture and long-term national economic trends (Lester and Edward, 1984). After 1990, sediment load and soil erosion were studied in more detail to evaluate the impact of erosion on the environment. Various empirical, conceptual and physics-based models have been used. Some models have become the most popular due to the long term application and verification of results certified by many scientists. The USLE (Universal Soil Loss Equation) was innovatively developed and widely applied in America (Wischmeier *et al.*,1978). Although the USLE was one of the root models and had been tested on over 10,000 plots of land in America with over 20 years rainfall data, the model still received some criticisms about over prediction and low applicability to certain areas (Risse, Nearing, Nicks and Laflen, 1993). The Revised Universal Soil Loss Equation (RUSLE) has been applied worldwide due to its flexible applicability (Renard and Freimund, 1994; Renard, Foster, Weeise and Porter, 1991). Although widely applied, it was still found to be inappropriate in some cases (DE ROO, Offerman and Crement, 1996). With the support of high capacity computing and information technology, conceptual models have become strongly developed. The SWAT model (Soil and Water Assessment Tool) brought an effective mathematical model to evaluate sediment fate in specific hydrological conditions (Arnold et al, 1998; Arnold, William, Nick, and Sammon, 1990); WEPP (*Water Erosion Prediction Project Model*) and EUROSEM (the European Soil Erosion Model) were very successfully applied in Europe (Morgan, Quinton, Smith, Govers, Poesen, Auerswald, Chisci, Torri, and Styczen, 1997; Flanagan et al, 1995), and MUSLE (the Modified Universal Soil Loss Equation) was specially designed basing on the root equation USLE but replaced rainfall factor by a runoff in specific terrain conditions to give results for every storm event (Williams and Berndt, 1977). These models support users modeling soil erosion, estimating the sediment loading, sediment yield, sediment accumulation not only in small watersheds but also at a global scale.

In the Mekong river basin, sediment yields and sediment discharge have been measured and evaluated at stations along the river from 1962 until today (Wang, Lu, and Kummu, 2009). In the last 3 decades, a regular increase in sediment yields has been recognized. Sediment discharge from the Mekong delta was estimated to be around 144±36 million tonne.yr^{-1} (Ta Thi Kim Oanh, Nguyen, Tateishi, Kobayashi, Tanabe and Saito, 2002). From 1980, computer tracking and spatial mapping of sediment load in Mekong delta basins was used to define issues (Lap Nguyen *et al.*,2000) in order to gain a better understanding about the condition of sediment and its short-term and long-term effects on human life either directly or indirectly.

This chapter presents a methodology to calculate the volume of runoff, sediment losses and sediment accumulation within the Mekong Delta. The design and development of a mathematical model for estimation of sediment yield and sediment accumulation is outlined. The importance of understanding the contribution of soil accumulation and sediments in water runoff after rainfall events in the redistribution of pesticides is outlined.

Integrating the soil loss erosion models into GIS

In the last decade, the value of integrating the soil erosion and sediment load models into GIS has been outlined (Stone and Hilborn, 2000; Renard *et al.*,1991). Such integration would provide users with an effective tool to manage the data and carry out the spatial analysis as well as being able to describe soil loss conditions in the past, present and future, and also to evaluate results in the real world (Fu, Chen, and McCool, 2006).

5.2. Data Preparation

5.2.1. Land-use data

Land use and land cover data are necessary for calculating soil loss and sediment yields. They contribute to soil losses and sediment calculations as a restriction factor contributing to the soil erosion process (van der Knijff, Jones, and Montanarella, 2000). Land-use used in the model was discussed in Chapter 4.

5.2.2. Rainfall data

Rainfall data preparation was presented in Chapter 3 (3.4). Rainfall in Mekong delta is affected by tropical monsoon typical of South East Asia, rainfall intensity and is clearly separated into two seasons, as exemplified figure 5.1. In the soil loss model, rainfall data was aggregated into 4 day episodes.

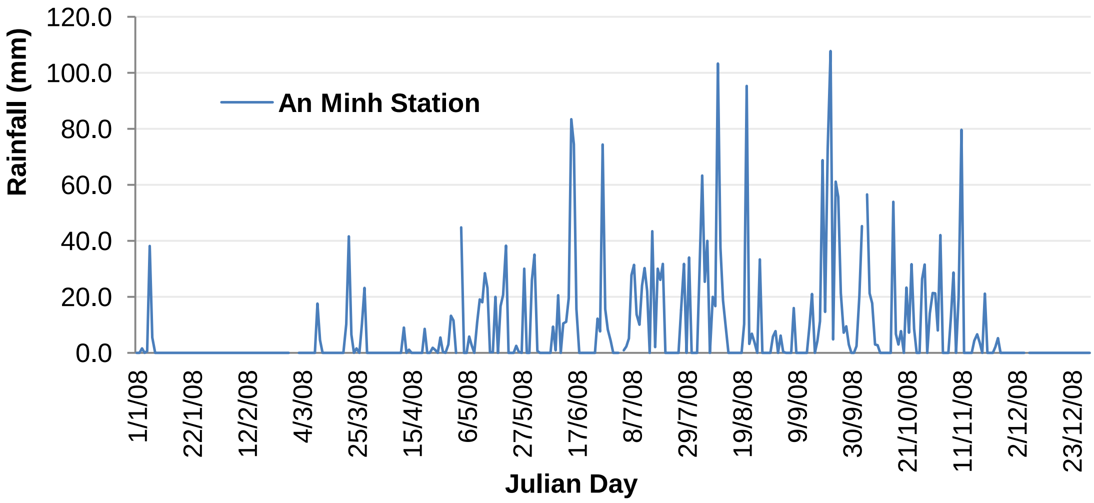


Figure 5. 1. Daily rainfall (mm) distribution by time at a station (An minh station) in 2008

5.2.3. Topographic, slope data, and aspect

The topographic data layer construction was outlined in Chapter 3 (3.4) and the slope data was computed from a DEM image using the SURFACE module in IDRISI (Figure 5.2).

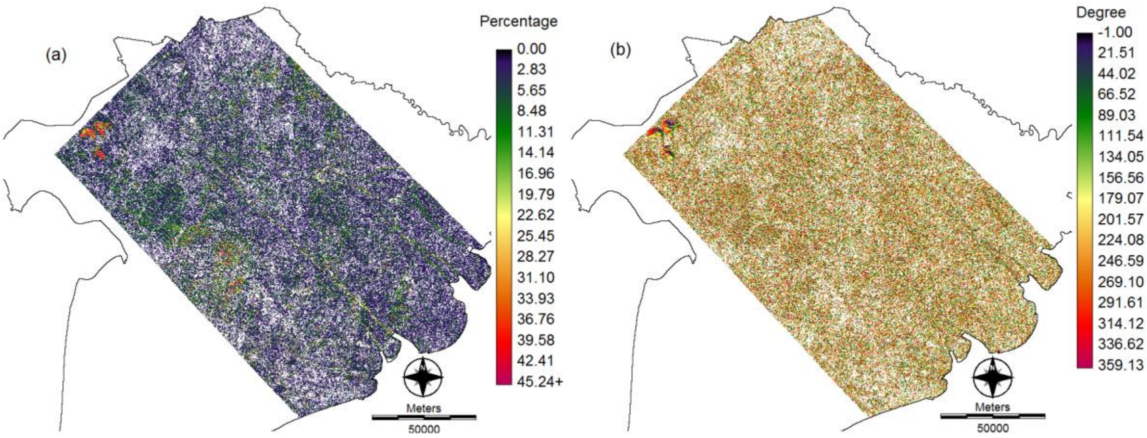


Figure 5. 2. Mekong delta slope as percentage slope (a); and aspect in degrees (b)

5.3. Methodology and model construction

5.3.1. Overall methodology

The sediment yield model was approached in 3 main steps (Figure 5.3). Every step was built in the GIS environment using mathematical modules. The required data input sources differ and some re-calibration was required to prepare the data for use in the models. More specifically, soil type data comprises 5 typical soil types, but the model only accept these after being converted into other form data (K factor) which is the coefficient to represent the erodibility of each soil type. Similarly, Land-use data was reclassified to a constraint indicating the retention of the soil erosion process. Topography data was converted into data on length of slope which will control the length for sediment load travel and accumulation. Rainfall data was converted into the runoff factor which will reveal the volume of erosion, sediment yield and sediment accumulation. The methodology for re-calibration of the factors will be clarified in detail in further contents GIS pre-processing was carried out once all factors affecting erosion were available using macro modeller functions in IDRISI. The final step is GIS spatial analysis of the results of soil erosion for a rainfall event. To archive

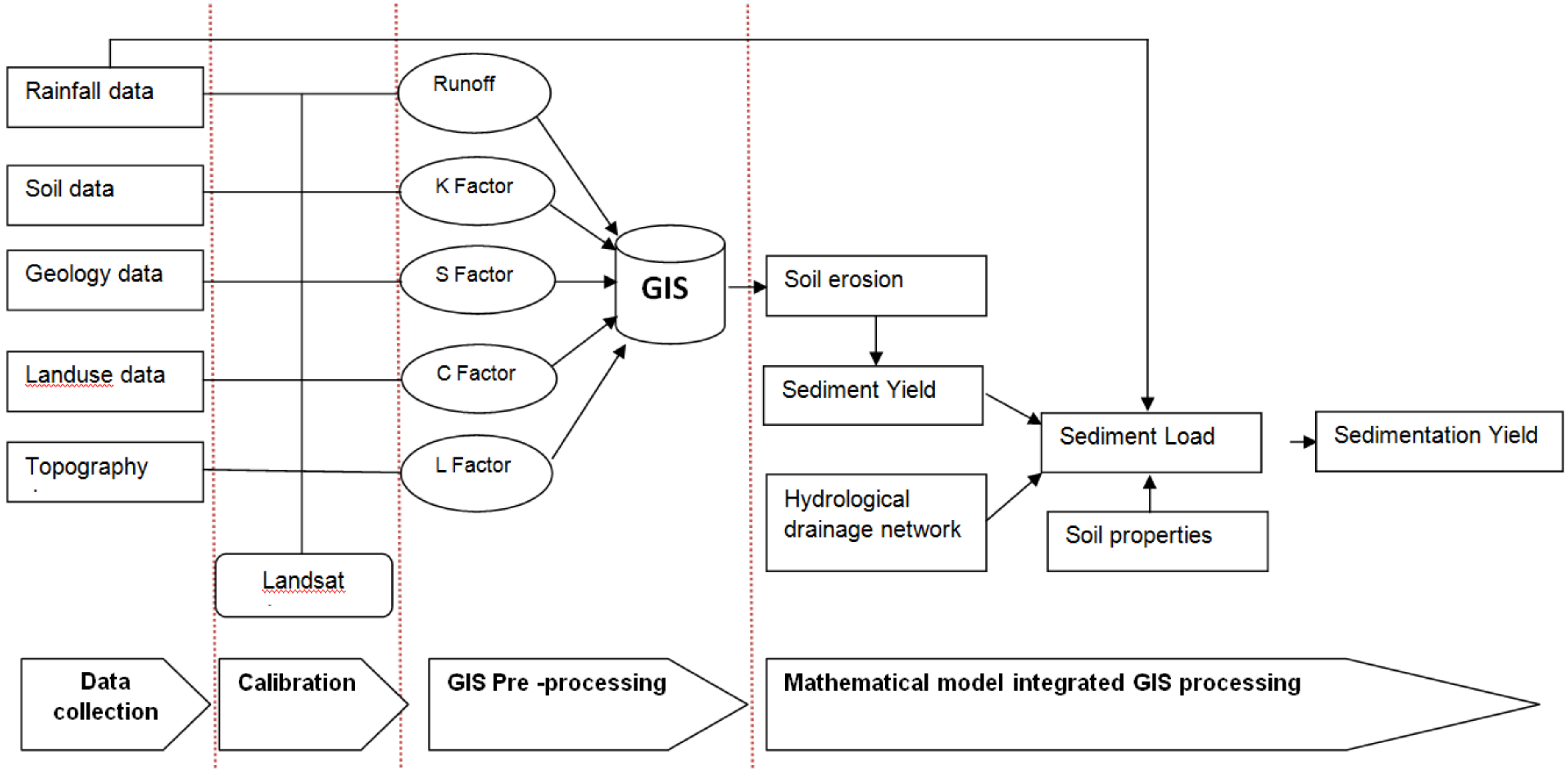


Figure 5. 3. Flowchart of GIS based modelling of sediment yield and accumulation in the Mekong delta.

sediment yield loss, sub-components including soil properties, sediment delivery ratio, and hydrological networks were prepared for the next iteration of the model and this process continued until the full series of time steps had been completed. During the year, there are many periods with no rainfall or where rainfall is lower than the initial abstraction of soil. In this case, rainfall was set to a zero value.

This model accept the assumptions that the time step is 4 days and that the maximum rainfall duration was1day.

5.3.2. Concept on soil detachment

Soil detachment is a concept which represents the cohesion ability between soil particles, and is related to the features of how raindrops come into contact with particles (Springer, 1976). Rainfall as drops have a kinetic energy, which transforms into kinetic energy when they fall to the ground (soil surface) (figure 5.4). The amount of kinetic energy is related to the falling velocity of the drop. If higher than the attachment strength between the soil particles, the kinetic energy attacks and breaks down the cohesion forces of soil particles. It also provides the energy to move these particles to gradually combine with other wet particles to a loading condition. This contributes to the process of soil erosion and transport, and forms part of the overall model.

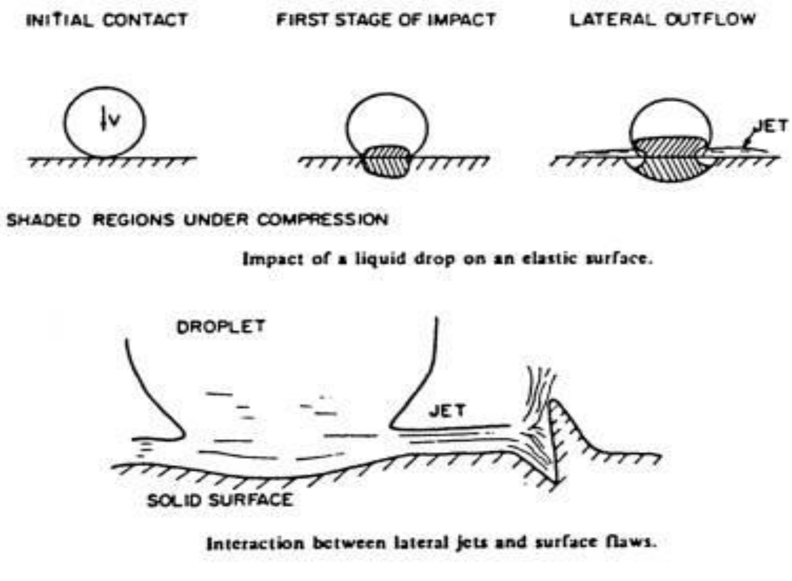


Figure 5. 4. Representation of raindrop impact power.

(Kinnell, 1981)

In conclusion, there are 2 periods of kinetic energy which are created by the same source (raindrops). The first is formed by the momentum of raindrops' impact on soil particles. The second occurs through water movement after the raindrops break down the particles, and contributes to the runoff process when the this energy accumulation is greater than the gravitation between the detached particles.

5.3.3. Erosion equations

The RUSLE soil loss equation was originally formed by a multiplication of six major factors, as follows:

$$A = R.K.L.S.C.P \qquad \text{(Williams et al, 1977)} \qquad \text{Equation 5. 1}$$

Where*,* A is soil loss in a particular time in (tonne) per unit area

R is rainfall and runoff factor in a specific area. This is the mean of total erosion index unit (EI)

K is soil erodibility factor, is defined as the soil loss rate per erosion index unit (EI) for a particular soil type

L is length slope factor

S is slope steepness, the ration between the soil losses per a given steepness and soil loss in 9% slope steepness under same condition.

C is cropping management factor, determined by ration soil loss in a particular crop area per soil loss in tilled continue fallow

P is erosion control practice factor, expressed by ration soil loss with farming practice (stripping, contouring) per soil loss with farming up and down slope

Renard *et al* (1994), described use of the RUSLE equation in studies for the estimation of sheet and rill erosion of upland areas for a specific rainfall. Stream banks, snowmelt and wind erosion were not taken into account and the equation did not include calculation of the accumulated soil at the base of slopes. RUSLE is an empirical model requiring accurate data to enhance its reliability.

There were some difficulties in calculating the factor *R* which requires longitudinal data recorded for the whole year (Wischmeier, 1959). Factor *R* has been estimated for annual values (Lee and Heo, 2011; Nazzareno, 2004; Wischmeier et al, 1978) and so the results of soil erosion and soil loss are an annual prediction. Some improvements have enabled calculation of *R* for a shorter period, monthly (Renard and Freimund, 1994) or even shorter (Barfield, Warner, and Haan, 1983).

Given the current rainfall data available for this study, application of RUSLE for soil loss prediction in the Mekong delta would not be reliable, Williams and Berndt (1977) suggested a method for applying the RUSLE equation on single storm events by calculating soil loss and sediment yield by using runoff and potential rainfall runoff volume to replace factor *R*, as follows:

$$\boldsymbol{Y_s = 11.8(V.q_p)^{0.56}.K.C.P.LS}$$ (Williams et al, 1977) (Equation 5. 2)

Where:

Y_s= Sediment yield (tonne.ha^{-1}/year)

V= Volume of storm runoff

q_p= Peak flow discharge

K, C, P, LS = as defined in USLE

Equation 5.2 has since been used widely as a tool to predict total sediment yields discharged from a single storm event (Willian, Karl, and Bruce, 2011; Zhang.Z, Degroote, Wolter, and Sugumaran, 2009; Kinnell, 2005; Lim, Sagong, Engel, Tang, Choi, and Kim, 2005; Sadeghi, 2004)

5.4. Runoff volume and peak discharge

Normally, in a storm event, the volume runoff value is proportional to the amount of rainfall and is modified by local topography. Runoff only takes place when rainfall volume exceeds the total water losses by initial processes which are considered here as merging to the soil gaps, infiltration, soil porosity fulfilment and the minor effects of evapo-transpiration or transformation into water vapour (Shi, Chen, Fang, Qin, and Cai, 2009; Singh, Bhunya, Mishra, and Chaube, 2008). The process can be expressed by the water balance in equation 5.3

$\boldsymbol{P = Q + G + S + E_a}$ (Singh, Bhunya, Mishra, and Chaube, 2008) (Equation 5. 3)

Where:

P= precipitation

Q= runoff volume

G= Infiltration rate to the groundwater

S= soil moisture storage (or filled porosity water)

E_a= actual evapo-transpiration

Evapo-transpiration was not included in this model. The evapo-process is a complex process for modelling, requiring a huge climate dataset which was not possible to collect in a short time. Soil moisture storage and infiltration rate was be represented by the initial abstraction *(I_a)*

5.4.1. Relationship between runoff volume and a rainfall event

Further to equation 5.3, the relationship between runoff volume *Q* and rainfall *P* is expressed by:

$$\boldsymbol{Q = \frac{(P - I_a)^2}{P - I_a + S}}$$ (USDA-SCS, 1986) (Equation 5. 4)

Where:

Q= runoff (mm)

P= rainfall (mm)

S= potential maximum retention

I_a= Initial abstraction

The most widely used method to predict the runoff volume is runoff curve number method which was developed by USDA-SCS (1986). The method was evaluated and validated at that time by experimental tests in various conditions of different soil types and land cover (Chow *et al.*,1988; USDA-SCS,1986) and was applied for predicting relationship between rainfall and runoff volume in small watersheds. In the present study this equation is used to estimate runoff volume in each grid cell (equal to a plot of 900 m^2).

The potential maximum retention *S* corresponds to the initial absorption into the first soil layer. This process extracts rain water to fill to the porous spaces between soil particles. A high density of vegetation cover on tilled soils will protect against erosion by rain water by extracting water before it reaches the top soil layer but in soils bare of vegetation rain water is lost directly through absorption (Lee, 2004). When water–storage occurs in the first soil layer, gravity forces water gradually to deeper layers. The speed of the process is dependent on soil properties and type of land cover. Runoff Curve Number (CN) value can be used as an indication of soil characteristics and land cover which can be used to calibrate the value of absorption and infiltration of water (USDA-SCS, 1986). The relationship between I_a and *S* is found in equation 5.5

$$\boldsymbol{I_a = 0.2S} \quad \text{(USDA-SCS, 1986)} \quad \text{(Equation 5. 5)}$$

and;

$$\boldsymbol{S_{(mm)} = \frac{254000}{CN} - 254} \quad \text{(USDA-SCS, 1986)} \quad \text{(Equation 5. 6)}$$

where I_a is initial abstraction;

S is potential maximum retention

CN is curve number values.

CN values for different soil types and land use conditions are accessed in the SCS Agriculture Handbook TR-55 with a value from 0 to 100 (USDA-SCS, 1972) which supports users estimated *CN* values based on hydrological soil groups (HSG) and land cover types or land use, hydrological condition and antecedent moisture. The higher *CN* values, the lower runoff retention, and higher runoff capacity.

5.4.1.1. CN value determination

CN value is calibrated by using two common datasets: land-use and soil type. The method to determine *CN* value is described by (USDA-SCS, 1986).

Hydrologic soil groups (HSG) represent the soil's ability to resist water runoff. Surface permeability depends significantly on both soil type and soil properties. USDA-SCS (USDA-SCS, 1972) divided HSG into 4 groups A,B,C,D based on soil profile and texture (USDA-SCS,1978) as shown in Tables 5.1 and 5.2

Table 5. 1. Hydrology soil groups classified by soil textures (USDA-SCS. 1986)

HSG	Infiltration rate (cm/hr)	Runoff	Soil texture
A	>0.76	Low	Sand, loamy sand, sandy loam
B	0.38 – 0.76	Moderate	Silt loam, loam
C	0.13 – 0.38	High	Sandy clay loam
D	0.00 – 0.13	Very high	Clay loam, silty clay loam

Table 5. 2. Definition of hydrologic soil group (USDA-SCS. 1986)

Hydrologic Soil Group	**Soil Group Characteristics**
A	Soils having high infiltration rates, even when thoroughly wetted and consisting chiefly of deep, well to excessively-drained sands or gravels. These soils have a high rate of water transmission.
B	Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.
C	Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.
D	Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission

The HSG groups of the Mekong delta soil types are in , categories A,B, and D (Table 5.3).

Table 5. 3. Hydrologic soil groups definition in the Mekong delta.

Soil type	Soil textures	Runoff	Area (Hectares)	HSG
Ferric Acrisol	Loamy sand	Low	16,638	**A**
Gleyic Acrisol	Clay loam	Very high	13,933	**D**
Eutric Gleysol	Sandy loam	Low	835,884	**A**
Thionic Fluvisol	Loam	Moderate	845,192	**B**
Eutric Fluvisol	Sandy loam	Low	385,239	**A**

In this study land-use represents land cover and treatment to determine CN values. Land-use categories are one of the most important factors lowering the runoff water and also soil erosion. High densities of forest generate a canopy which will absorb/remove rain water before falling to the ground and reduce the kinetic energy caused by impact of raindrops onto soil particle cohesion. Table 5.4 shows the land-use categories and their cover types for the Mekong delta, and includes hydrological condition and cultivation types.

Table 5. 4 . Runoff Curve Number (*CN*) value for different land use and soil types.

Land use	**Hydrologic soil groups**			**Cover types**
	A	**B**	**D**	
Rivers and canals	100	100	100	Water body
Intensive paddy (2 crops)	72	81	91	Row crops
Dry paddy (3 crops)	72	81	91	Row crops
Paddy fields mix orchards	71	80	90	Wood grass combination
Cash crops areas, vegetable zone	35	56	77	Brush-grass
Coconuts, sugar cane zones	32	58	79	Wood grass combination
Brackish aquaculture, mangrove, shrimp farms	86	91	94	Fallow
Mangrove forest, Clouds and cloud shadow	45	66	83	Woods

(Chow *et al.*,1988; USDA-SCS,1986)

The combined attribute data shown in Table 5.4, gives a specific value for each soil type and land-use category and from this, the ASSIGN and OVERLAY functions in

IDRISI were used to create the *CN* raster layer. The value of *CN* is a constraint which will be used to calculate runoff volume for every rainfall event.

Curve number in study area is shown in (figure 5.5) and ranges from 35 to 100. Curve number in water bodies is calculated as the maximum value as there is no retention factor. Large areas of paddy fields scored from 71 to 91 indicating the high potential for runoff in these areas.

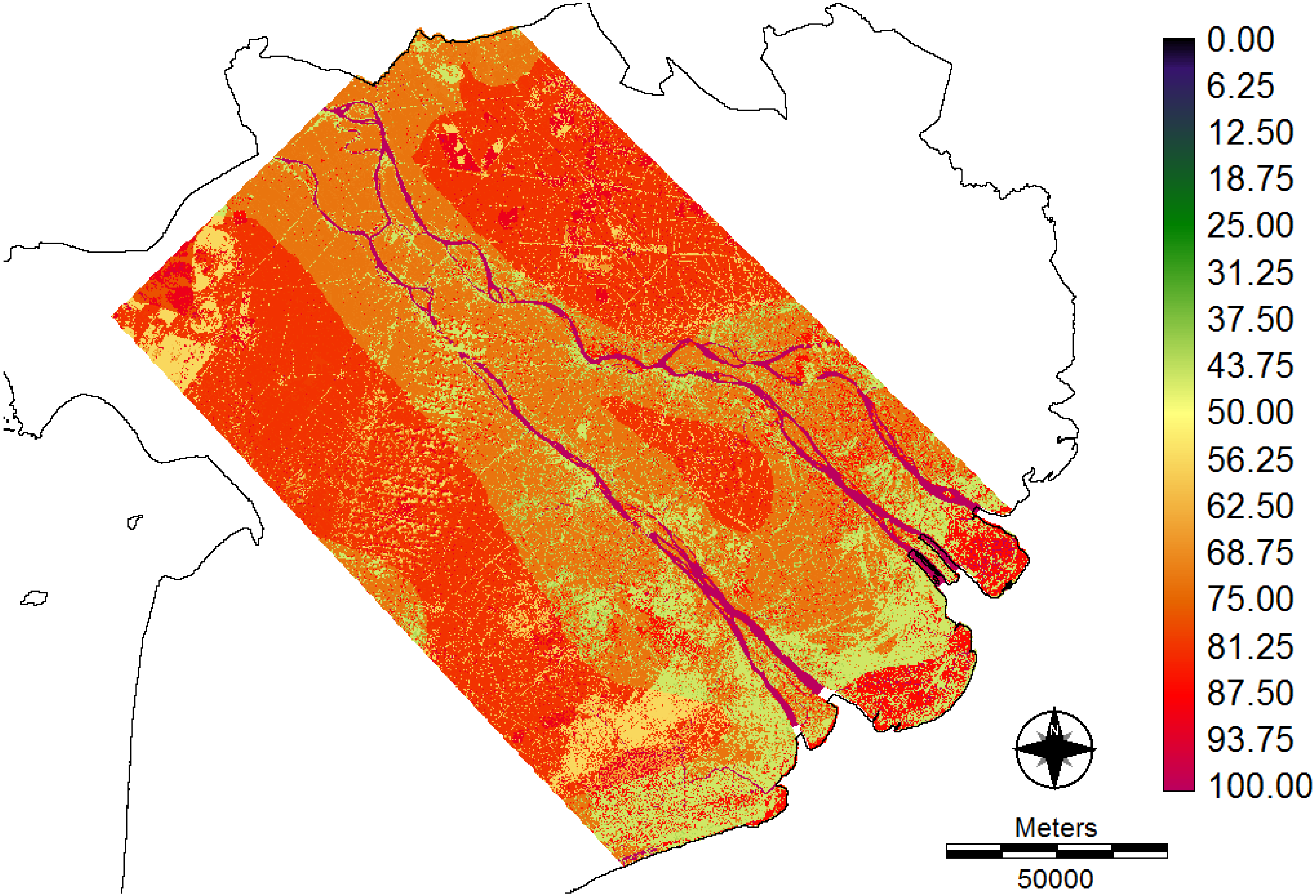


Figure 5. 5. CN value in the Mekong delta

5.4.1.2. Runoff volume

Runoff volume was calculated using in (equation 5.4) using total rainfall every 4 days and the maximum retention factor (equation 5.6). The runoff depth was estimated as potential millimetres lost in each grid-cell per event (figure 5.6).

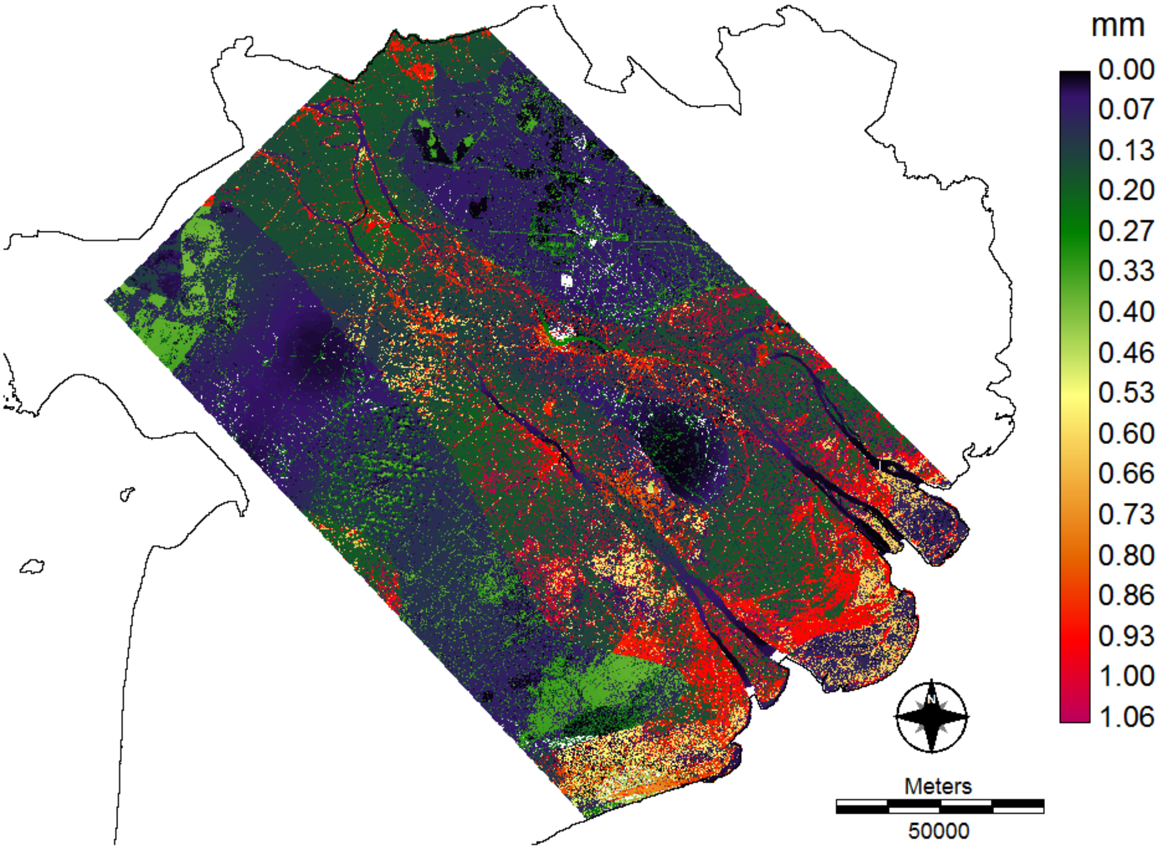


Figure 5. 6. Runoff volume *Q (mm)* for the rainfall event on the 04 of April (2008)

The extraction of runoff value for different land-use for the rainfall event on 04_April was ~10mm. The potential runoff occurs most strongly in cash crops, vegetable areas and industrial crops and mangroves with ~0.7mm, ~0.8mm and ~0.4mm respectively (Figure 5.7). Paddies, on the other hand, are a different situation with very high resistance to runoff with ~ 0.15mm. Other types of land-use are also highly resistant to runoff

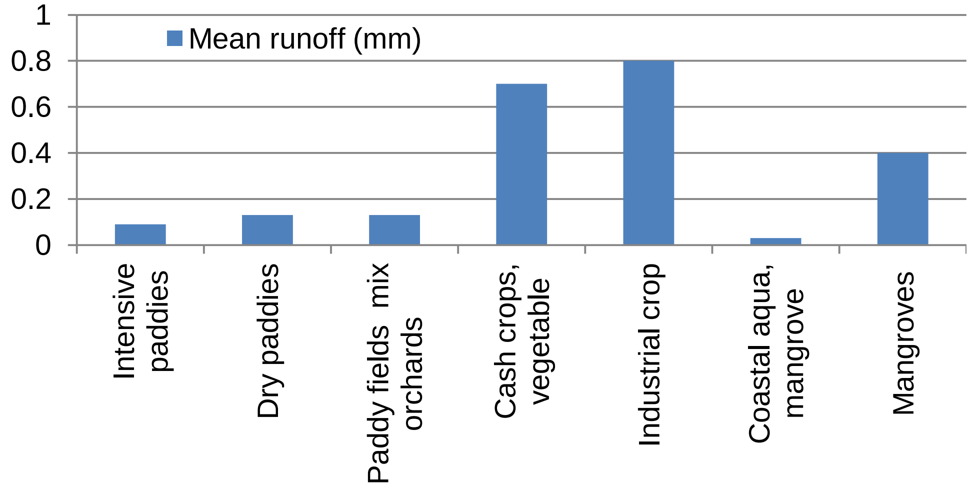


Figure 5. 7. Potential runoff from different land-use in the Mekong delta.

In the 5 different soil types in the study area, Eutric Gleysol and Eutric Fluvisol (distributing in riverside and coastal provinces) are strongly affected by runoff with ~0.35mm and 0.4mm (figure 5.8). The other types are highly resistant to runoff.

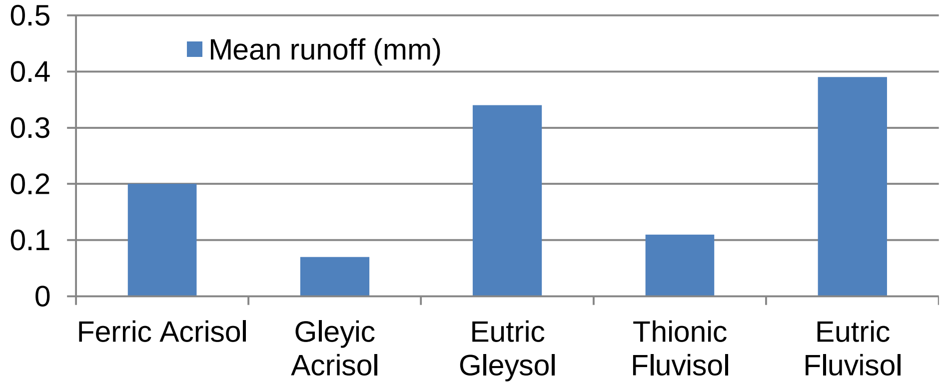


Figure 5. 8. Potential runoff from different soil types in the Mekong delta.

5.4.2. Peak discharge (q_p)

The peak discharge was calculated using the commonly used tabular hydrograph method (USDA-SCS, 1986). The hydrograph data requires basic information on (1) 24 hour rainfall (mm), (2) appropriate rainfall distribution, (3) curve number, (4) runoff volume (mm), (5) time of concentration T_c (in hours) which will be explained in the next category , (6) travel time T_t (hours), and (7) drainage area topographical condition. The peak discharge used in this study is graphical peak discharge method who's evaluation was much simpler than the tabular hydrograph method. The equation to calculate peak discharge is shown in equation 5.7

$$q_p = Q.A_m.q_t.F_p \qquad \text{(Equation 5. 7)}$$

where: q_p is peak discharge (ft^3/s); Q is runoff volume(inch); A_m is drainage area of sub areas (mi^2). All units in this equation has been kept in original definition. During data manipulation, the unit conversion coefficient was used to convert current data units into suitable for equation.

In this model, drainage area was equal to the area of a single satellite image pixel (30m x 30m) ; q_t is peak unit discharge ($cfs/mi^2/inch$). Determination of q_t is the key point in peak discharge calculation and it was estimated using the function *f*(T_c, I_a/P, and rainfall distribution type) which was already calculated by the graphical unit peak method (USDA, 1983). Therefore, to extract value q_t, the user must input information for 3 sub-components in the tabular (T_c, I_a/P, and rainfall distribution type).

F_p is the adjustment factor for pond and swamp areas and was only applied for water body category (in land-use map). Values for F_p is estimated by the percentage of pond and swamp areas in the total area of watershed (USDA-SCS, 1986). The calculation in this model is based on every grid-cell with homogeneous characteristics, therefore, at water bodies, the cell will totally present 100% water (not differentiate between pond and swamp). The extraction value F_p for water body and river will be 0.87 (USDA-SCS, 1986). The other land cover types will be ignored, and F_p was assigned to be 1.

5.4.2.1. Travel time and time of concentration (T_t and T_c)

As components of unit peak discharge calculation, the calculation of travel time (T_t) and time of concentration (T_c) is always included. Travel time (T_t) is the time for water runoff travelling from a particular point to another specific location in a watershed. Time of concentration (T_c) is the time for water moving from multiple-directions from all over the watershed until it accumulates in a specific area. T_c is estimated by the sum of travel time T_t. Travel time is affected by several of factors: surface roughness (*n*), channel shape and flow patterns, slope (*s*) and intensity of runoff (*P*) (USDA-SCS, 1986), as follows:

$$T_t = \frac{0.007(nL)^{0.8}}{(P)^{0.5}s^{0.4}} \qquad \text{(Equation 5. 8)}$$

where: T_t is travel time (hr); n is Manning's roughness coefficient; L is flow length (ft) which was defined as the longest distance of a pixel (equal to the length of the diagonal at ~139.5ft) , P is daily rainfall (inch); s is slope of a pixel. As the purpose of this study is to calculate soil erosion loss in overland flow. Travel time (T_t) in this study was established for every pixel and the database also held information on runoff, rainfall, slope, and aspect and roughness coefficient. In this case, time of concentration (T_c) is considered as equal to travel time (T_t) of water cross a single pixel (30 m).

In this study, manning "*n"* value was determined by land-use and land cover combined with user knowledge, based on the description of USDA (1986). The smallest "*n*" value was established at 0.011 where runoff take place without any obstacle (bare land or water body areas), and gradually increases depending on the higher density of surface barriers (e.g forest, mangroves).

5.4.2.2. Unit Peak discharge calculation

Unit peak discharge is determined by using the logarithmic function in equation 5.9 (USDA-SCS, 1986).

$$\log(q_t) = C_0 + C_1 \log(T_c) + C_2[\log(T_c)]^2 \qquad \text{(Equation 5. 9)}$$

Where q_t is unit peak discharge; C_0, C_1 and C_2 are coefficient extracted from value of I_a/P; T_c is time of concentration.

In order to establish the coefficients C_0, C_1 and C_2, the ratio between initial abstraction (I_a) and precipitation P was calculated. According to the location and climate conditions given in the description by USDA (1986), the rainfall type I was chosen for the calculation. Values C_0, C_1 and C_2 were determined for the Mekong delta is shown in table 5.5.

Table 5. 5. Extracted coefficient C_0, C_1 and C_2 in the Mekong delta

Rainfall Type	**I_a/P**	**C_0**	**C_1**	**C_2**
I	0.1	2.30550	-0.51429	-0.11750
I	0.2	2.23537	-0.50387	-0.08929
I	0.25	2.18219	-0.48488	-0.06589
I	0.30	2.10624	-0.45695	-0.02835
I	0.35	2.00303	-0.40769	0.01983
I	0.40	1.87733	-0.32274	0.05754
I	0.45	1.76312	-0.15644	0.00453
I	0.50	1.67889	-0.06930	0.0

Knowing the rainfall type, I_a/P, and coefficient C_0, C_1 and C_2 and type of rainfall, the function of q_t can be readily solved. Applying equation 5.7, the peak discharge was calculated and figure 5.9 shows the peak discharge for every pixel in m^3/s.

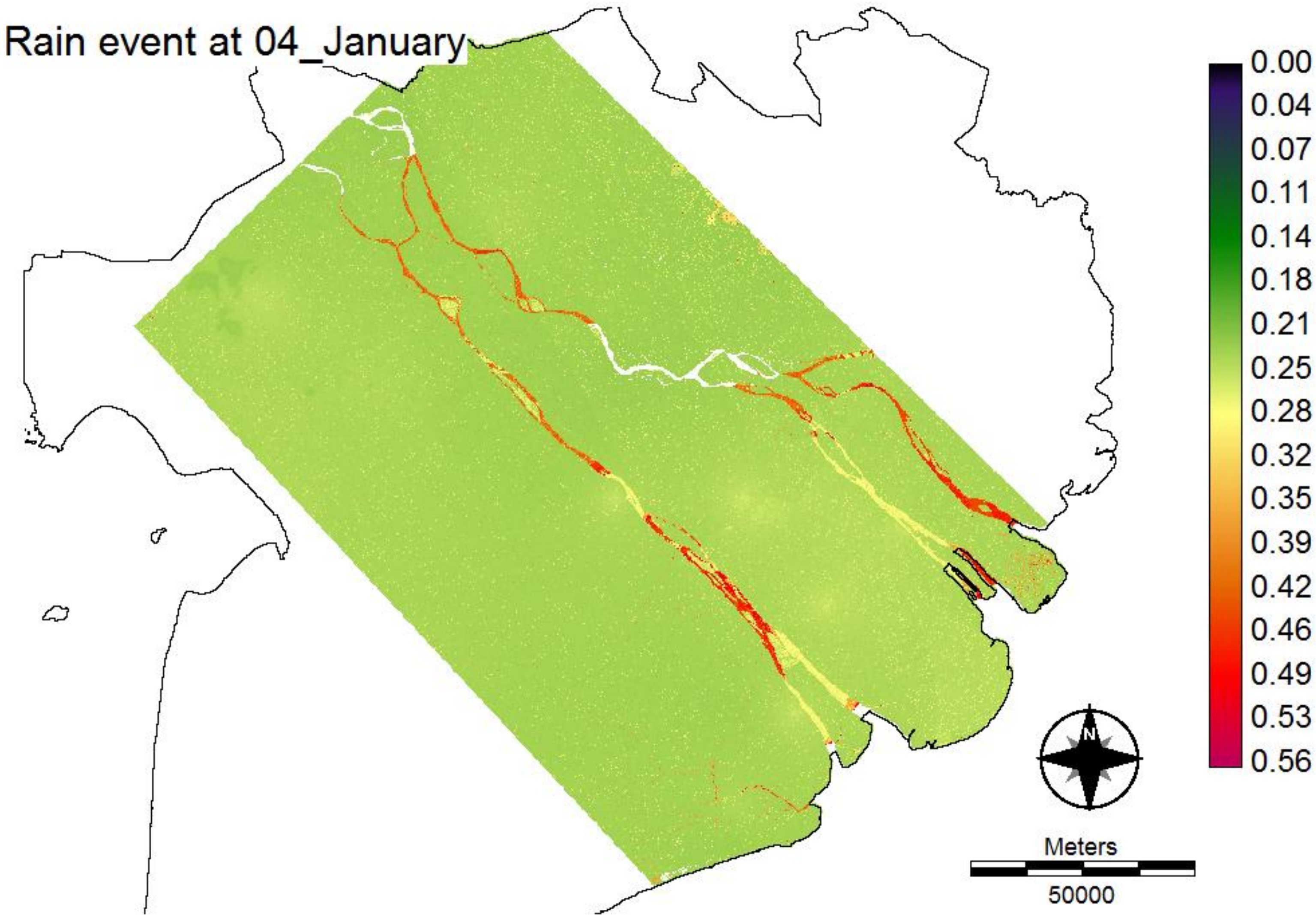


Figure 5. 9. Peak discharge (m^3/s) following the first rainfall event in January in the Mekong delta.

5.5. Soil erodibility Factor (K factor)

The soil erodibility factor is the resistance of soil structure to water and is defined as the rate of soil loss per erosion index unit [(metric ton)(hectare)(hour)]/[(hectare)(mega joule)(millimeter)] (Wischmeier, 1959). Empirically, *K* factor is determined by obtaining the soil resistance in testing plots of land with constant slope (9%) and a 22.12 m length slope. Determination is closely related to soil types and soil textures and low values of the K factor characterizes low erosion resistance while high values show high erosion resistance. The soil erodibility value depends on soil surface conditions. In this study, *K* was calculated based on soil properties such as particle size, percentage of organic matter, soil structure categories and textures, a profile permeability classes (Wischmeier et al, 1978)

Soils in the Mekong delta are primarily Acrisol, Gleysol and Fluvisols. Chiem, (1993c), revealed the high concentration of very fine sand and silt (total ~70%), allowing calculation of the K factor using a nomograph (Wischmeier et al, 1978) from equation 5.10.

$$\mathbf{100K = 2.1.10^{-4}.(12 - a).[Ss.(100 - Sc)]^{1.14} + 3.25(b - 2) + 2.5(c - 3)}$$ (Equation 5. 10)

where *K* is soil erodibility factor (t.ha.h/ha.MJ.mm); S_S is percentage of clay; S_c is percentage of silt; *a* is organic matter percentage (OM). $S_{S,}$ $S_{c,}$ and *"a"* were available to use from the FAO soil database (FAO, 2003). A lower organic matter percentage indicate a higher resistance to runoff (Wischmeier et al, 1978).

Parameter *"b"* is the soil structure status code which represents the effect of organic matter on the soil structure in the first layer of soil available for sediment loss (Schwab, Fangeier, Elliot, and Freverk, 1993);

Parameter *"c"* is the soil permeability class. Both "b" and "c" are defined for the Mekong delta soil types following methods provided by (Zhou and WU, 2008; Renard, Foster, Weesies, McCool, and Yoder, 1997). The result from equation 5.10 is shown in figure 5.10.

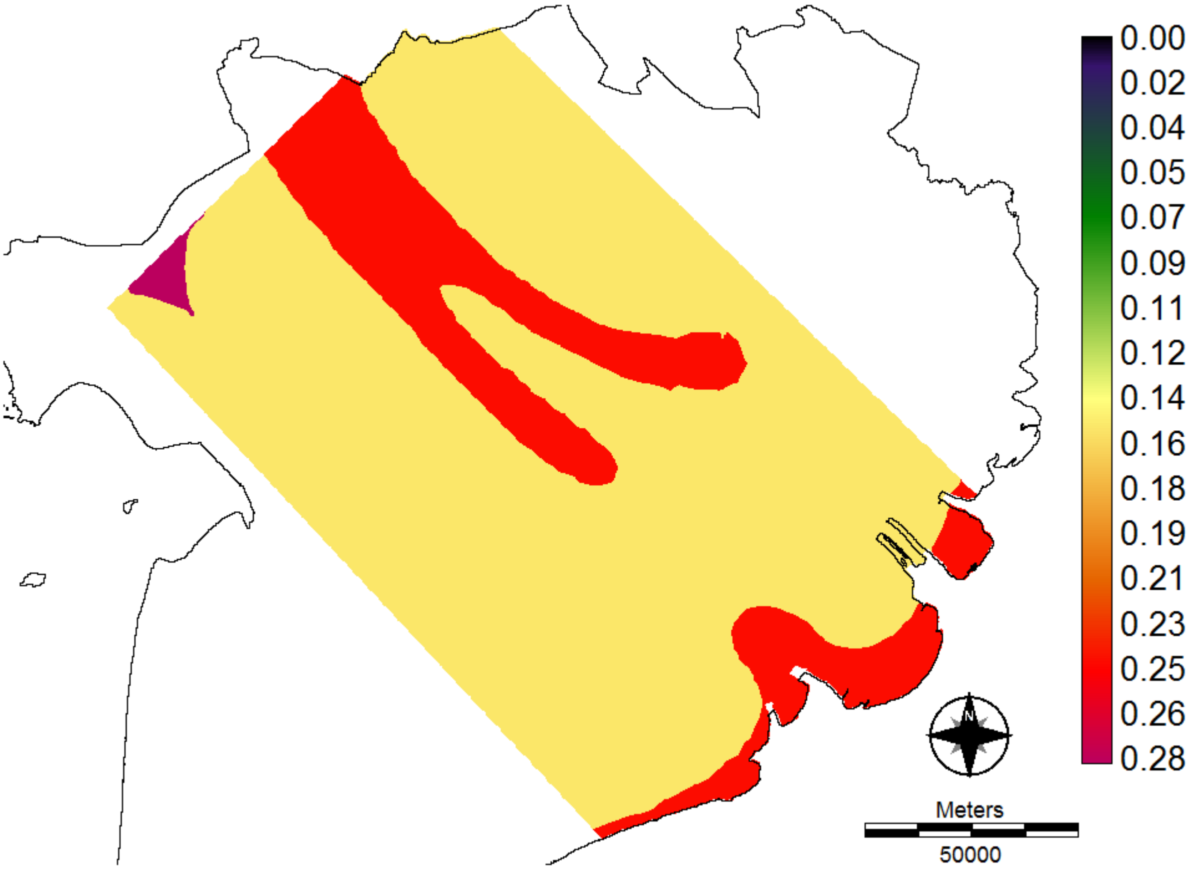


Figure 5. 10. Soil erodibility factor (*K*) of different soil types in the Mekong delta.

5.6. Topographic factor (LS factor)

The topographic factor, LS, represents a combination between length of slope and its steepness, which is important for defining hydrology, volume of run-off and sediment yield, where the greater the steepness, the larger volume of runoff occurs (Kinnell, 1981).

Zing (1940) showed that there was an exponential relationship between soil erosion (y) and steepness (x). Thus, $y=ax^b$ where "a" is 0.065 and "b" is 1.49, was conformed experimentally for conditions in Kansas and Alabama, USA. When rainfall happens, the detached soil moves from the higher to the lower slope. Considered at pixel level, , there are several kinds of slope shapes which influence overland flow (Figure 5.11). As the model was constructed to run in a single pixel with homogeneous data, the steepness could be estimated as the mean steepness using equation 5.11 (Mc Cool, Foster, Renard, and Yoder, 1995; Cowen, 1993).

$S_{(Steepness)} = 65.41 \, Sin^2 \, \theta + 4.5 \, Sin \, \theta + 0.065.$ (Equation 5. 11)

Where θ is the slope angle in degrees.

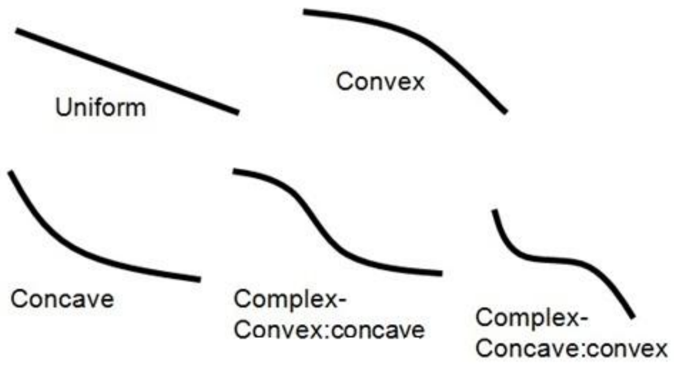


Figure 5. 11. Different shapes of flow path may have in a pixel

L is the slope length (in metres) over which water or sediment mixing with water runoff travels from the highest point to lowest point where deposition begins. Wischmeier (1978) suggested an equation to calculate *L* which is given by equation 5.12.

$$\boldsymbol{L = \left[\frac{FL}{22.13}\right]^{m}} \qquad \text{(Equation 5. 12)}$$

where:

FL is the field cumulative slope-length (metres) and 22.13 is the constraint extracted from the experiments (Wischmeier *et al.*,1978)

m is the index of categories of steepness classes which were calibrated by (Renard *et al.*,1997; Wischmeier *et al.*,1978), where:

$m = 0.5$ if slope $S > 5\%$

$m = 0.4$ if slope $3\% < S < 5\%$

$m = 0.3$ if slope $1\% < S < 3\%$

$m = 0.2$ if slope $S < 1\%$

However, the calibration for *m*, above, was criticised for areas with slope over 9%. To specify the exact value of *m*, Kinnell (2001; 1987) and McCool (1987) recommended a method as shown in equation 5.13. In the Mekong delta, slope lower 9% occupies the majority of areas. The minority of mountain areas in Angiang Province appears to have a slope over 9% which occupies only ~0.43% in total 20,000km^2 of study area.

Specifically, *m* is calculated by

$$\boldsymbol{m} = \frac{\boldsymbol{\delta.\beta}}{(\mathbf{1}+\boldsymbol{\beta})} \qquad \text{(Equation 5. 13)}$$

and ;

$$\boldsymbol{\beta} = \frac{[\boldsymbol{Sin\,\theta}_{(\boldsymbol{aspect})}.\ \ (\mathbf{0.0896})]}{\mathbf{3.0}\ (\boldsymbol{Sin\,\theta}_{(\boldsymbol{aspect})})^{\mathbf{0.8}}+\mathbf{0.56}} \qquad \text{(Equation 5. 14)}$$

Where θ is the slope aspect in degrees (calculated by the ASPECT module in IDRISI from DEM input, the result of aspect is the angle 0^0 - 360^0 clockwise to the north); δ value is the coefficient to show the relation of soil condition and current land-use. Practically, overland flow erosion is not only affected by steepness, but also by multiple factors. Land-use (or land cover) and soil detachment ability were one of several important factors having a strong effect on erosion capacity, explaining why some authors include the effect of land-use when calculating LS by using the δ value (Renard et al, 1997). δ for the Mekong delta soils is classified in table 5.6

Table 5. 6. Classify δ value in Mekong delta

Soil condition	Agricultural Soil	Erosion prone soil	Unsusceptible soil
Current Land-use	Intensive paddy Dry paddy Paddy mix orchard Cash crops Coastal Aquaculture	Residential areas Rocky areas	River Mangrove Coconut and garden
δ Value	1.0	2.0	0.5

By method of Kinnell (2001)

Field cumulative slope-length (*FL)* was computed simply using a trigonometric method which is described as the ratio of flow direction length (*X*) per value of Cosine of the slope angle *θ* (figure 5.12) and by the equation 5.15.

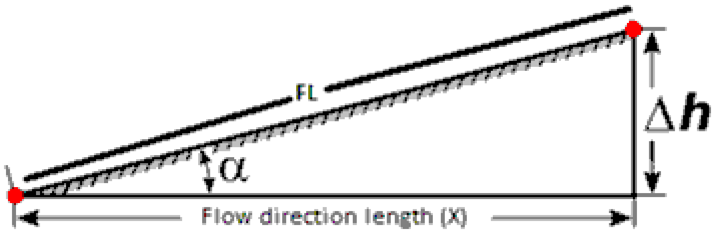


Figure 5. 12. FL calculation basing on a simple trigonometric model

$$FL = \frac{X}{Cos(\propto)} \qquad \text{(Equation 5. 15)}$$

X is the flow direction length*.* Calculation flow direction length (*X*) is primarily based on the aspect which was derived from the FLOW direction image. Based on the work of Perez (2002), angles from 337.5^0 to 22.5^0, 67.5^0 to 112.5^0, 157.5^0 to 202.5^0, 247.5^0 to 292.5^0 were assigned a new value equal to one side of a pixel resolution (30 m) whereas angles from 22.5^0 to 67.5^0, 112.5^0 to 157.5^0, 202.5^0 to 247.5^0, and 292.5^0 to 337.5^0 were assigned the value of 42 m, equal to the diagonal of a pixel.

The slope length and steepness factor is shown in figure 5.14. The LS factor is not easy to differentiate from place to place due to the flat terrain in the Mekong delta and the fact that the calculation was at the individual grid cell level of $900m^2$.

5.7. Cover and management factor

Soil loss erosion is effected by canopy cover and mulches and is represented by factor *C*. This factor was defined as the ratio of soil loss in land cropped in a specific condition to soil loss in almost bare land or bare land (NASA Landsat program,2003; Wischmeier *et al.*,1978; Wischmeier,1959) and ranges from 0 to 1.

Modern Landsat imagery allows more accurate estimation of the C factor using the NDVI (Normalized Different Vegetation Index) (De Jong and Riezebos, 1997) and based on a linear regression model to analyse the correlation between factor C values which were supported in USLE guide tables or measured on the field, and the NDVI values derived from Landsat imagery. NDVI is a numerical indicator which allows users to delineate the distribution of vegetation cover on the ground and is based on spectral reflectance of NIR (Near Infrared Radiation) and red band colour (equation 5.16).

$$\boldsymbol{NDVI = \frac{NIR-Red}{Nir+Red}} \qquad \text{(Equation 5. 16)}$$

or, when applying to Landsat images, the equation will be written:

$$NDVI = \frac{Band4 - Band3}{Band4 + band3}$$

C factor was calculated using a linear correlation between factor C and NDVI as indicated in figure 5.13.

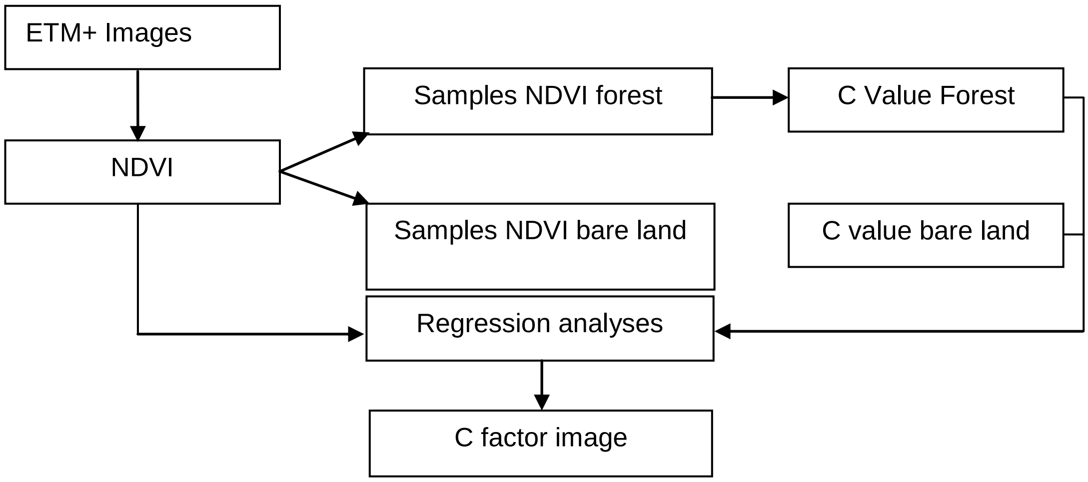


Figure 5. 13. Flowchart summarizing the process of calculation of the C factor by using NDVI.

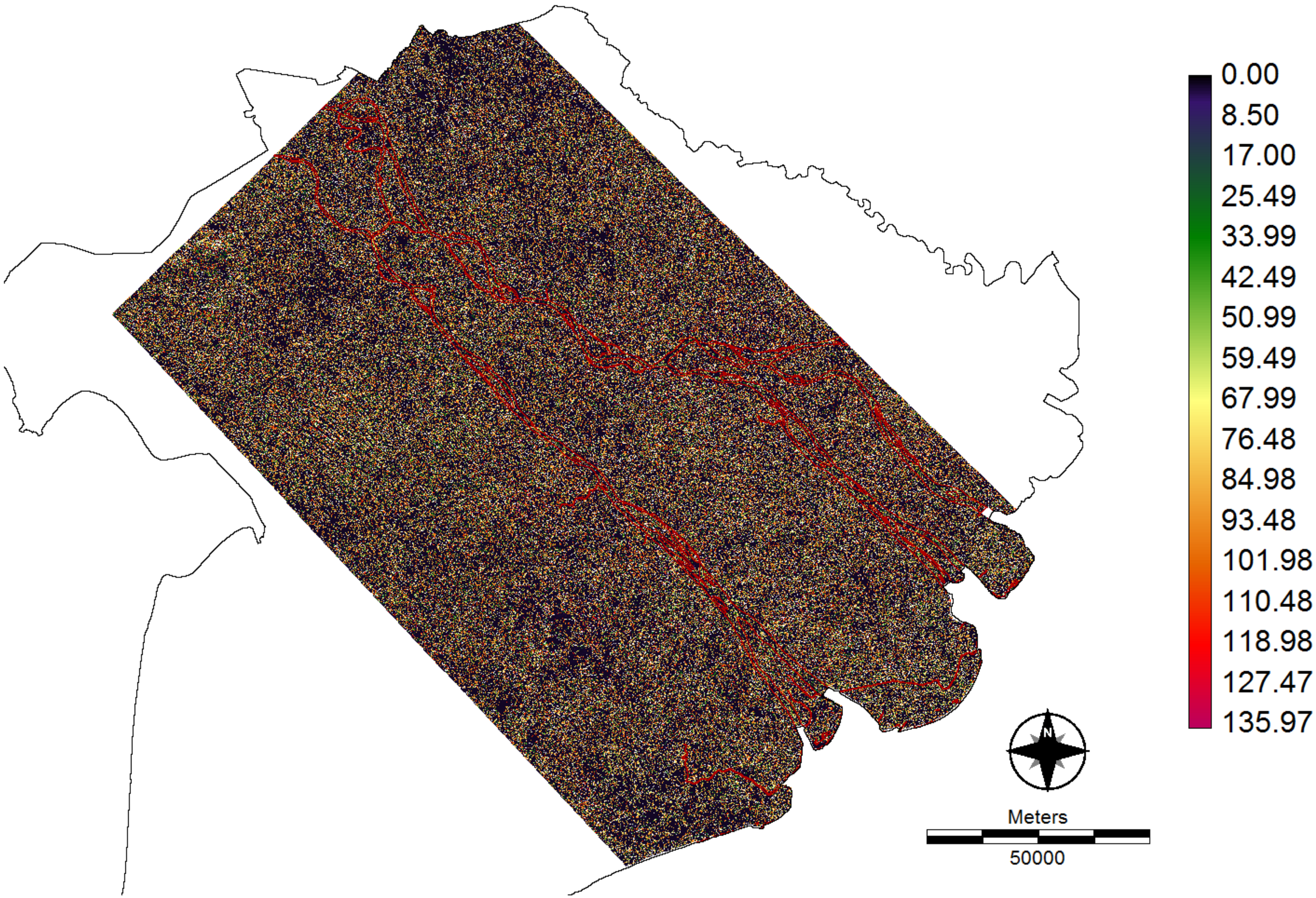


Figure 5. 14. Length slope and steepness factor (LS)

By cursory revising some points in Landsat images combined with personal user knowledge on land cover in study area, two NDVI datasets were formed by extracting 20 points of high density canopy cover and another 20 of bare soil (Figure 5.13). In the correlative dataset, a value of factor C was assigned for each point of the extracted NDVI value. The factor C ranged from 0 to 1, where values of "0" was assigned for forest which has less affect by soil erosion and a value of "1" for bare soil land and prone to greatest soil erosion. The regression was carried out within IDRISI resulting in the following relationship:

C-factor = 0.3363 - 0.4842 NDVI

The correlation coefficient, R^2, was 92%.

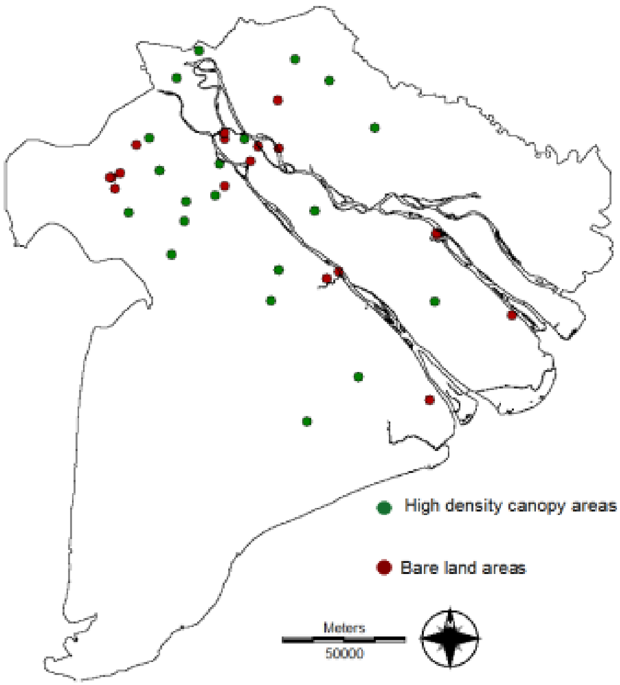


Figure 5. 15. Position of sample points of forest areas and bare land area

The linear regression equation was applied to calculate all pixels in the NDVI image following some corrective reclassification of aberrant pixels in the thermal band of the Landsat images The final C factor values are shown in figure 5.16.

As shown in figure 5.16 the majority of the Mekong delta consists of paddy fields with high density of vegetation cover (C factor = 0.01 to 0.2) whereas forest and orchard areas (C factor = 0.2 to 0.3) occupy a smaller overall area than those of bare land and water bodies (C factor 0.3 to 1).

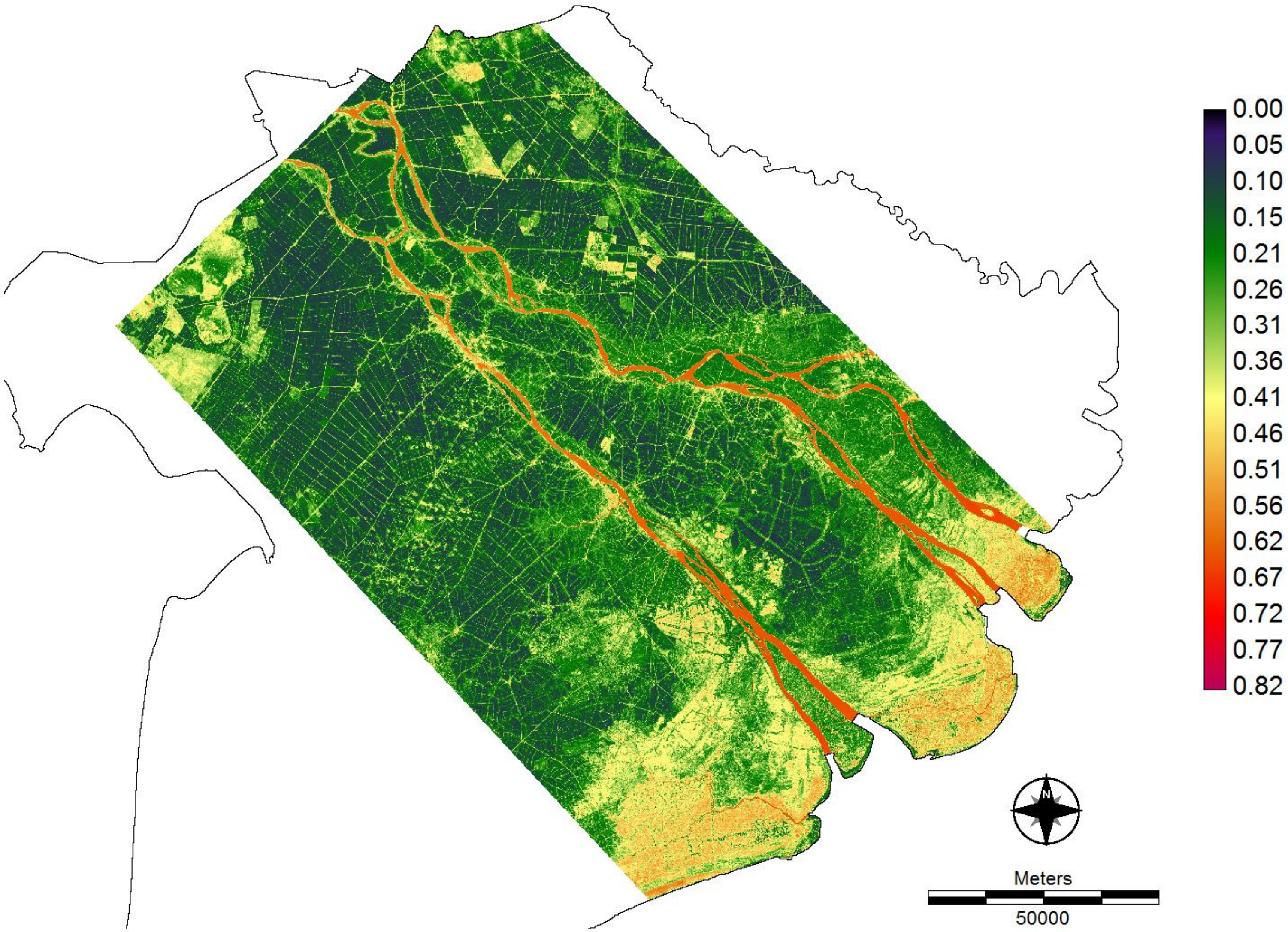


Figure 5. 16. C factor value representing land-use and land cover contribution to soil loss as a restriction feature.

5.8. Support practice factor (P)

Support management factor in RUSLE is the ratio of soil loss in a particular support practice to the corresponding soil loss with farming in up and down slope. This factor shows the actual vegetation distribution and slope conditions which affect the erodibility of the soils. The support practice factor implies the different farming systems occupying particular types of slope, including strip cropping, terrace, contouring and tillage cover. Wischmeier (1987) stated that factor P was the only factor that humans can use to control and reduce the soil loss erosion through appropriate farming methods. High values of *P* show there is only weak support practice culture, so will represent bare land areas or construction zones (value *P=1*), whereas low values correspond to high resistance soil losses through use of high density planting or specific cropping/culture systems. In this study, value of P was calculated by using method proposed by Agriculture Research Service and Conservation Service (USDA-SCS, 1972). The estimation for P values in the study area is shown in Table 5.7 which represents the existing forms of farming system relative to land slope (cross slope, contour farming, strip cropping and cross slope, strip cropping and contour). Factor P was classified by the actual condition of contouring or cropping of farm combined with the knowledge of user. As the majority of slope in the Mekong delta is flat, the value *(P=1)* for up and down practical culture was not found in the images. However, this value will be assigned for water bodies and was considered non-resistant to runoff or sediment loss (Figure 5.17). Paddy field (~65% of land-use) was considered as a homogeneous slope, characterised by low, flat topography (maximum 10 meter elevation).

Table 5. 7. P factor estimated for the Mekong delta

Support practice	Land-use	P-factor
Up and down slope	1	1
Cross slope	5,7	0.75
Contour farming	6	0.50
Strip cropping, cross slope	3,4	0.37
Strip cropping, contour	2,8	0.25

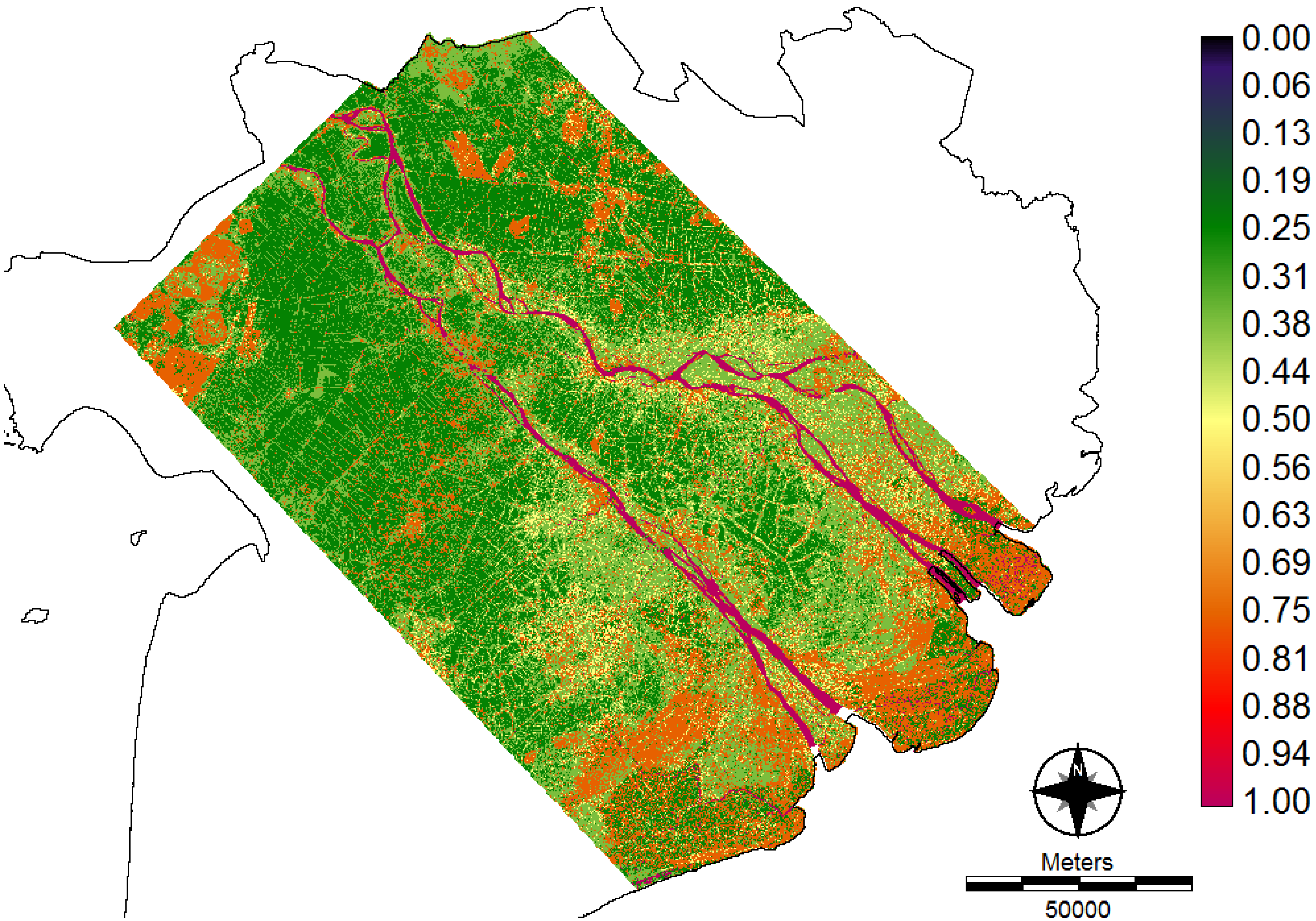


Figure 5. 17. *P* factor in the Mekong delta, indicating the capacity of different cropping styles for resistance to soil erosion.

5.9. Sediment net accumulation calculation

This study aims to quantify the fate of pesticide existing in soil and water environments. Therefore sediment net accumulation is considered as a potential storage of accumulated pesticides. Sediment net accumulation is computed based on the soil loss for single rainfall event and elevation.

Net accumulation of sediment loss comprises 2 concepts. 1) Temporal accumulation is the accumulation at a pixel where a rainfall event brings an amount of sediment from other places to that point. The next event will continue to bring further sediment to that location and as rain events continue, eventually there is a large accumulation of sediment at this place. Using this concept, some points always have a net accumulation of sediment from other locations and other points a net loss. In the other words, this is a progressive accumulation of sediment which continues after every rainfall event. 2) Spatial movement of sediment which through topographic effects on cumulative sediment loss was already described in (**5.6)**. and equation 5.12.

In this study, the total sediment yield for the period of the *1st* to *4th* of *January (2008)* was chosen as the first step of accumulated sediment estimation. The final output of sediment accumulation from this (at the *4th* of *Jan*) becomes the self generated sediment accumulation *(M_o)* for the second rainfall event (period from 5th- Jan to the 8th - Jan). This process is summarised in Equation 5.17, continues for the full year.

$$\boldsymbol{M = M_o + \sum_0^t (M_{nt} - M_{lt})} \qquad \text{(Equation 5. 17)}$$

Where:

M is the total sediment yield at *t* time

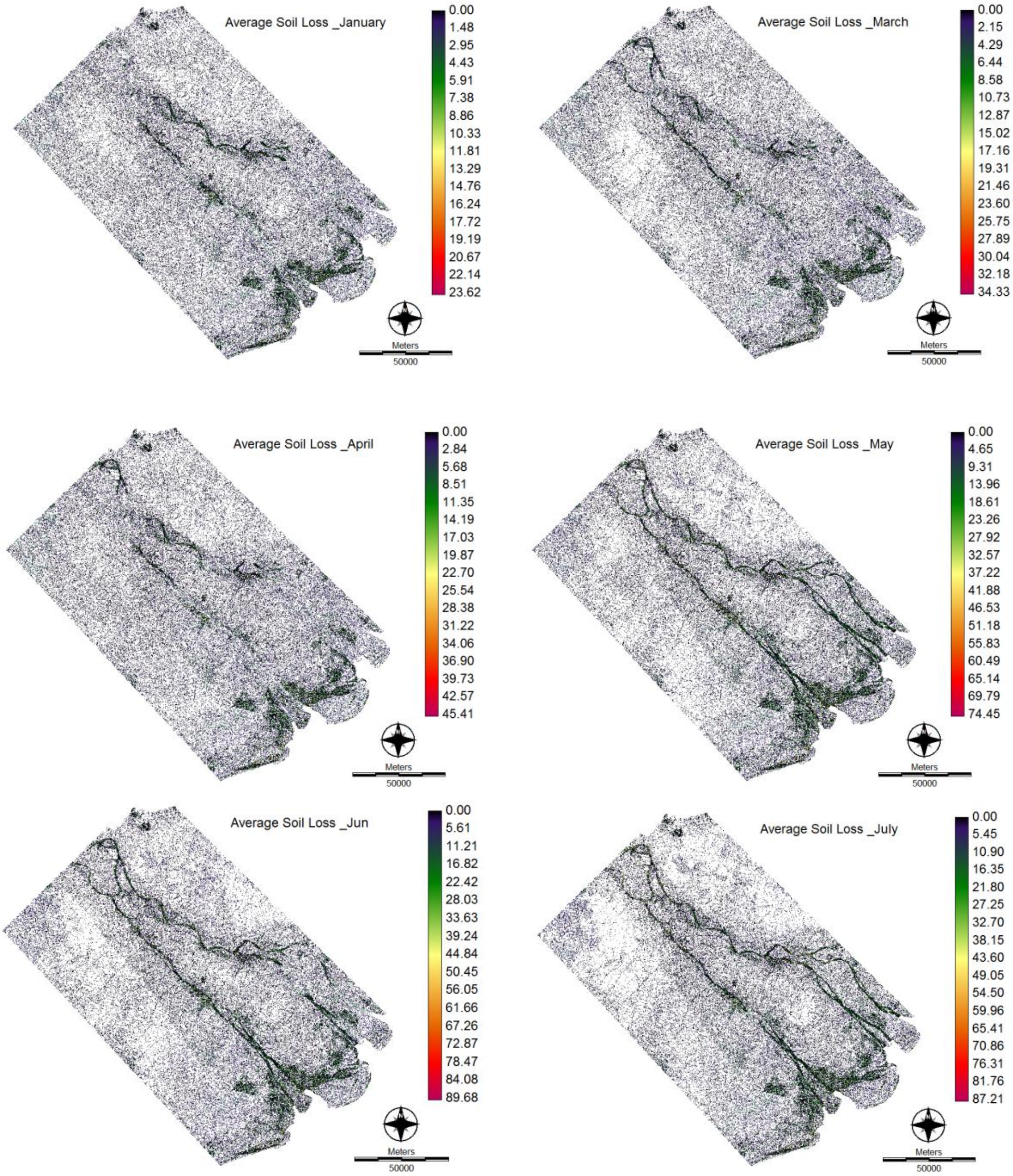
M_{nt} is the sediment yield received from higher places at *t* time

M_{lt} is the total sediment yield lost to other lower places by runoff at *t* time

5.10. Results

5.10.1 Sediment losses in the Mekong delta

Figure 5.18 shows the mean monthly sediment loss over the whole year, although the model generated outcomes for every four day step. For runoff and sediment loss to occur, the ratio of initial abstraction and precipitation (I_a/P) has to be smaller than 1, in other words rainfall volume must be higher than the initial abstraction (I_a), which depends considerably on soil type. The model operates only when rainfall is greater than I_a and this explains why there is no sediment loss data created for February and December as there was no rain in these two months. A further condition in this model requires total rainfall 4 days to be higher than 10mm as lower values may cause a soil detachment but will normally not generate a runoff (Huber, Bach and Frede, 1998). Spatially, sediment loss strongly occurred in rivers and riverside areas and in coastal zones, whereas a large inland areas of paddy fields have very light sediment losses.



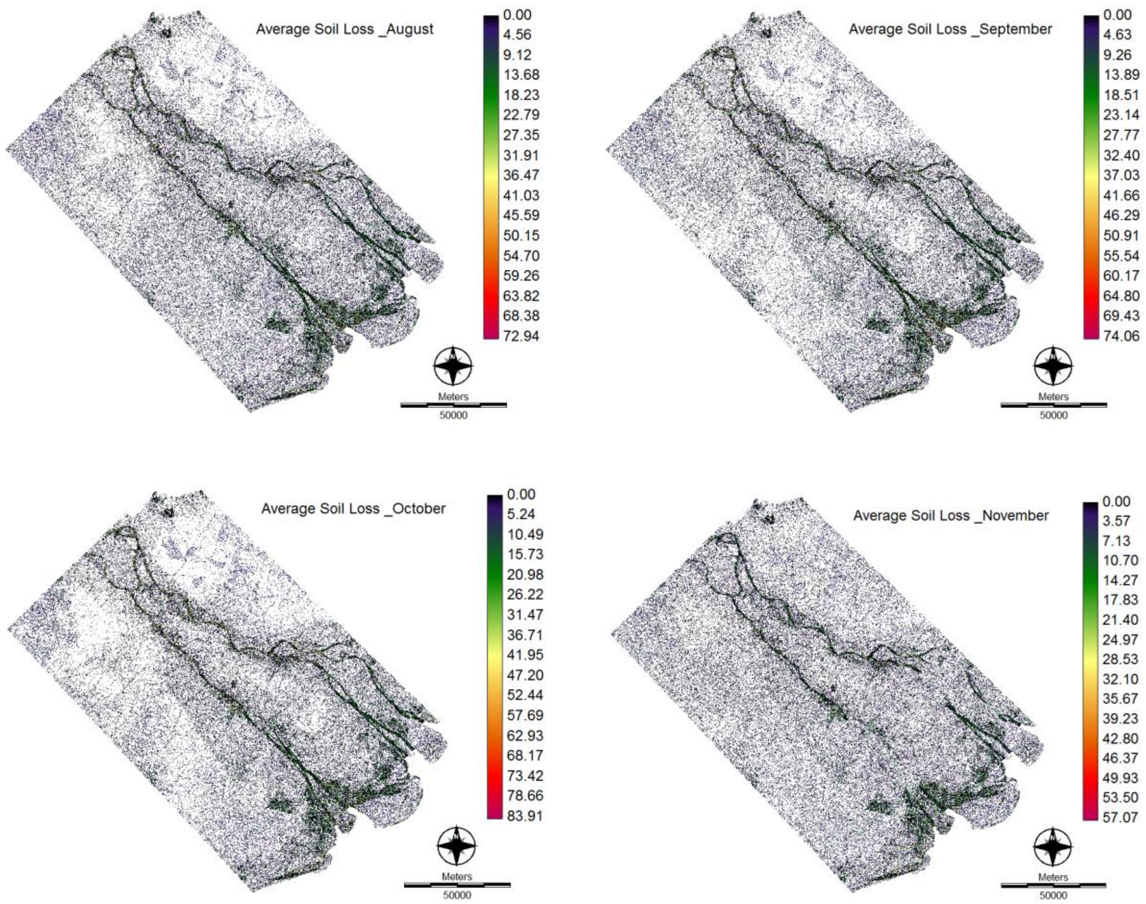


Figure 5. 18. These images show average monthly sediment losses (ton/ha/y) in 2008

- **<u>Sediment losses in different land-use</u>**

The total values of sediment loss in the Mekong delta shows that areas of cash crops and vegetables was the most vulnerable to soil erosion with maxima at ~53 tonne/ha in Jun and July, ~50 tonne/ha in October, ~45tonne/ha in August and September, and ~34 tonne/ha in November (2008). The second most vulnerable land-use for sediment loss is industrial crops (oil fruit or sugar canes fields) with >35tonne/ha in June and July. Paddies, although occupying the largest land-use areas, seem to be more stable and the mean monthly sediment loss is not significant (smallest sediment losses in the fields) with only 1.46 tonne/ha in June. Dry paddies and orchards on the other hand, were affected by soil erosion with a maximum at ~ 4.8 tonne/ha in June and July. The remaining land use categories have medium impact from soil losses with around ~10tonne/ha in during rainy season (figure 5.19).

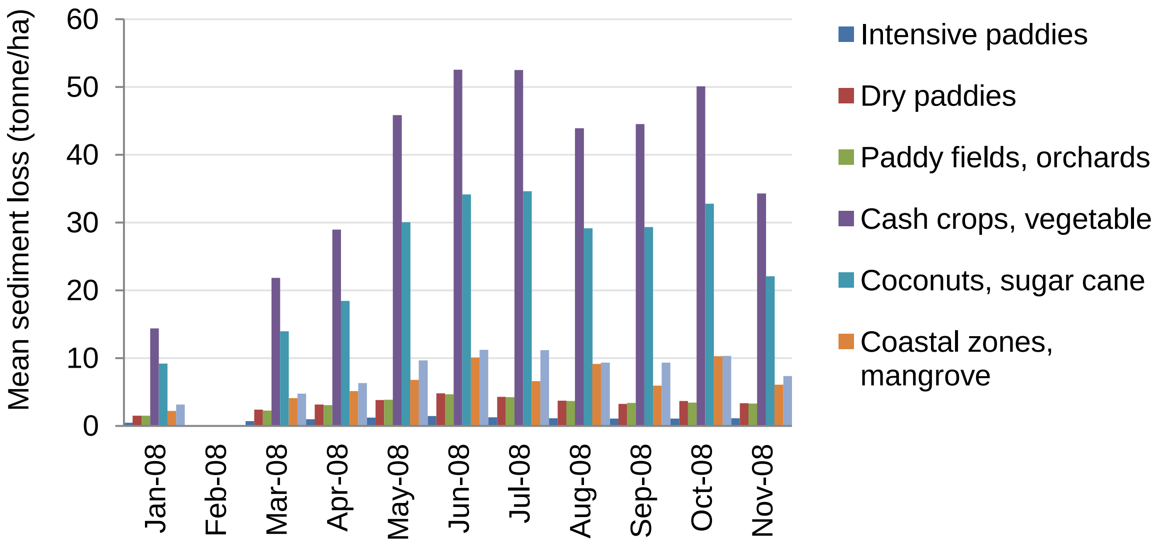


Figure 5. 19. Total monthly sediment losses in different land-use categories in 2008.

Sediment loss in the wet season is much higher than in the dry season. In cash crop areas, total wet season sediment yield losses reach ~280tonne/ha whereas only ~100tonne/ha are lost in the in dry season. The second highest is industrial crop areas with ~180 tonne/ha wet season whereas only ~60 tonne/ha in dry. Paddies seem to have a high resistance to sediment loss and erosion with all values smaller than 20 tonne/ha in both seasons (figure 5.20)

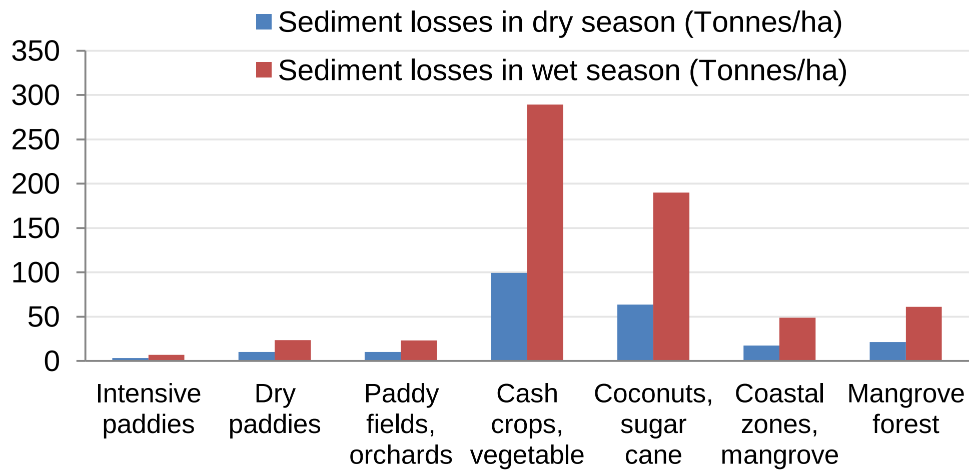


Figure 5. 20. Total sediment losses in different land use categories in dry and wet season in 2008

- **Mean sediment losses in different soil types**

Eutric Fluvisol seems to have the lowest capacity to resist erosion and sediment losses. In months with high rainfall intensity, total sediment loss in this soil type reaches >30tonne/ha (in June, July and October), over 25 tonne/ha in May, August and September. Fluvisol soils in Mekong delta are concentrated in coastal areas and in river side areas where sediment losses monthly are able to approach ~3.2 to max ~6 tonne/ha in June and October. The second mist eroded soil type is Eutric Gleysol with over 15 tonne/ha in during May to October (figure 5.21).

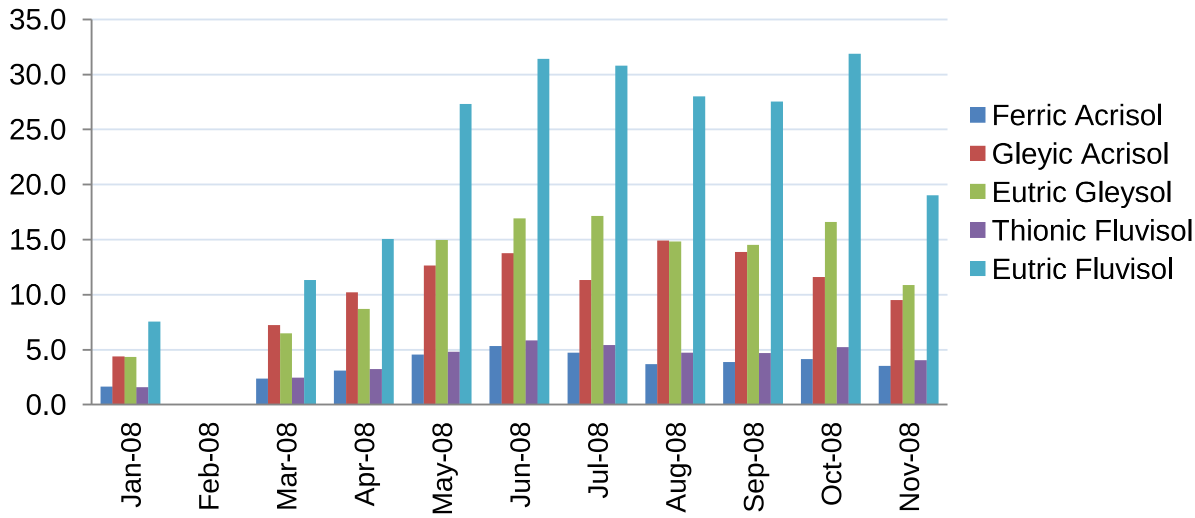


Figure 5. 21. Total monthly sediment loss in different soil types in 2008

In the rainy season, sediment losses are almost three times those in the dry season, especially for Eutric Gleysol and Eutric Fluvisol with >90 tonne/ha and ~180 ton/ha respectively in the wet season. Ferric Acrisol and Thionic Fluvisol are considered as the most stable soil to the erosion process with a total sediment yield of <30 tonne/ha in both seasons (Figure 5.22).

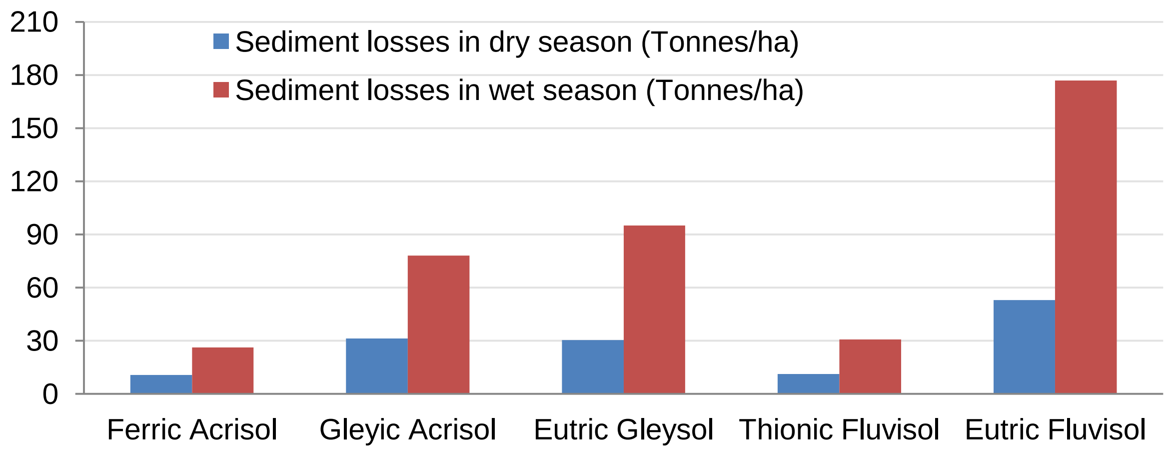
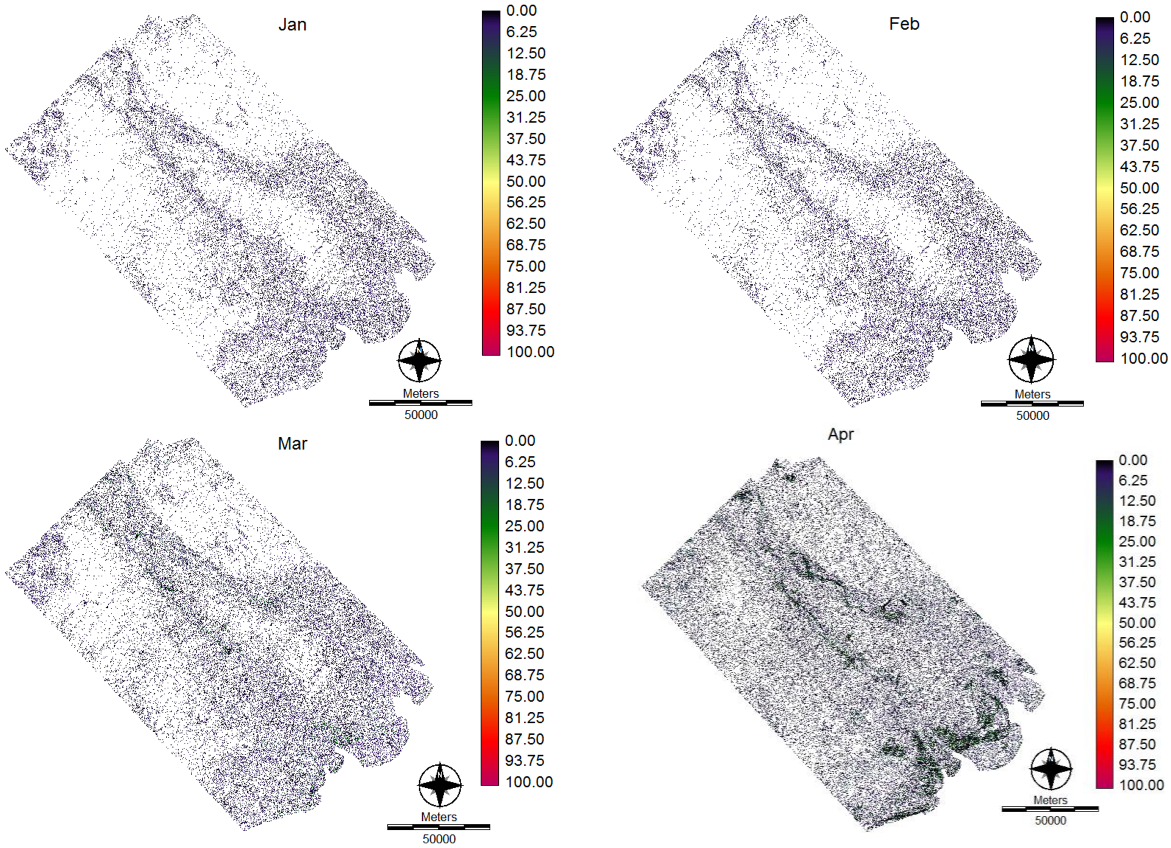
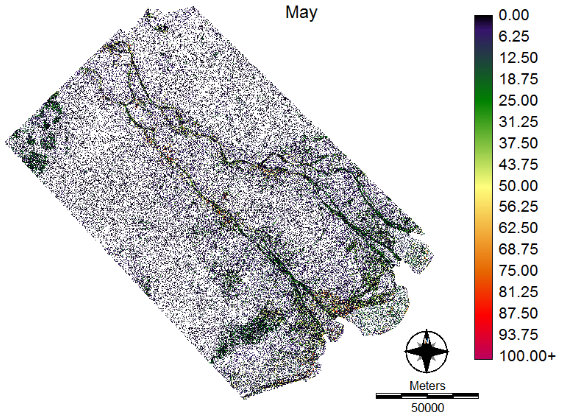


Figure 5. 22. Total sediment loss in different soil types in wet and dry season in 2008

5.10.2. Sediment net accumulation

Accumulation in January and February was unchanged as there was no rainfall in this period. A similar effect was seen in November and December. The sediment accumulation significantly increase from April (increased remarkably in June to November) because it closely relate to high rainfall volume in these periods (figure 5.23). The principal effect was seen in the river and riverside areas. The coastal zones also the most vulnerable areas for sediment accumulation. Hilly areas in the west side of the Mekong delta was also the noticeable areas with high concentration of cumulative sediment increased significantly during rainy season (May to November), but only occupies a minor areas. Whereas the largest areas located in low land seem to have lowest impact to cumulative sediment.

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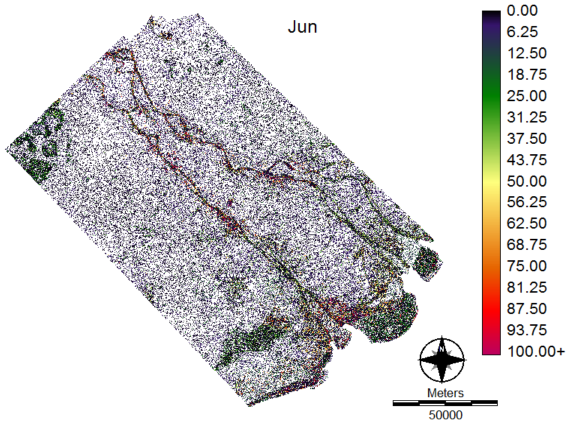
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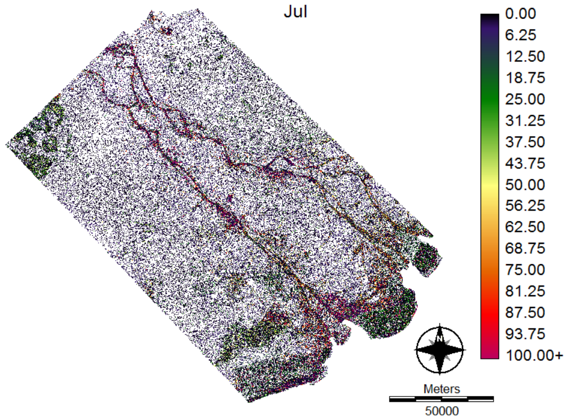
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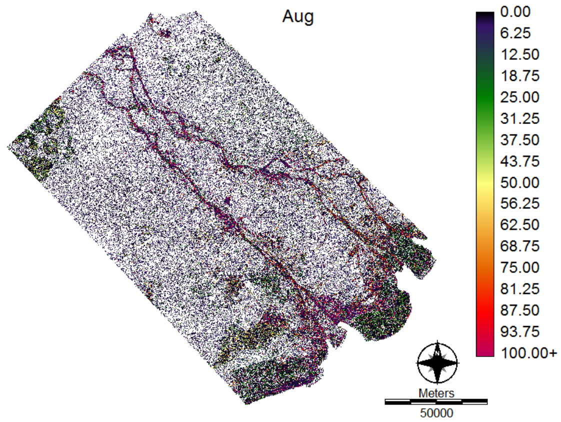
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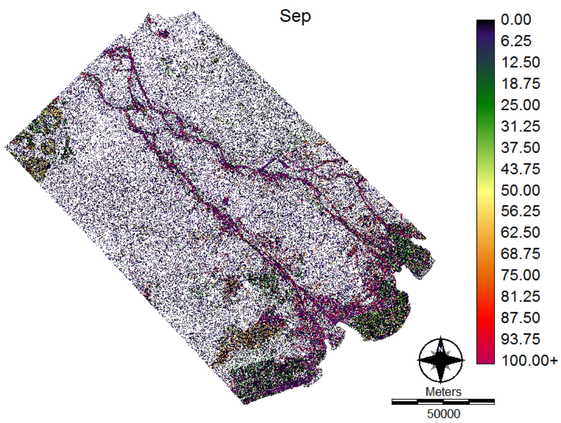
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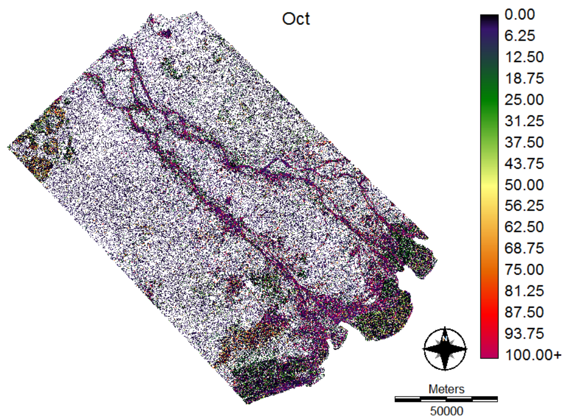
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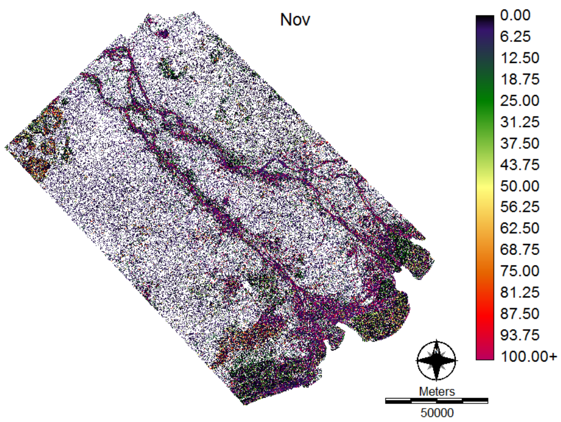
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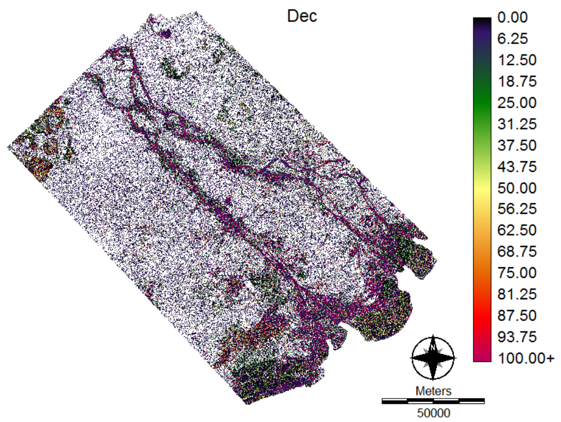
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Figure 5. 23. Monthly sediment yield accumulation (tonne/ha)

Figure 5.25 show the net accumulation of sediment three randomly chosen stations in the riverside and hilly areas of Angiang province and in a paddy field area in Haugiang province (figure 5.24).

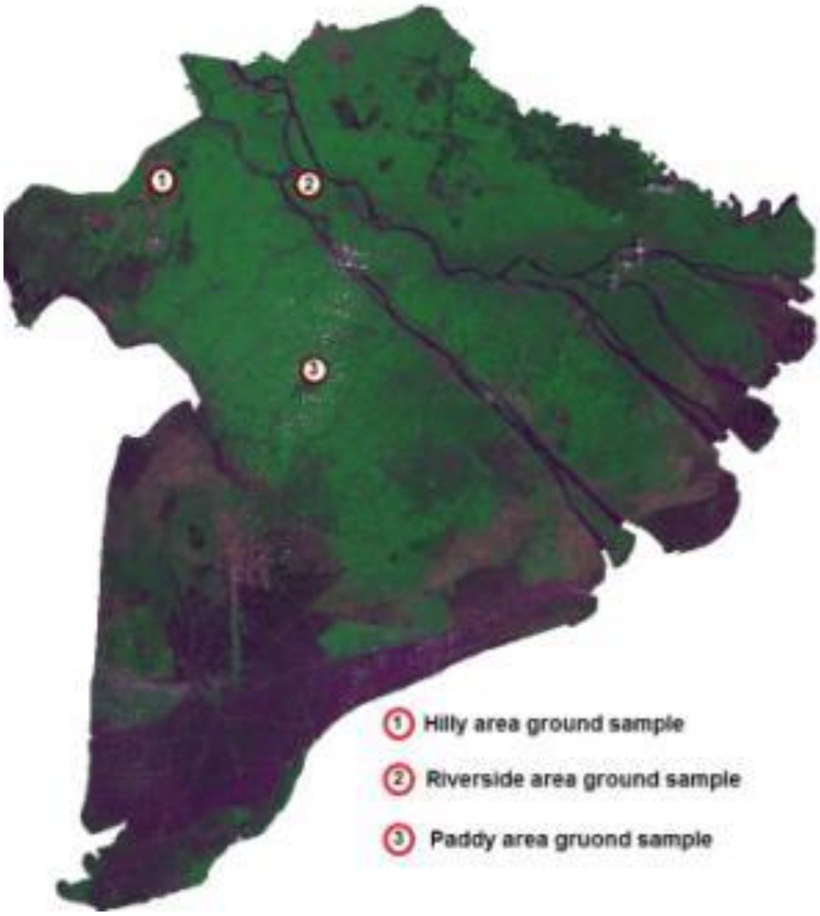


Figure 5. 24. Three randomly chosen stations in hilly area (1); riverside area (2); and inland paddy areas (3) where all them were used to extract the sediment accumulation data

The hilly areas with high slope actually have a high capacity for soil erosion and sediment loss. The results show the accumulation around the hilly areas was also very high. Comparing this with the same area of riverside and wet paddy field, the amount of sediments accumulated in the hilly region was 4 times higher than those of other areas (figure 5.25). Moreover, the trend of accumulation increased significantly from the end of March to the end of November, whereas the other 2 sections only increased moderately with maximum accumulation not exceeding 250 tonne/ha.

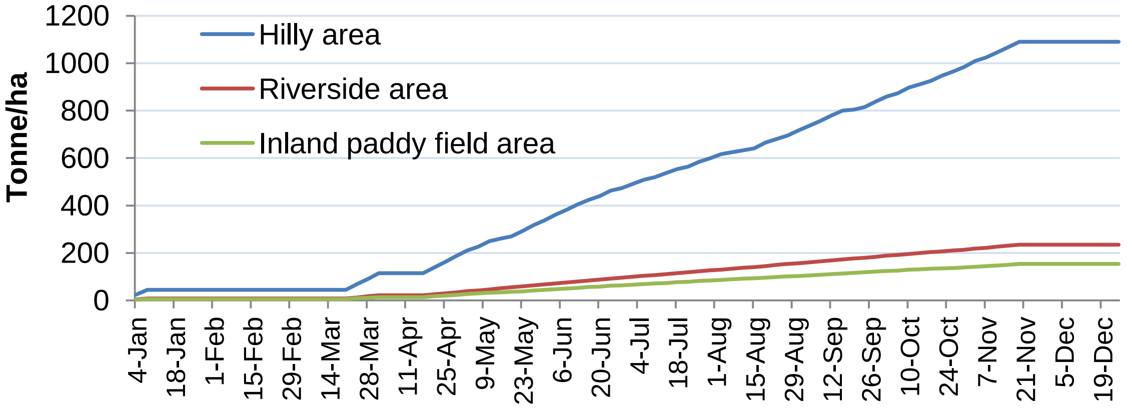


Figure 5. 25. Sediment accumulation in 3 particular areas: Hilly area, riverside and wet paddy area

Sediment accumulation in the 3 areas depends upon several factors, including soil types, rainfall volume and the percentage slope land-use and topography. An area that has higher percentage slope will not necessarily mean this area has higher runoff, or higher accumulation percentage as a multitude of factors have an effect such as geographical and current status of the actual conditions at this location. Table 5.8 below shows the total sediment at a place received from other areas. In general, one hectare in a hilly area received total ~1066 tonne sediment yields in every year, ~203tonne at riverside area and ~150tonne in paddies.

Table 5. 8. Total volume accumulation with other factors of 3 extracted points

Position	Slope (%)	Total rainfall (mm)	Soil types	Total volume accumulation (Tonne/ha)
Hilly area	2.16	2253	Thionic Fluvisol	1066.42
Riverside area	0.54	1688	Eutric fluvisol	230.39
Wet paddy area	3.92	1914	Thionic Fluvisol	150.15

5.11 Discussions and conclusion

Although the soil erosion and sediment loss model from RUSLE and MUSLE were not specifically designed for delta areas, this study used the MUSLE in the specific conditions in the Mekong delta where the terrain primarily characterised by low and flat land. Spatial distribution of sediment loss and accumulation was modelled over a large area of ~20,000km^2. In general, there are high erosion risks in mountain areas, the riverside catchments and some other places in coastal provinces, while the large areas of central low land seem to have low risk for sediment loss and accumulation processes.

The integration and development of the model within a GIS system provides an efficient tool for modelling, management, quantification and analysis of sediment losses and accumulation (Kim, 2006; Lim *et al.*,2005). Based on the spatial resolution of Landsat raster images, this model runs at the level of the grid cell in which the original RUSLE and MUSLE was implemented. This contrast with previous studies where these tools have been employed at the watershed scale (de Vente and Poesen, 2005).

The MUSLE model is derived by the multiplication of all factors together and each factor has significant contribution to the final results. In almost all soil erosion studies, rainfall is considered as one of the most important factors which affects the volume of erosion and sediment loading in the environment (Lopez-Vicente, Poesen, Navas and Gaspar, 2011; Deng, de Lima and Jung, 2008). However, besides rainfall, the other factors have their own contribution to soil loss depending on the different geographical and hydrology condition. For example, when calculating on soil loss and sediment yield in an area with highly fluctuating topography, the result from MUSLE equation will be strongly affected by the LS factor over others.

A simple linear correlation model was used to examine the relationships between the sediment yield losses as dependent variable and the factors *LS,K,C,P, and runoff* as independent variables to evaluate the contribution level of each factors to the model results (Xu, Xu, and Meng, 2013). The results shows that the outcome of sediment yields varies among different sites. Disregarding runoff factor, the length slope and steepness factor contributed the least, around 0.0072, to the results (table 5.9). Reflecting the actual elevation data (DEM) in the Mekong delta, this shows a small contribution of this factor where there is the low fluctuation in the DEM data. This disregards the criticism of inaccuracy in the soil loss result when applying the equation to slopes higher than 9% (Liu, Nearing, and Risse, 1994; Kinnel, 1991). However, in the Mekong delta study area only ~0.43% of the surface had a slope higher than 9% and so this error caused by high slope was indeed not significant in the sediment loss results.

Although land-use and land treatment are important in the Mekong delta, the contribution of these coefficients are lower than 1 (table 5.9) indicating that soil erosion risk was reduced by the protective effects of tillage and coverage of vegetation. The cropping practice factor *P* had a coefficient of ~0.38. Although tilled cropping was widely applied in large paddy areas, it is not easily encouraged for sediment loss protection in the Mekong delta because the rice cropping cycle is so rapid.

Table 5. 9 . Multiple linear regression analysis for all MUSLE factors. Based on sediment yield losses in the first rainfall event in April_2008.

Factors	Coefficients	T-test(23298754)	R^2
Intercept	-0.560738	-1361.25	42.77%
C FACTOR	0.401881	426.17	
P factor	0.381723	688.11	
LS	0.007157	3168.37	
K factor	1.181516	502.76	
Runoff	7.575691	1528.95	

For flat land runoff remains the most important factor affecting soil erosion and sediment yields. Although the Mekong delta has high annual rainfall, the runoff factor was not significant. It is widely known that land-use and land cover can minimize the impacts from runoff and erosion (Williams *et al.*,1977). High vegetation cover appears to have provided good protection from runoff activities especially for small rainfall events. For example, although a maximum rainfall of 10mm was found in 04 of April (2008), this only resulted in ~1mm runoff. More importantly, large areas of paddies contributed to runoff prevention, having the lowest runoff rate compared to other land-use. The runoff factor contributed tremendously to sediment yield loss with a contributing coefficient of ~7.57 (Table 5.9). This also indicated that the model results are very dependent on rainfall data. The rainfall data in this study was created using filed data from only 39 station and so the interpolated surfaces may have differed from actual rainfall. This is, however, likely to represent only a minor potential error. Previously, sediment yield has been modelled as a yearly result, especially when using RUSLE and USLE (Renard *et al.*,1991). By establishing runoff conditions in the model, this study was able to generate sediment yield loss as a time series data, so allowing users to track result at anytime of the year. On the other hand, data from a single event may reduce the accuracy of the result (Renard *et al.*,1994) and a monthly or yearly rainfall have been recommended when modeling soil loss because the cumulative rainfall in 1 month or in a year will give better coverage of the study area. Nevertheless, the MUSLE in this study employed rainfall data in a single storm event in which some areas may have rainfall generating runoff and erosion while other areas do not.

The most significant loss occurred in areas of cash crop and vegetables. In general, the results show that sediment loss in these areas in the wet season are four times higher than mangrove and coastal areas, and almost 10 times greater than other land-use categories.

Soil accumulation differed with location. Although smallest amounts concentrated in paddies, these sediment yields were not able to discharge into channels. The principal risk area is in riverbanks where sediment accumulation is much higher than in the fields. Sediment yields concentrated in riverside areas are probably the main sediment resource contributing to the sediment discharges of Mekong rivers.

Although the model was designed for use in the Mekong delta with certain assumptions made during model running, it represents a quantitative methodology for estimation of sediment loss and accumulation at a much finer spatial resolution than has been achieved to date. Although the model was not validated by actual observation of soil loss and sediment yield accumulation data in the field, the conceptual model provides a method which can be applied to sediment loss in other geographical areas with daily rainfall data at large or small scales. However, slope and steepness data is always an important factor which needs to be taken into account because the method to calculate this factor would be modified to make the model suitable to actual terrain conditions of the area.

In this project, the model sediment loss and accumulation was designed as an individual, free-standing model but it could be linked to other models as an individual or a sub-model in a wider project framework. The iterative sequence used the results of sediment accumulation as the input component to the following model run in time order.

(see Chapter 6). This model will contribute to pesticide loss calculation as the component used to estimate pesticide concentration in soil, and the hydrological component with runoff and flow accumulation.

In conclusion, this chapter focussed on the following issues:

- The CN-method was applied in the Mekong delta to determine runoff. The runoff in the Mekong delta is much lower compared with rainfall volume due to the effective tillage and coverage of vegetation.
- By land-use category, cash crops and industrial crops were found to have the lowest resistance to runoff. Eutric Gleysol and Eutric Fluvisol are two soil types with very low infiltration rates, and high risk for runoff
- There was a high rate of sediment losses in cash crops, vegetable and industrial crop areas.
- A high rate of sediment loss were found Eutric Fluvisol and Eutric Gleysol soil type areas.
- There was a high resistance to sediment loss in paddy areas, especially paddies located in Thionic Fluvisol and Ferric Acrisol distributions.
- The highest sediment accumulation is in hilly areas, but they only occupy <1% of the total study area.
- The model provides a methodology for application of MUSLE and daily rainfall data to modelling the quantitative sediment yield loss in a time series.

Chapter 6

GIS modelling for pesticide accumulation and its impact on aquaculture sites in the Mekong delta

6.1 Introduction

Pesticides are used widely in Vietnam, especially in the Mekong Delta which is characterised by a complex distribution of channel networks playing an important role in nutrients, wastes and chemical distribution over catchment areas. Pesticide residues are found not only in agricultural land but also in water, sediment and biota samples along the Mekong main river and its branches (Minh *et al.*,2007a). Despite warnings from organizations on negative impacts, the usage of pesticides has not decreased as farmers in the Delta prefer to use these chemicals in their production systems.

Pesticides are applied mainly to agricultural land and the amount of pesticides left in environment depends on how much is lost through different pathways, such as plant uptake, volatilisation and dispersion, self degradation, and runoff (Toan, Thao, Walder, Schmutz and Ha, 2007). In reality, some fraction of an applied pesticide will always reach water bodies because after application, almost all pesticides exist in a layer associated with soils, depending upon their physico-chemical characteristics (Renaud, Bellamy and Brown, 2008; Manz, Wenzel, Dietze and Schérmann, 2001).

6.1.1 Chemo-dynamics and environmental impacts of pesticides

When pesticides enter the environment, they undergo changes which affect the physical volume of material and toxicity level. Pesticides from agriculture enter the soil surface and water body through several pathways. Pesticides are firstly lost by direct attachment to the target plants (Holvoet, van Griensven, Gevaert, Seuntjens and Vanrolleghem, 2008). The actual amount of loss depends on the level of the canopy coefficient which the plant population creates during their growth period, and the ratio of the amount of pesticides deposited on leaves relative the deposition of the ground. This is determined by land use. By measuring pesticide concentrations at river outlets, Holvoet et al (2007) also showed a relationship between the peak concentration of pesticides and intensive application by farmers up stream.

Pesticides exist in the hydrological environment by association with suspended sediment and their concentration depends on factors such as organic matter content, and absorption coefficient (solubility or hydrophobicity). The higher the organic matter content, the more potential there is for absorption of pesticides (Zhou, Zhu, Yang and Chen, 2006; Henrry and Kishimba, 2003).

Pesticide transportation is based on hydrological processes such as rainfall, runoff, leaching, overland flow and erosion. The movement of pesticides in the environment is mainly related to movement of individual soil particles which are created by the soil erosion process. When entering a water body and in the runoff fluxes, some pesticides in suspended sediments will be transferred to other vectors, such as adsorption by sediment particles, intake by organisms, or settlement to bottom sediments (Nowell, Capel and Dileanis, 1999) (Figure 6.1).

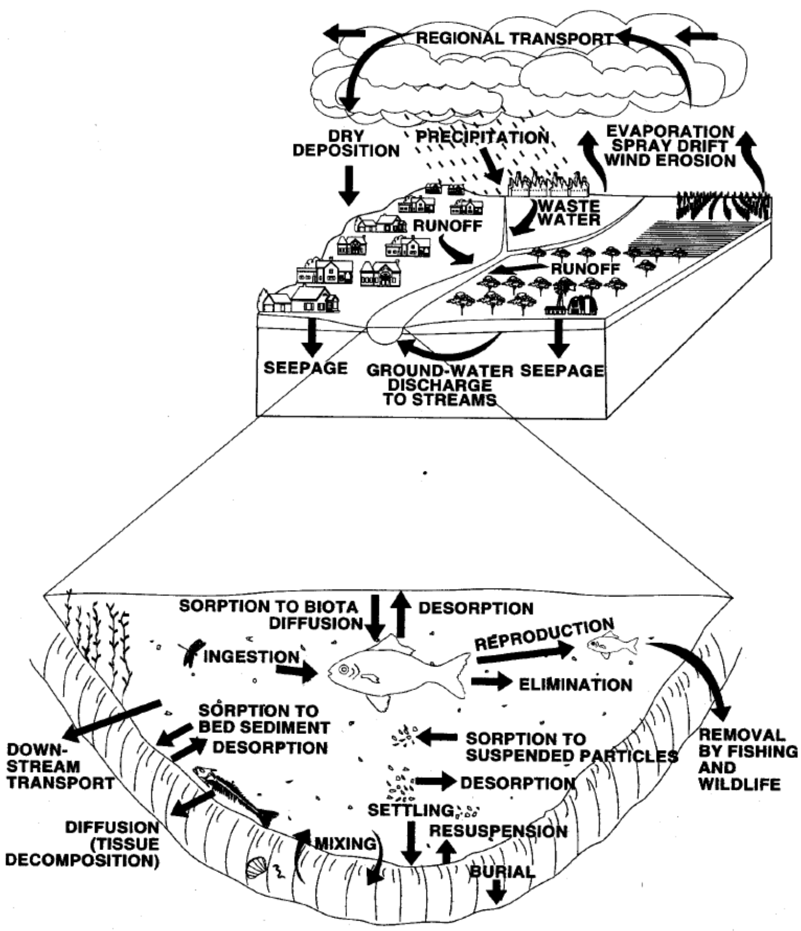


Figure 6. 1. Pesticide movement under the hydrology cycle

(Nowell *et al.*,1999).

6.1.2 Models for persistent pesticide runoff, loading and accumulation.

Understanding the fate and predicting the impact of pesticides on the environment is a challenge which, in recent decades, has resulted in the development of a number of experimental (simulation) and statistical models (Li, Li, Huang, Struger, Fishcher, Wang, Chen, Li and Nie, 2003). Statistical models have been developed based upon specific long term data sets which may be analysed numerically using tools such as SPSS, Minitab, Matlab or spatially using GIS software IDRISI, or ArcGIS. Often these use simple empirical regression modules developed from field measurements.

By contrast, simulation models have been developed from initial conceptual models to describe natural environmental processes. The basis of such models is built-up from a set of equations usually derived from experimental works. For modelling of pesticide fate or transport and for non-point source pollutants, combined parameter and distributive parameter models are mostly applied for modelling at the watershed scale. In combined parameter models, all component parameters (e.g. water, air, soil) are considered as homogenous within a watershed meaning that the spatial characteristics of these parameters are ignored. PTR (Pesticide Transportation and Runoff model) (Crawford and Donigian, 1973) and ARM (Agriculture Runoff Management) (Donigian and Davis, 1978) are typical examples of combined parameter models. As shown by Dillaha (1990), these types of model give effective results within a watershed area of around 200 to 500 hectares, and been applied to predict pesticide or chemical runoff at paddy scale (Comoretto, Arfib, Talva, Chauvelon, Pichaud, Chiron and Hohener, 2008).

However, combined parameter models generate errors if applied to a large watershed where the component parameters and hydrological conditions are varied. Distributive parameter models have been developed to include spatial data into the modelling process so watersheds of can be divided into extremely small plots or hydrological response units (Easton *et al.*,2008) with uniform component characteristics. Due to the micro analysis in every hydrologic response unit *(HRU_s)*, the models need very large data sets and powerful tools to carry out the analyses. ANSWERS (Areal Non-point Source Watershed Response Simulation) (Beasley *et al.*,1980) and AGNPS (Agricultural Non-Point Source pollutant model) (Young *et al.*,1987) are typical examples of such distributive models.

A number of mathematical models have also been developed to model pesticides and non-point source substances in the environment. The widely used numerical one dimensional models for simulating pesticide transport in the unsaturated zone include PRZM (Pesticide Root Zone Model) (Carsel, Smith, Mulkey, Dean and Jowise, 1984), and RUSTIC (Risk of Unsaturated/Saturated Transport and Transformation of Chemical Concentrations) (Dean, Huyakorn, Doginian, Voss, Schanz, Meek and Carsel, 1989). One dimensional models concentrate on the vertical transport of pesticides by including GLEAMS model (Groundwater Loading Effects of Agricultural Management Systems) (Leonard, Knisel and Still, 1987); and LEACHM (Leaching Estimation and Chemistry Model) (Wagenet and Hutson, 1989). The PRZM has also been incorporated in the FOCUS (Forum for the Co-ordination of Pesticide Fate Models and their Use) model used by the EU and the additional model, namely MACRO (A model of water flow and solute transport in macroporous soil) (Larsbo and Jarvis, 2005), and PELMO (Pesticide Leaching Model) (Klein, 1995). All these models were developed by a complex formulation of processes, requiring lengthy verification periods and have been used widely.

Several numerical models have also been developed for surface runoff and overland flow of pesticides through the environment (Branger, Tournebize, Carluer, Kao, Braud and Vauclin, 2009; Renaud, Bellamy and Brown, 2008a; Chu and Marinõ, 2007). Among these, the CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) model is the most widely used and is the root of the model developed by (Kinsel, 1980) to simulate pesticide fate in the environment. The widely used SWAT (Soil and Water Assessment Tool) model is a further version developed from the CREAMS equations by Arnold et al (1998).

6.2 Model selection

The present study was not based upon use of any single published model, because of the study objectives and data availability. As described by Thornton et al (1999), the selection of suitable models was based on four basic concepts: (1) the objectives of the modelling process, (2) the spatial scale of the study, (3) the temporal scale of the study, and (4) the availability of data. The models used were derived using the relevant components of a number of mathematical models, implemented within the GIS framework and appropriate to the specific situations.

The overall objectives of the work presented in this chapter were to quantify pesticide concentrations in environment and to estimate pesticide losses by a variety of routes, as well as the predicting the accumulation after a particular time at a large watershed scale. The review of possible models identified the CREAMS PRZM, ANSWERS, and SWAT models (developed from the root of CREAMS and CN method) as theoretically being most appropriate for use. Models derived by Li (2003) such as PeRM (PEsticide Runoff Model) or PeLM (Pesticide Leaching Model) (Chen, Li, Huang, Huang and Li, 2004) were also used.

6.3 Model design and development

6.3.1 Grid cell system

At a wide spatial scale, description of the study area requires up to date information on crops, elevation, soil type, land use, pesticide use, and hydrological components. Pesticide runoff and losses, cannot be accurately estimated based on a large watershed scale because of the different characteristics of the component sub-catchments (Arnold and Fohrer, 2005). In this study, this was overcome by representing the thematic data layers using a raster system of rows and columns in which each grid-cell is equivalents to the pixel size of Landsat ETM+ images (30m x 30m).

6.3.2 Pesticide losses and transport in environment

The overall movements of pesticides in the environment are summarised in Figure 6.2 After spraying, a proportion of the applied pesticide will be lost by plant uptake and this direct loss is inversely related to the land use and the nature of the leaf canopy cover. Cumulative pesticide losses will be higher near the end of the crop cycle and less at the beginning. Direct pesticide loss is expressed as the application efficiency which is the ratio between canopy cover rate and total area of application.

After allowing for direct losses, the remaining material will settle to the ground or be incorporated within root zones of the plants. The latter can be partitioned in two ways (1) absorption into the soil layer during the time of application and after for a maximum 4 days. The estimation of pesticide absorption is based on the adsorption coefficient of each chemical (K_{OC}, K_d) and soil features such as soil types, clay content, and soil textures and organic matter compounds; and, (2) during rainfall, some of the pesticides existing in the soil will be desorbed into runoff water. This quantity of pesticide can be calculated based on the concentration of pesticides in sediment and runoff water fluxes.

The surface runoff and overland flow can be simulated based on soil erosion and sediment loss.

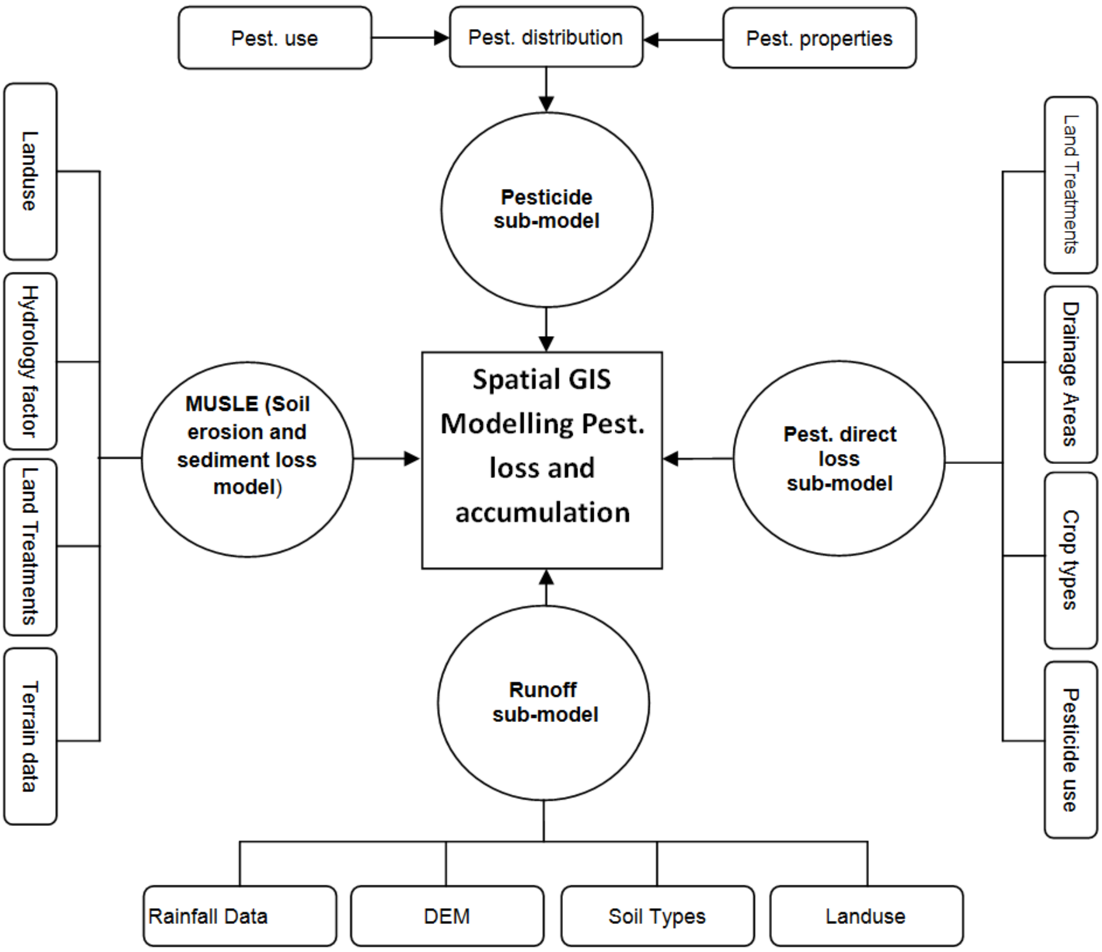


Figure 6. 2. Conceptual framework of pesticide loss and accumulation modelling. (Pest = Pesticide)

The model calculates the accumulative pesticides, sediment, and water runoff for every time step through a runoff function which is based on land use data, land treatment, hydrology and geology. The runoff model generates the volume of water and overland flow through each grid cell. The most important factors affecting this are rainfall volume and elevation.

In this study, the temporal scale of the model was structured to run at every time step which was determined 4 continuous days. The model then reiterates for the following time step and is repeated until the last time step in a year (the 365th day). At each step, the functions are identical but the input parameters are updated.

The pesticide component in water and sediment during runoff was estimated in two periods. The first period is the pesticide input volume at the starting point of modelling (first event). However, the total input is then changed for the second rainfall event to the event number *"n"*. The final output of the model gives the expected net accumulation of pesticide. The net accumulation at any location will be calculated by the total pesticides remaining from the application and cumulative pesticide from first event to event "n" minus the loss of pesticide transport to other places from first event to event "n" and the degradation of pesticide after every time step. The total pesticide input to the model is outlined in Figure 6.3.

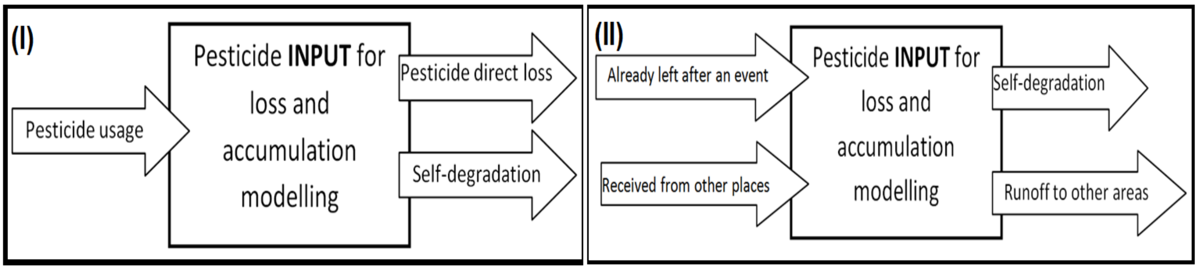


Figure 6. 3. Conceptual framework for calculating pesticide input to the model for the first rainfall event (I), and for next event until the end of the year (II).

In practice, the amount of pesticide imported and applied in Vietnam is not known exactly due to government policies and minimal management of local pesticide manufacturers. This study used the data of pesticide use collected during the 2009 survey in the Mekong delta, where data accuracy is dependent upon the experience and memory of the farmers when answering survey questions.

The modelling to simulate all pesticide processes is valid subject to the following qualifications and assumptions: (1) The model did not include the pesticide volatilization loss. This calculation needs meteorological and hydrological data which was not available for the Mekong delta. (2) Leaching was not calculated and was assumed to be zero during the pesticide loss calculation. (3) The temporal scale of the model established each time step as 4 continuous days. During each time step, rainfall was summed to find the total rainfall. (4) Pesticide existence in runoff water fluxes could be very complicated due to adsorbed and desorbed processes between water, sediment and organic matter in solution. The total pesticide concentration focused on concentration in water and in sediment which mainly depended on the adsorption coefficient of pesticide. (5) Pesticide transformation was not included in this study.

6.3.3 Reclassification of pesticide risk to aquaculture

The initial output of pesticide accumulation as a concentration in soil was reclassified in terms of the risk to aquaculture using a fuzzy classification function based on a sigmoidal membership utility (Eastman, 2006). The fuzzy classification aims to simplify the complex data into an easily understood format (Burrough, 1989). The classification aims to identify the suitable areas where there was high, average and low risk from pesticide concentrations. The sigmoidal fuzzy classification is controlled by 4 control points (*a,b,c* and *d,* in Figure 6.4) in which the *"a"* value indicates where the sigmoidal function rises above zero, the *"b"* value shows where the function reaches 1, the *"c"* value implies the starting point where function begins to decline from 1, and the *"d"* value shows where the function become zero again. Applying to pesticide toxicity affects on aquatic organisms, the value at *"a"* is the lowest toxicity impact, whereas *"b,c, and d"* is the lethal death point where the aquatic organisms start to get death effects.

The production systems considered in this study were the most two popular aquaculture organisms in the Mekong delta: catfish *(Pangasius hypothalmus)* and tiger shrimp *(Penaeus monodon)*.

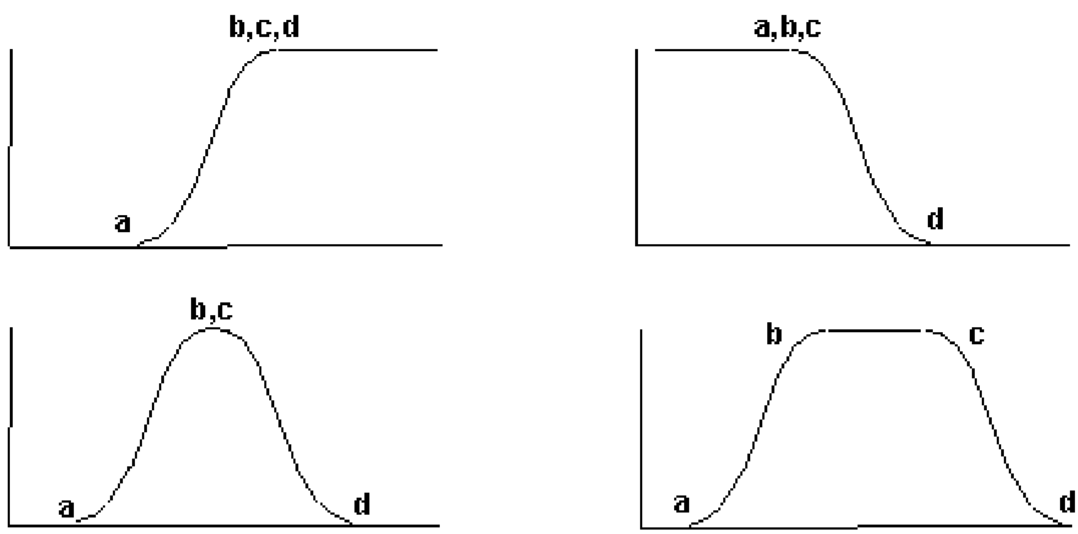


Figure 6. 4. Sigmoidal membership functions and control points

(Eastman, 2006)

The risk and non-risk pesticide areas for a specific cultured species. The simple methodology will be illustrated as following the flowchart in figure 6.5. Pesticide database will be input two sub-models (MUSLE and water runoff) to calculate the pesticide loss under the concentration in cumulated sediment yield and in water runoff fluxes. Both these two sub-models has been done in chapter 5. The total cumulative pesticide will be the summation from 2 resources. Them a constant value representing the toxicity of a chemical on a target species will be used (this project used half-loss lethal concentration LC_{50} 96 hrs test value). By the input of pesticide accumulation, the fuzzy sigmoidal membership function was apply to classify the risk and non-risk areas for this culture species.

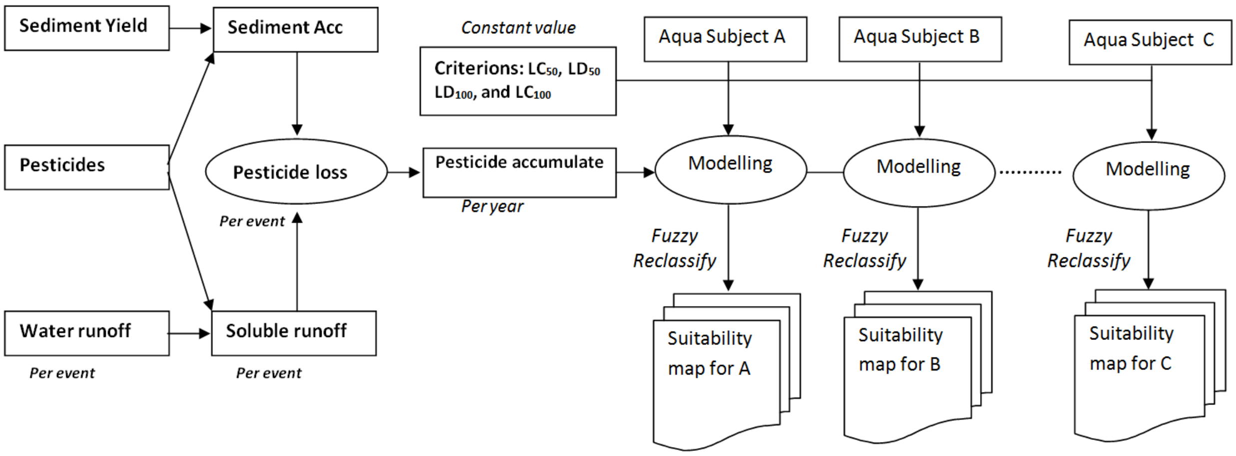


Figure 6. 5. Flowchart for the classification of pesticide risk area for aquaculture based on pesticide accumulation database

Abamectin is a compound of Avermectin B1a and Avermectin B1b. They are one of the most popularly used biological insecticide in rice fields in Vietnam. In the conversation to do pesticide survey in the Mekong delta in 2008, almost farmers revealed the expectation of looking for an effective insecticide to treat on their land with less harmful to human body, especially bearing instant shock after application. Abamectin was most mentioned as a potential target insecticide used in the future. By this reason, this study considers Abamectin as an example of pesticide input for modeling pesticide loss, accumulation, and applying the results of pesticide accumulation to define the risk and non-risk areas for catfish and tiger prawn. Similarly, model can be applied for any other type of pesticides found in the survey.

6.3.4 Acute toxicology endpoint: The lethal concentration (LC)

Abamectin, formulation structure closely related to Ivermectin is an insecticidal or anthelmintic compound derived from the soil bacterium *Streptomyces avermitilis*. It has been used widely in the Mekong delta on paddies because of its reduced impact on the environment. In soil, half-life degradation take ~30days which is considered as moderately persistent and the organic-carbon sorption is ~5638ml/g (PPDB, 2012). Although Abamectin has low toxicity with mammals, however it has a high bio-toxicology in fish and other aquatic organisms (Jencic, Manica, Erzen, Kobal, and Cerkvenik-Flajs, 2006b).

Acute toxicology endpoints indicate the concentration and dosages derived from toxicity tests of a substance on the death rates of target species. This lethal concentration of pesticide can be expressed as LC_{25}, LC_{50}, $LC_{100,}$ causing 25%, 50% and 100% population loss, respectively, usually in a time of 96hrs which normally express the level concentration of pesticide where it might harm to the rearing objects. In the other hand, PNEC (Predict No Effect Concentration) is used as the level of concentration where a specific rearing object will not be effected by that chemical.

This study would to express the impact of pesticide to aquaculture. Therefore LC data was preferred to use to clarify the risk areas for a specific species. LC was not differentiated among the percentage of death population in the lethal test. Therefore, the concentration value zero is assigned as the safe point, and to the value of LC_{50} will be considered as the highest risk point.

The LC_{50} of Abamectin has been investigated for a variety of aquatic species. Crustaceans are particularly sensitive having toxic effects as low as $0.001 ng.g^{-1}$ (Halley, Jacob, and Lu, 1989). Examples of toxicity determinations on species relevant to aquaculture are shown in Table 6.1

Table 6. 1. LC_{50} of Abamectin in some aquaculture species.

Test organism	Species	LC values (LC_{50})	Duration (Hours)	Ref.
Fish	*Salmo gairdneri* (rainbow trout)	3.0 µg/l	96	(Fisher and Mrozik, 1992)
	Oncorhynchus mykiss (rainbow trout)	3.2 µg/l 1.5 µg/l	96 96	(Lucija and Nevenka, 2006; Wislocki, Grosso, and Dybas, 1989; Halley et al, 1989); (Jencic, Manica, Erzen, Kobal, and Cerkvenik-Flajs, 2006a)

	Salmo gairdneri	3.2 µg/l	48	(Halley et al, 1989)
	Lepomis macrochines (bluegill sunfish)	4.8 µg/l	96	(Halley et al, 1989)
	Lepomis macrochine	9.6 µg/l	48	(Halley et al, 1989)
	Cyprinodon variegatus (sheep head minnow)	15 µg/l	96	(Lucija et al, 2006; Wislocki et al, 1989)
	Ictalurus punctatus (channel catfish)	24 µg/l	96	(Wislocki et al, 1989)
	Cyprinus carpio (carp)	24 µg/l	96	(Wislocki et al, 1989)
	Cyprinus sp. (carp)	42 µg/l	96	(Kövecses and Marcogliese, 2005)
	Anguilla anguilla (eel)	0.2 ppm	24	(Geet, Liewes, and Ollevier, 1992)
	Salmo salar	500 ppm	96	(Kilmartin, Cazabon, and Smith, 1996)
Shrimp	*Crangon septemspinosa*	17.9 µg/l	24	(Burridge and Haya, 1993a)
	Crangon septemspinosa	11.5 µg/l	48	
	Crangon septemspinosa	11.5 µg/l	96	
	Panaeus duorarum (pink shrimp)	0.016 µg/l	96	
	Penaeus sp. (Mysid shrimp)	0.022 µg/l	24	

6.3.5 LC_{50} for Pangasius (catfish) and Tiger shrimp

No data was found on Abamectin toxicity for Vietnamese catfish (*Pangasius hypothalmus*). There are several reasons for this, but one of these is that Vietnamese aquaculture agencies have strategies to limit the information on toxicity tests related to two main target aquaculture species in Vietnam (Pangasius and tiger shrimp). Consequently, the LC_{50} 96Hrs for Vietnamese catfish was assumed to be similar to the values measured by Wislocki (1989) and Halley (1989) for channel catfish (Ictalurus punctatus); a proxy value of 24 µg/l. Similarly, for tiger prawn, the proxy data of Burridge (1993) on *Crangon septemspinosa* was used for LC_{50} 96hrs; 11.5 µg/g.

The standard parameter used to classify risk level of chemicals for aquaculture is the acute toxicity test based on the LC_{5c} (Lethal Concentration for 50% of catfish and tiger shrimp populations). LC_{50} data was sourced from the acut e toxicity tests by several authors (Kövecses et al, 2005; Burridge and Haya, 1993c; Wislocki et al, 1989), but where specific data was not found for the target species, so appropriate proxy data was used. Lethal concentration (LC_{50}) parameter is constant while the cumulative pesticide quantities are variable.

6.4 Pesticide direct loss sub-model

This sub-model was designed for calculating the direct loss at the time of application. Using the assumptions developed earlier on timing of application of pesticides, the direct loss model is applied following the number of applications. For example, for insecticides, the direct loss will be calculated twice in a year, at the beginning of May and beginning of November.

6.4.1 Model formulation

Direct loss of pesticides was calculated using equation 6.1 which accounts for application rate and application efficiency as well as the total area sprayed. There was no further allowance for chemo-dynamic activities of pesticides such as degradation, runoff loss, transport, washoff or other losses. The computation established direct loss in each cell or hydrological response unit (Holvoet *et al.*,2008; Neitsch, Arnorld, Kiniry, Srinivasan and Williams, 2002).

$$\boldsymbol{Direct\ loss_{Point} = ap_{rate} \cdot (1 - AP\_EF) \cdot area_{hru} \cdot 1e^{8}} \qquad \text{Equation 6. 1}$$

where *Direct* $loss_{point}$ is direct loss during application (*mg*); ap_{rate} is the application rate (*kg/ha*); *AP_EF* is pesticide application efficiency coefficient; $area_{hru}$ is the area of a cell (equal to the area of 1 pixel); $1e^{8}$ is the unit conversion factor.

The application efficiency coefficient *AP_EF* is determined by Equation 6.2.

$$\boldsymbol{AP\_EF = \frac{Pest2}{Pest1}} \qquad \text{Equation 6. 2}$$

where *Pest2* is the effective pesticide application or the amount of pesticide left on the leaves of plants and *Pest1* is the total pesticide application.

To determine the effective pesticide, the crop types in study area were divided into 3 periods: (1) seedling period from the first to the second month, (2) developing stage from the second to the third month, and (3) mature period from the third month until crop harvest. Each period has a different percentage canopy cover which will affect pesticide application efficiency. This parameter can be calculated through the leaf area index (LAI) which can be determined by using the spectral reflectance from Landsat images with (Vaesen, Gilliams, Nackaerts, and Coppin, 2001). However, this method could not be applied in this study because the acquisition Landsat data was never sufficiently contiguous during a full crop cycle.

Fortunately, approximately 70% of land-use areas in the Mekong delta was rice fields which represented the majority of canopy cover in study area (Chen *et al.*, 2011), therefore canopy cover was estimated using area of paddies as proxy values. The percentage canopy cover assumed for the 3 growth periods was 30% during seeding, 60% during developing stage and up to 90% in the mature stage (Table 6.2).

Table 6. 2. Assumed percentages of canopy cover based on different land-use in the Mekong delta.

Crops types	**Percentage leaf covers area (%)**			
	Landuse	**0-1 month**	**1-2 month**	**2-3 month**
River and water body	1	0	0	0
Intensive paddies	2	30	60	90
Dry paddies	3	30	60	90
Orchard, mixed rice fields and orchards	4	30	60	90
Cash crop and vegetable, bushes	5	30	30	30
Coconuts, sugar canes and cajuputs	6	0	0	0
Coastal aquaculture, mangroves	7	0	0	0
Mangroves	8	0	0	0

Based on the schedule in table 4.19 (see Chapter 4), there were two rice crop starting points, in early April and October. During this period herbicides are normally applied during the first month, whereas insecticides are used in the second month, and fungicides are used in the final month. In this study, the insecticide Abamectin was used as a case study to develop the pesticide models. Consequently, it was assumed to be applied in the second month crop with the average canopy cover for different crops given in table 6.2. and remaining areas such as water bodies, mangroves or aquaculture set to zero. The overall canopy cover is shown in Figure 6.6 and the application efficiency is shown in Figure 6.7.

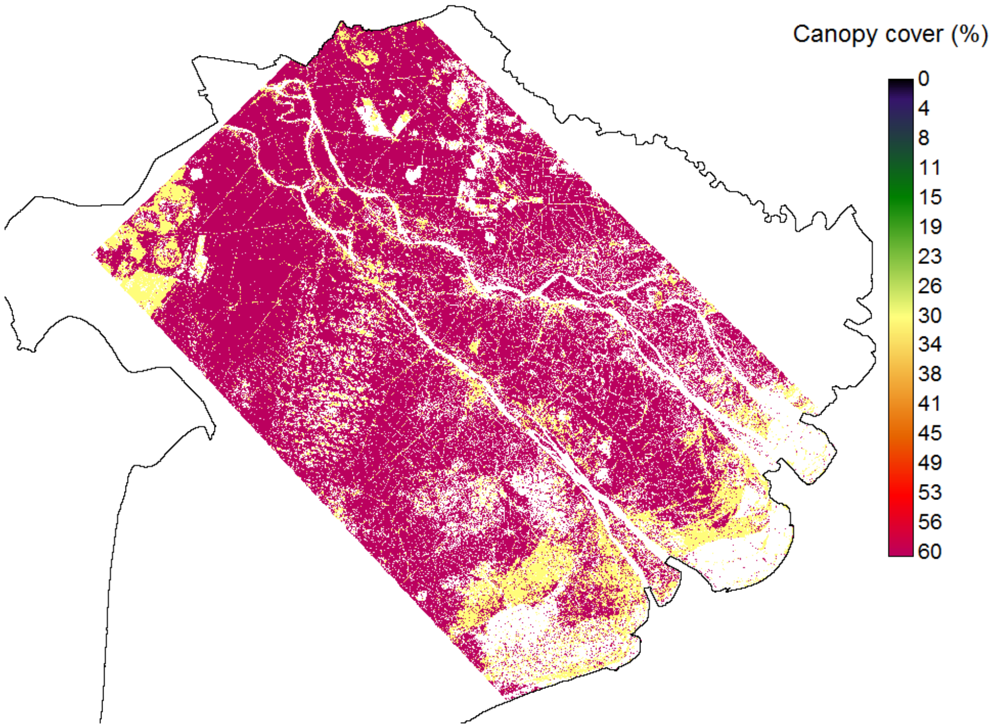


Figure 6. 6. Overall canopy cover percentage in the Mekong delta.

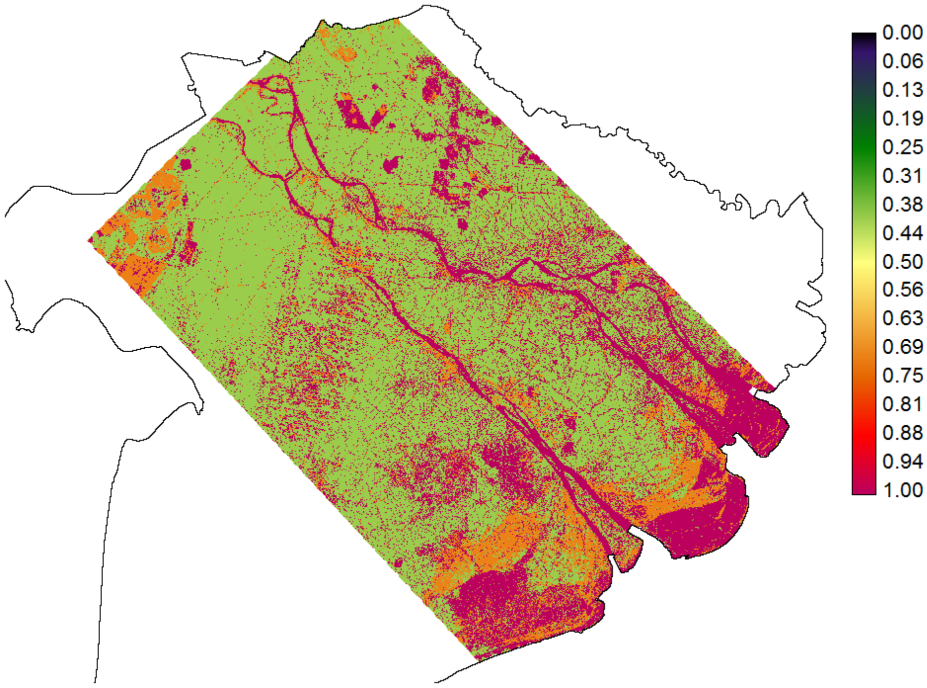


Figure 6. 7. Pesticide application efficiency coefficient AP_EF. Value 1 represents a higher efficiency of pesticide application, while lower values indicate less efficient pesticide use.

6.5 Pesticide runoff sub-model

Mathematical modelling of pesticide runoff has been considered by several researchers (Chen et al, 2004; Li et al, 2003a; Li, Li, Struger, Chen, and Huang, 2003b). The runoff modelling in this study considers overland flow rather than stream runoff networks, rills or inter-rill flow (a flow path or flow channel created by erosion at the top soil layer). Each grid cell in the spatial database contains indicators of the flow direction, quantity losses, and received amount from other cells. The runoff of pesticides was modelled for every rainfall event and was designed to simulate pesticide losses and accumulation at each time step (4 continuous days). The model combines two components, sediment and water runoff, with the final cumulative pesticide losses being the summation of these. It must be noted that any errors in the outcome, principally due to the lack of reliable pesticide input data, could be improved by a well organised pesticide application collection system.

6.5.1 Pesticide runoff in sediment loss

6.5.1.1 Pesticide available in sediment when runoff.

After application direct loss by foliage uptake will occur in the soil layers. Normally, the volume of pesticides available for surface runoff is calculated after deduction of this direct loss. In this model, pesticide input quantities were set lower than the actual application rate to allow for the fact that many factors decrease the amount of pesticide on plant canopies, such as degradation by sunlight, strong volatilization, and movement in wind-blown aerosols.

a. Pesticide residue in soil

Pesticide residues in soil always decrease because they auto-degrade and affected by many exchange processes, such as emission from soil, biological and physical degradation, dissolution from granules into water, adsorption, and desorption. The proportion of pesticide concentration in water and sediment may also vary depending on physical features and formulation, (Evans and Duscja, 1973). The pesticide residues available for runoff were defined by (Li et al, 2003b) in equation 6.3

$$\boldsymbol{R_t = U(1 - F_i)e^{-\beta . t_i}} \qquad \text{Equation 6. 3}$$

where R_t is the pesticide residue at time *t (days)* after application; U is total applied pesticides; F_i is the daily emission factor of pesticide; $t_{1/2}$ is half-life of pesticide in the soil.

Abamectin is considered as moderately persistent in the environment (PPDB, 2012). Its half-life was obtained from the literature (Al Housari, Höhener and Chiron, 2011; Neitsch *et al.*,2002; Nowell *et al.*,1999; Reyes *et al.*,1983). In this study a typical half-life of Abamectin (insecticide) of 30 days was used (PPDB,2012). Pesticide half-life was recalculated every 4 days using the following equation 6.4.

$$\boldsymbol{\beta = \frac{ln2}{t_{1/2}}} \qquad \text{Equation 6. 4}$$

The emission factor, *Fi*, is the ratio between quantity of pesticide emitted to the air and the total amount applied (Li, Venkatesh, and Li, 2004). Processes affecting emissions through volatilization of agricultural pesticides applied to soils or plants have been studied in numerous laboratory and field investigations. The 3 major parameters that influence the rate of volatilization are the nature of the active ingredient, the meteorological conditions, and soil adsorption. However, the method to determine amount emission pesticide in different soil type is complex and emission to the air from soil is usually micro quantities especially with high percentage clay soils (Li *et al.*,2004; Scholtz, Voldner, McMillan and Van Heyst, 2002). Consequently, the daily emission in the equation 6.3 was set to zero.

Modelled Abamectin residues in soils are shown in Figure 6.8. The residue amount in two applications per year is the main pesticide source to use as the input of pesticide any further modelling.

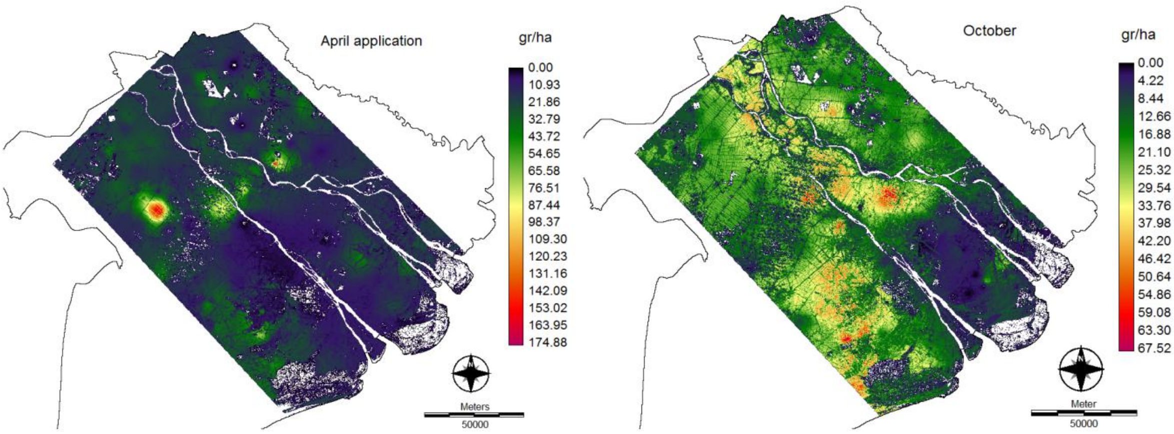


Figure 6. 8. Abamectin residues in the soil layer following application in April and in October (2008)

b. Potential pesticide concentration *(C_t)* in soil layer

Rainfall occurring during time *(t)*, also detaches soil particles to contribute to the runoff process. The concentration of pesticides in the soil layer was estimated by equation 6.5. The initial concentration at *(t)* time was the initial concentration of pesticide after application, less the amount lost by half-life degradation. The equation also was also appropriate in cases where there is no or not enough rainfall volume causing soil loss and runoff (Huber *et al.*,1998; Kenimer, Mostaghimi, Dillaha and Vo Shanholtz, 1989; Walker and Brown, 1987; Mills and Leonard, 1984).

$$C_{(t)} = C_{(o)} . e^{\frac{ln2}{t1/2}(t)}$$ Equation 6. 5

where $C_{(t)}$ is pesticide concentration at the time runoff is started (mg/kg); $C_{(o)}$ is pesticide concentration after application (this amount was excluded the direct loss). $C_{(o)}$ is calculated by the pesticide residue in soil *(R_t)* and weight of soil *(W_{soil})*. The sediment loss every 4 days, calculated previously, was applied as the weight of soil in equation 6.6.

$$C_{(o)} = \frac{R_t}{W_{soil}}$$ Equation 6. 6

Based on the assumption on pesticide application time in chapter 4 (see 4.6.2.(d)), Abamectin has been applied twice a year. That means there will be two pesticide input datasets in the model: first dataset is in April and second is in October. Concentration after application *(C_0)* were calculated at these 2 applications. The equation 6.6 was applied and the results shown in Figure 6.9. Corresponding to C_0, the concentration at *t* time were calculated by equation 6.5, the result of C_t is shown in Figure 6.10. Value of C_t of course smaller than C_0 because there is a small pesticide loss by half-life degradation from after pesticide application until the first rainfall event coming.

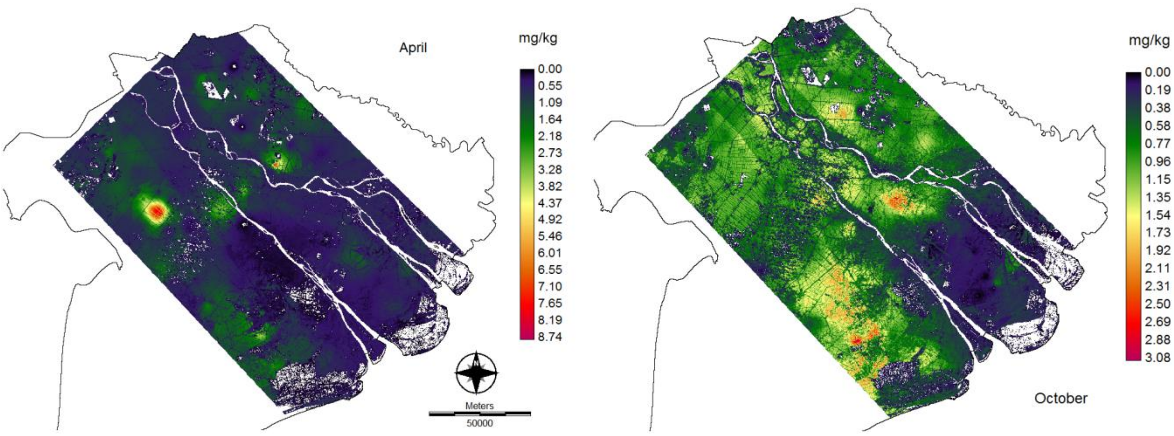


Figure 6. 9 .Concentration of Abamectin immediately after application *(C_o)*

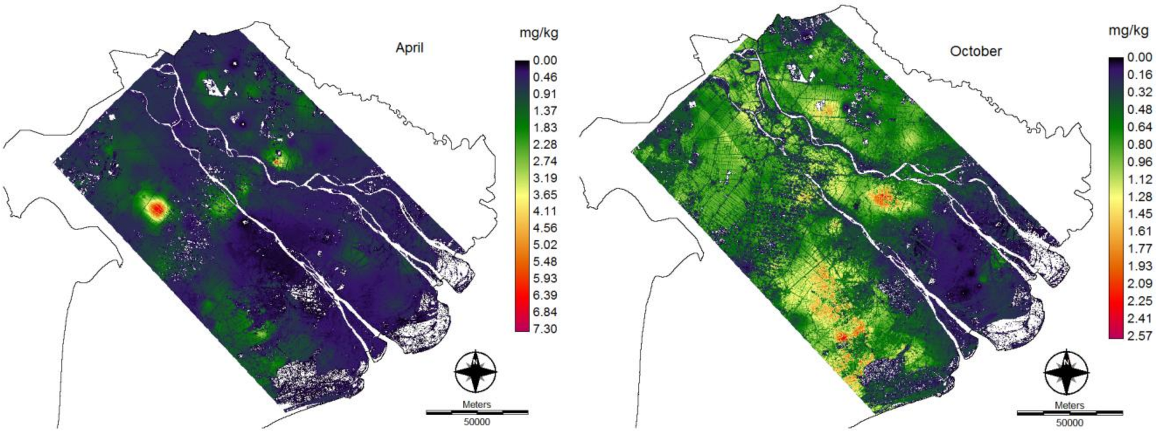


Figure 6. 10 .Concentration of Abamectin 4 days after application. This was also the concentration available after the first runoff *(C_t)*

c. Pesticide adsorption capacity

The adsorption of pesticide to soil is a reversible phenomenon which controls the pesticide concentration in sediments. It describes the capacity of pesticide to attach to soil particle and partly detach into water fluxes when all sediment and pesticides are in the soluble phase. Well-penetrated pesticides will result in a smaller pesticide dose for targeted pests in soil. The soil structure, organic matter content (%*OM*) and environmental conditions such as temperature, pH, ionic strength and salinity all effect the pesticide adsorption capacity (Nowell *et al.*,1999).

Adsorption was determined using the Freundlich equation (Equation 6.7) based on the instant equilibrium of active ingredient between soil mass and overland flow in the interacted zone (Kenimer *et al.*,1989; Donigian *et al.*,1978).

$$\boldsymbol{K_d = K_{OC} \cdot \frac{OC}{100}} \qquad \text{Equation 6. 7}$$

where K_d is soil-water partitioning coefficient; *OC* is organic carbon percentage; K_{OC} is the organic carbon sorption constant. K_d is determined by the correlation function between the constant of chemicals in octanol and water *(K_{OW})*. The methodology to calculate K_{OC} is well described by Rwetabula (2007) and follows the experimental models of Karickhoff (1984). The K_{OC} for Abamectin of 107 was taken from the pesticide properties database PPDB (2012), where K_{OC} was 107. Organic carbon percentage was obtained from the FAO soil property data (FAO,(2003)

d. Potential pesticide concentration in sediment runoff *(C_S)*

The concentration of pesticides as mg/kg in sediments *(C_S)* when runoff take place can be computed from equation 6.8 (Li *et al.*,2003b; Leonard *et al.*,1987).

$$C_s = \frac{C_t\,.K_d.B}{1+K_d.B} \qquad \text{Equation 6. 8}$$

where *B* is the extraction coefficient. Leonard *et al* (1987) classified the relationship between the soil-water partitioning coefficient K_d and B as follows:

B=0.5	For	K*d* < 1
B=0.7 – 0.2	For	Kd <1 and < 3
B= 0.1	For	Kd > 3

Applying equation 6.8, figure 6.11 illustrates the potential concentration in soil in for 2 applications (in April and in October)

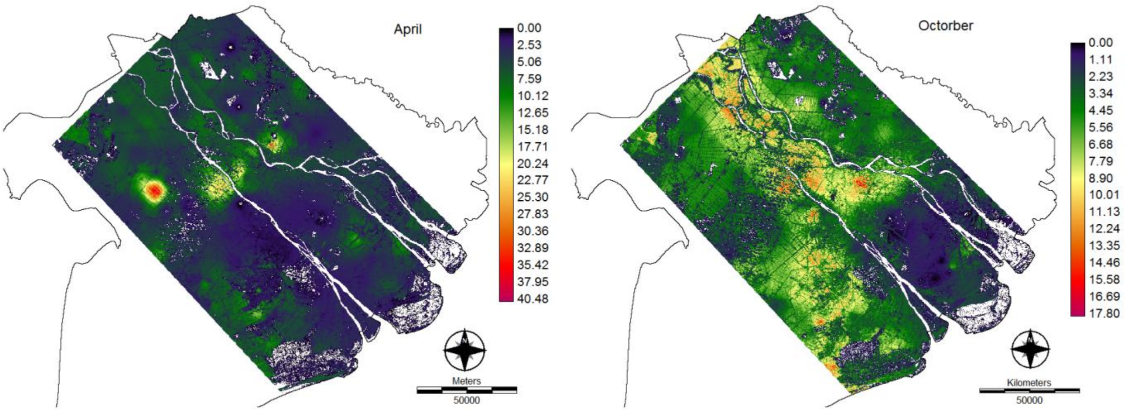


Figure 6. 11. Potential concentration of Abamectin in sediment when runoff takes place, during the wet and dry seasons

The pesticide desorption to water for runoff was extracted from the CREAMS/GLEAMS and AGNPS models (Chen *et al.*,2004; Li *et al.*,2003b; Leonard *et al.*,1987). The pesticide concentration in water (µg/L) was considered when the adsorption of pesticide in sediment in soluble phase approached the equilibrium condition. Given this assumption, pesticide concentration in water *(C_w)* can be estimated using equation 6.9. Potential pesticide concentration in runoff fluxes for 2 applications is shown in Figure 6.12

$$C_w = \frac{C_t.B}{1+K_d.B} \qquad \text{Equation 6. 9}$$

Once concentration in sediment yield and in water runoff were determined, the concentration in the fluxes could be calculated using equation 6.10.

$$\boldsymbol{C_{ro} = C_w + C_s . SC} \qquad \text{Equation 6. 10}$$

Where C_{ro} *(µg/L)* is the concentration of pesticide in the fluxes runoff which includes sediment losses from erosion process and runoff water from rainfall. C_s is based on the total sediment yield losses from erosion process, therefore the sediment concentration *SC* (g/L) in equation 6.10 will be assumed to be equal to the total amount of sediment in every runoff event.

The quantity of pesticide loss A_{ro} (*µg/ha)* at a grid cell at the end of every event will then be (equation 6.11):

$$\boldsymbol{A_{ro} = C_{ro} . Q_t} \qquad \text{Equation 6. 11}$$

where Q_t is runoff volume at *t* time (see section 5.4).

Pesticide concentrations based on pesticide application were determined only twice in the model processing, over the first 4 days after application (for example in 1st four days in April and in October for Abamectin). The model calculates the loss of pesticide concentration based on the sediment loss and runoff models and the computation step gives the results of accumulated pesticide concentration for each event, the previous cumulative result feeding into the next modelling event and the process repeats until it reaches the end point which was set up for every pesticide. For example, for Abamectin modelling, two end points of the model were set at the end of March and the last day of September. The model continues running in October using new concentration data which is equal to the concentration from the October application plus the cumulative quantities from the previous event in September (figure 6.13).

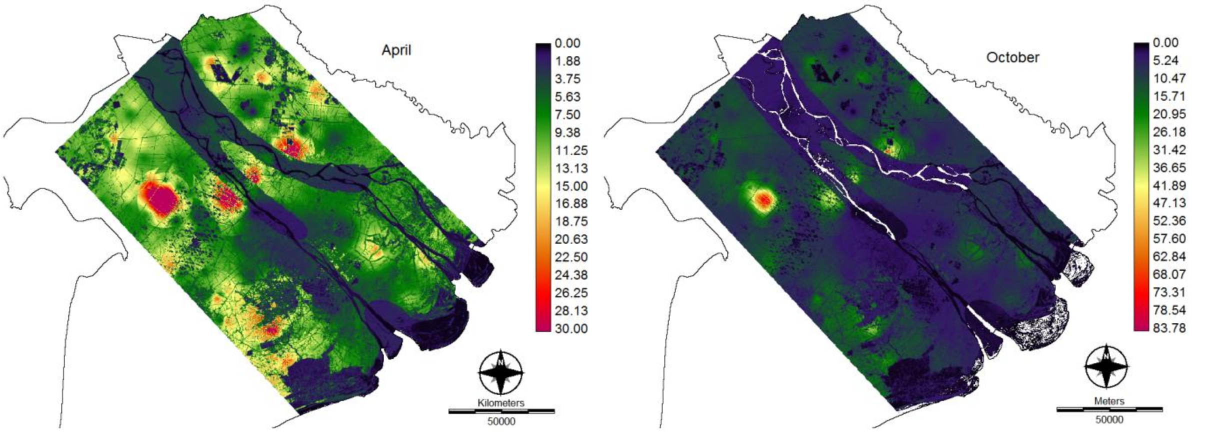


Figure 6. 12. Potential concentration of Abamectin in water runoff *(µg/L)* in the soluble phase during the wet and dry seasons

During the calculations, the degradation based on half-life was one of the major loss components in sediment. Theoretically, the losses by degradation could be divided between both sediment and water runoff. However, the rain (or runoff) time was much smaller than the time the pesticide was inside the soil layer. Moreover, the duration of rainfall events was not recorded and not available in this study and so only the half-life loss in the soil can be taken into account. The final pesticide concentration was estimated by summing all of the subcomponents; the sequence is shown in Figure 6.13.

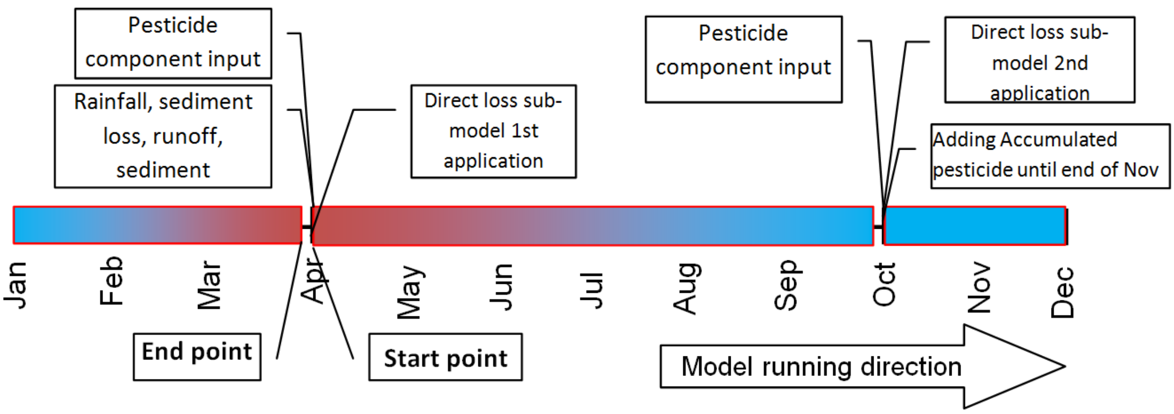


Figure 6. 13. A time scale flowchart of the overall modelling process

In cases where there was no rainfall or insufficient rainfall for soil detachment and runoff to occur, the model bases pesticide loss on half-life degradation using the data on the last accumulated pesticide. The cut off point was set to rainfall higher than 5 mm, although up to 10 mm has been used by other workers (Huber *et al.*,1998). This assumption was location dependent.

6.5.1.2 The hydrological component

The hydrological component was the basis for calculation of pesticide loss and accumulation. It considered the quantity of pesticide able to move to other locations in the environment under the influence of hydrological phenomena such as rainfall, runoff, soil erosion and sediment loss, transport of water and sediment and accumulation. Based on this factor, pesticides in the environment will changed in quantity and location compared to the initial condition.

Rainfall is the most important factor determining runoff in both quantity and time. Rainfall data was derived from information recorded at government stations in the Mekong delta. The method for incorporation of this data into the spatial database was presented in section 5.2.1.

Runoff volume (Q) was determined by the Curve Number method (CN method) presented in Chapter 5. Runoff accumulation was computed by equation 5.11 as in section 5.3.4.5.

6.5.1.3 Routing of pesticide accumulation

Routing of pesticide can be calculated using the continuity equation 6.12.

$$\boldsymbol{C}_{(\boldsymbol{out})} = \boldsymbol{C}_{(\boldsymbol{in})} + \boldsymbol{C}_{(\boldsymbol{generated})} \qquad \text{Equation 6. 12}$$

Where $C_{(out)}$ indicates the output concentration of pesticides in a grid cell, also the available pesticide concentration for next runoff, $C_{(in)}$ is the summation of all pesticide flow into this cell from surrounding cells at a higher elevation, $C_{(generated)}$ is total pesticide concentration generated within the cell.

Each grid cell is considered as an individual storage point for results from the model and the routing accumulation of pesticide is calculated for every time step. In consequence, the routing component is the last calculation to be evaluated in determining the quantity of pesticide at specific geographical locations.

The mass balance equation (equation 6.12) is used in this study. The input of pesticide to a cell will include the fraction of pesticides not removed by runoff from the previous time step, and the pesticides received from other cells after runoff in both accumulations in sediment and in water. In the grid cell structure, output from cells at higher elevation is routed to lower elevation cells or to the stream network and finally to the outlets. The model aims to calculate the concentration of pesticide, and therefore the continuity equation is also based on concentration whereas in other applications this equation has been used to calculate pesticide volume (Li et al, 2003; Li et al, 2003; Chen, Huang, Li, Li, and Liu, 2002). The calculated result will be the concentration of pesticide in every time step (4 day intervals), and the final accumulation at the end-point of the model. All mathematical functions and equations were implemented in the macro-modeller of the IDRISI GIS environment.

6.6 Results.

6.6.1 Pesticide direct loss

In this study, the insecticide Abamectin was used as a working example as the application time was definable. However, this would not be possible at present for many pesticides as there is often no recorded data available for time of application for a specific substance. The direct loss of Abamectin was calculated twice per year and is shown in Figure 6.14.

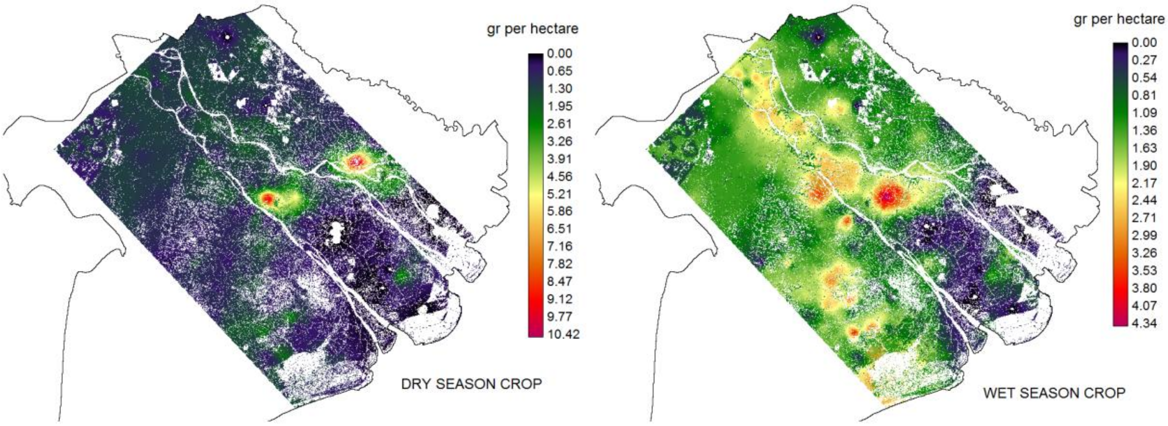


Figure 6. 14 Abamectin (insecticide) direct loss in crop on April (wet season) and October (dry season). These results will contribute to the pesticide input data for runoff modelling as a deduct factor to cut down a specific amount of pesticide lost by direct attach to foliages of the crop plants.

The total direct loss of Abamectin extracted from these outcomes was 0.89 g/ha from a mean total application volume of 27.54 g/ha in the dry season and 0.76 g/ha from 19.1 g/ha mean applied in the wet season. In general, direct loss in the dry season is 3.25% of total pesticide use and 3.99% in wet season

Abamectin was applied in 2009 mainly to intensive paddies, mixed paddies and cash crops. The other land-use types were not analysed because there was no real application to water bodies and to aquaculture areas or even to some agricultural targets such as industrial crops or mangroves, which have never had insecticide treatments. Pixels having these types of land-use will generate zero values (Figure 6.15).

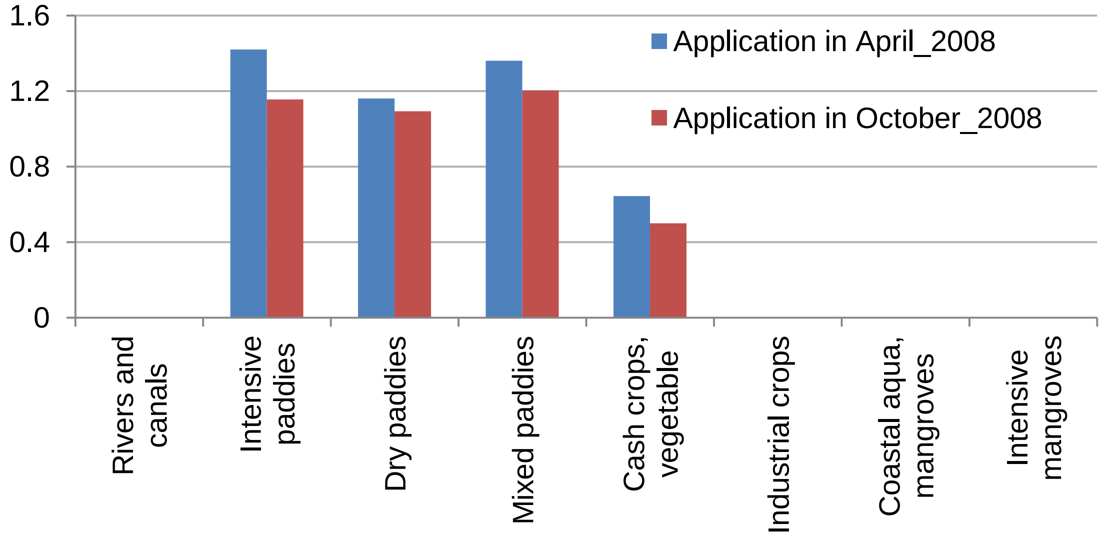
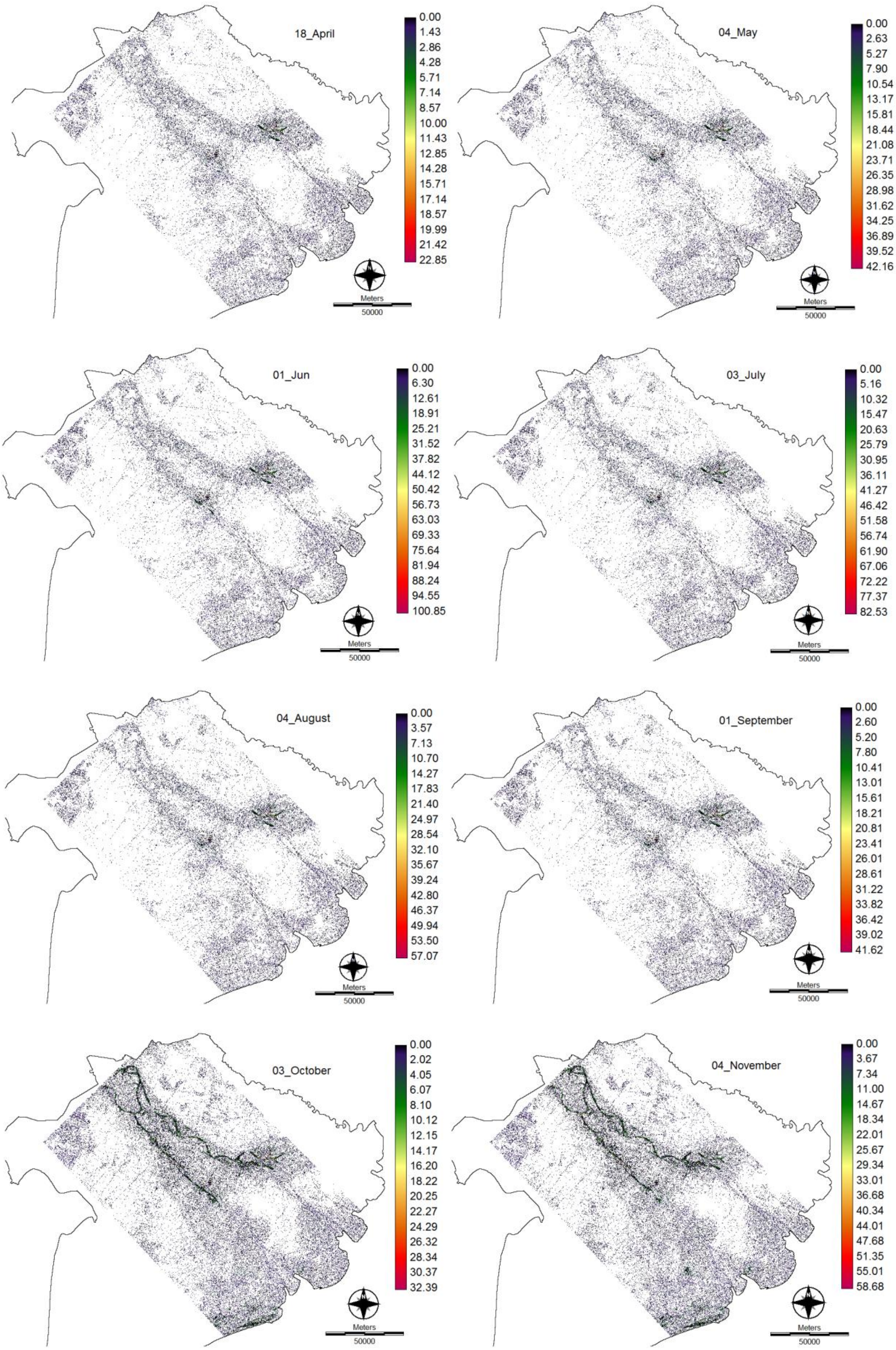


Figure 6. 15. Mean direct loss of Abamectin (g/ha) in different land-use categories in 2 main applications in 2008.

6.6.2 Pesticide loss in runoff and sediment yield

The concentration of pesticides in runoff water comes from the desorption process of chemical adsorbed to soil particles. The pesticide remaining in soil particles determines the concentration of pesticide in sediment loss during runoff fluxes. The resulting pesticide loss in sediment yield is shown as the concentration of pesticide *(C_{ro})* in every grid cell for one time step, with 90 time steps available for display. Figure 6.16 shows only the monthly pesticide concentration in runoff fluxes.

As there was no rainfall at the beginning of the month until the 18th of April, the initial concentration of pesticide commenced from this day instead of the beginning of April. However, the loss function due to self-degradation (half-life) was still was computed from the 1st of April. The potential pesticide amount input to the concentration computation was equal to the initial pesticide existing in soil layer after application minus the degradation due to half-life.


18_April
0.00
1.43
2.86
4.28
5.71
7.14
8.57
10.00
11.43
12.85
14.28
15.71
17.14
18.57
19.99
21.42
22.85
Meters
50000
04_May
0.00
2.63
5.27
7.90
10.54
13.17
15.81
18.44
21.08
23.71
26.35
28.98
31.62
34.25
36.89
39.52
42.16
Meters
50000
01_Jun
0.00
6.30
12.61
18.91
25.21
31.52
37.82
44.12
50.42
56.73
63.03
69.33
75.64
81.94
88.24
94.55
100.85
Meters
50000
03_July
0.00
5.16
10.32
15.47
20.63
25.79
30.95
36.11
41.27
46.42
51.58
56.74
61.90
67.06
72.22
77.37
82.53
Meters
50000
04_August
0.00
3.57
7.13
10.70
14.27
17.83
21.40
24.97
28.54
32.10
35.67
39.24
42.80
46.37
49.94
53.50
57.07
Meters
50000
01_September
0.00
2.60
5.20
7.80
10.41
13.01
15.61
18.21
20.81
23.41
26.01
28.61
31.22
33.82
36.42
39.02
41.62
Meters
50000
03_October
0.00
2.02
4.05
6.07
8.10
10.12
12.15
14.17
16.20
18.22
20.25
22.27
24.29
26.32
28.34
30.37
32.39
Meters
50000
04_November
0.00
3.67
7.34
11.00
14.67
18.34
22.01
25.67
29.34
33.01
36.68
40.34
44.01
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55.01
58.68
Meters
50000

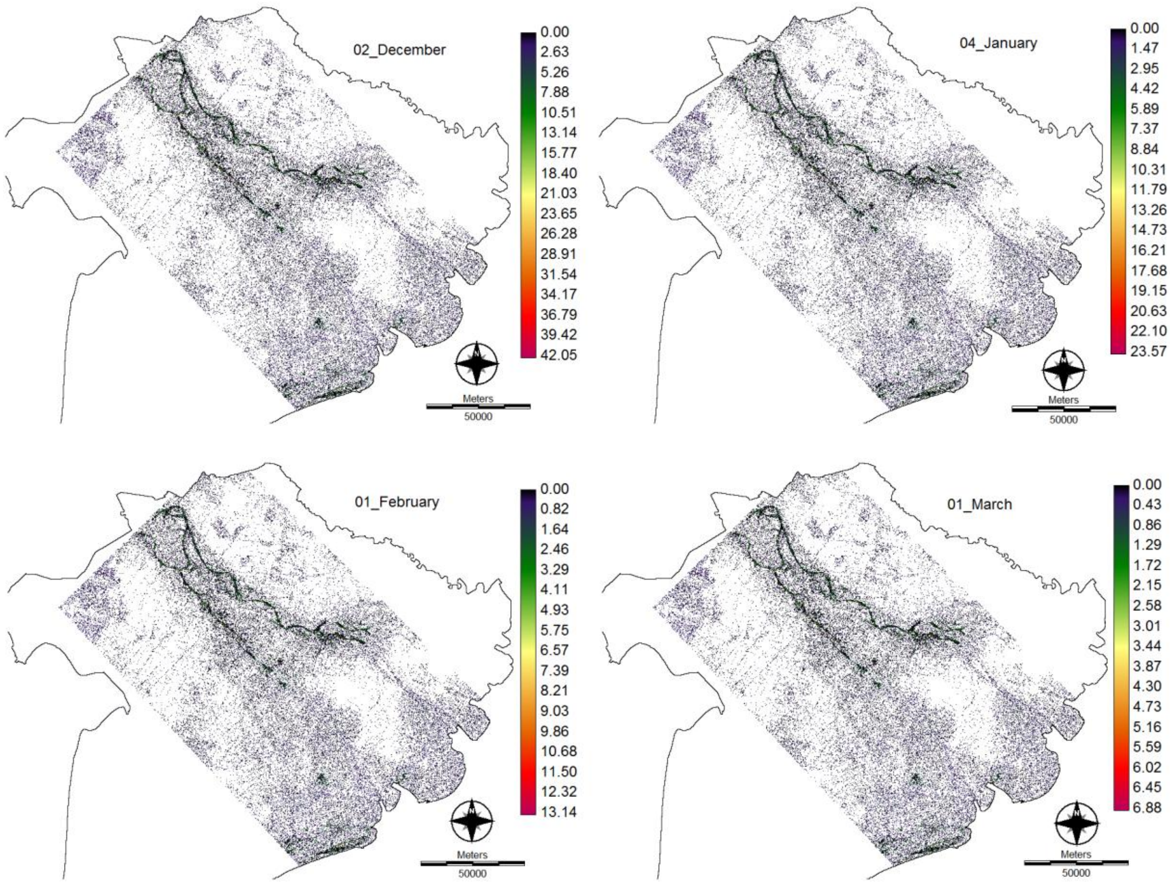
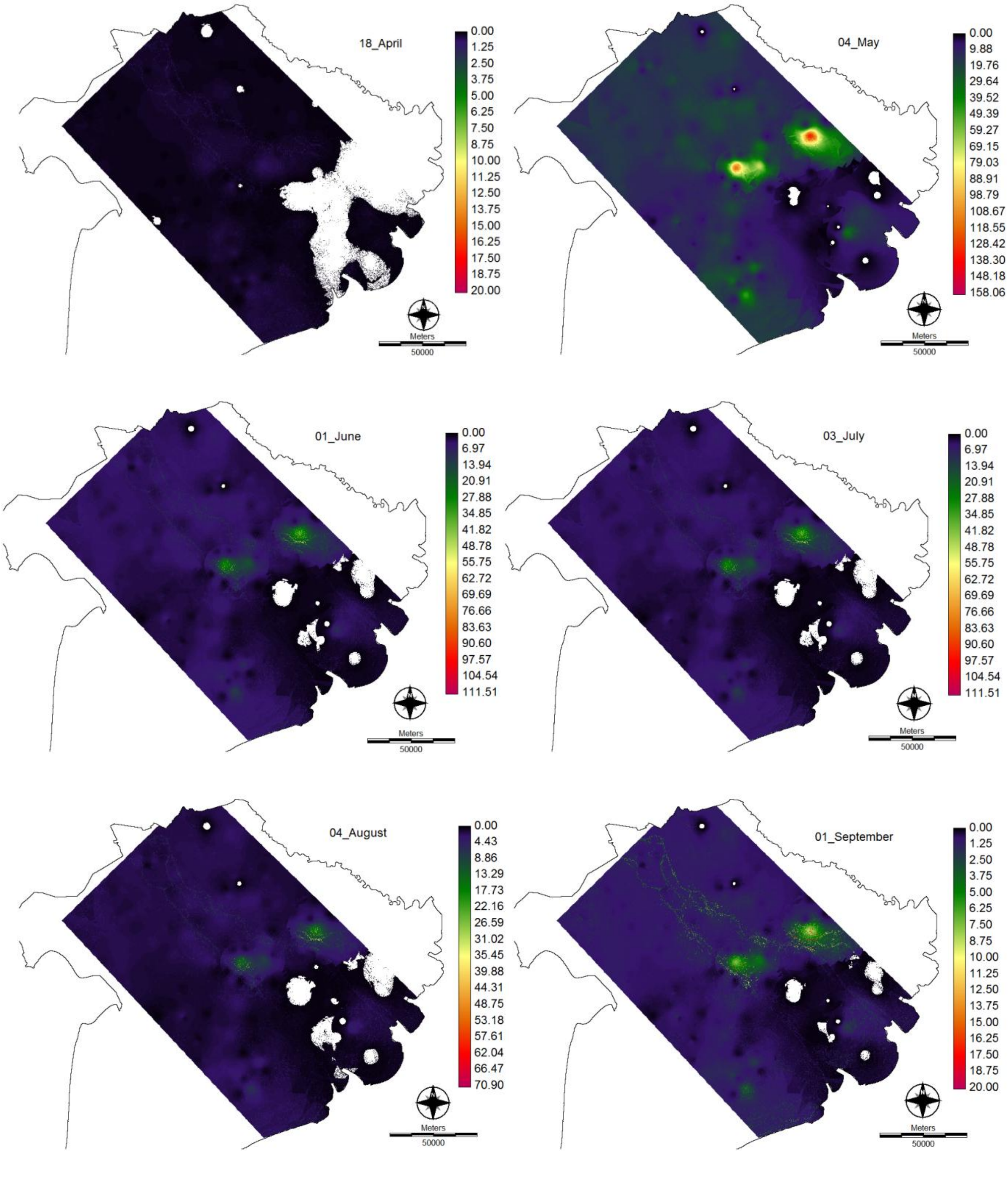


Figure 6. 16. Monthly Abamectin concentration in runoff fluxes (µg/L). This is the gross concentration of pesticide in both water and sediment when runoff takes place.

6.6.3 Total pesticide accumulation

Accumulation represented by concentration *(*the rate of *mg* of pesticide per *kg* of sediments*)* is highest immediately after application (in April and October), and then decreases with time due to self-degradation (Figure 6.17). Some areas have high concentrations where pesticide application rates were highest; although it appears that the runoff and accumulation do not disperse far from the original application sites. The results also confirm that the relatively flat terrain in the Mekong delta strongly affects the runoff and accumulation process.

Total pesticide accumulation was modelled for every time step during the year and, depending upon requirements, specific time step data was extracted. Figure 6.17 shows that accumulation commenced at the second rainfall event and after the first sediment loss. The model, was not run when no rainfall or no runoff occurred during which time the actual accumulation of pesticides was affected only by the half-life degradation function.



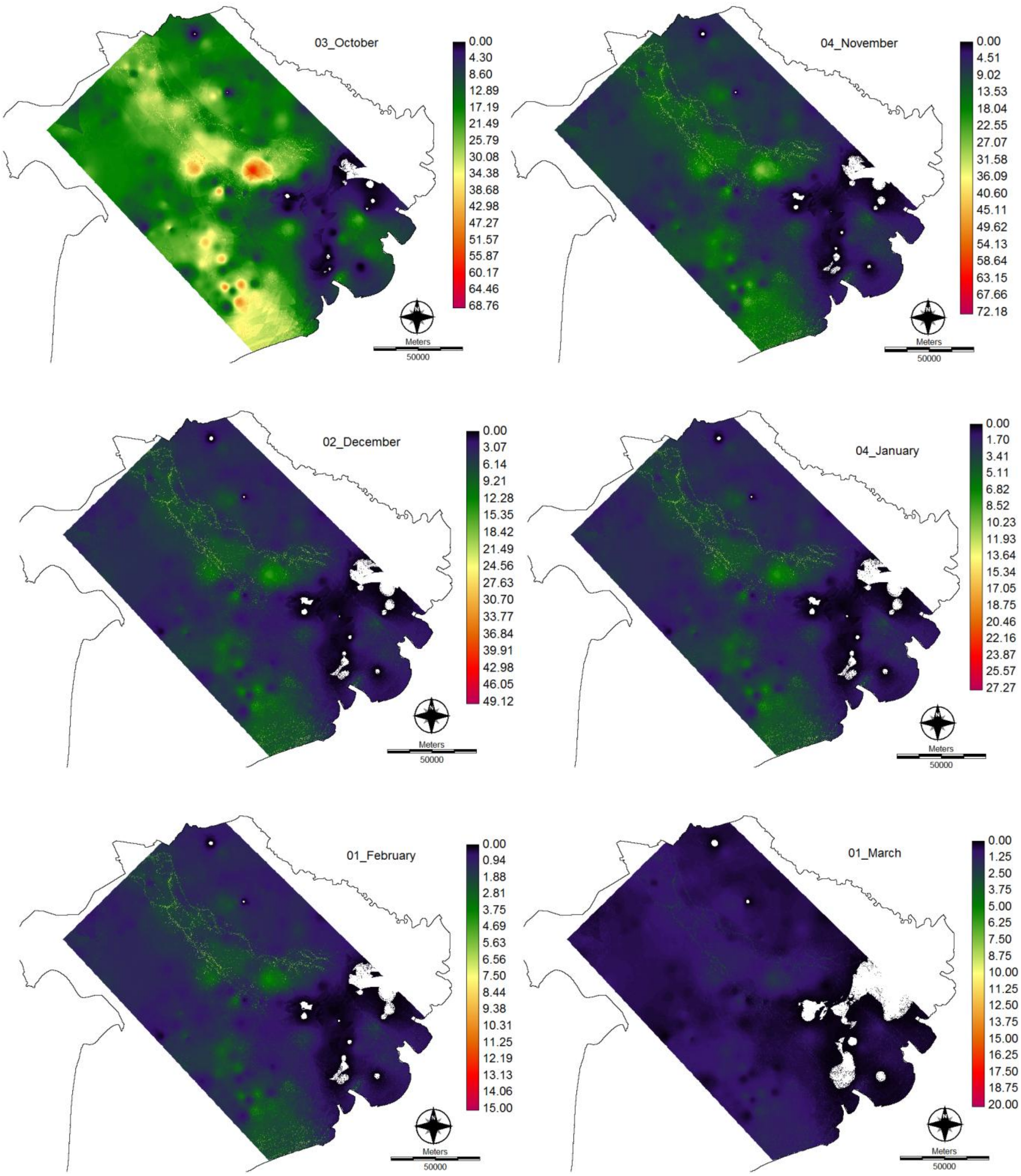


Figure 6. 17. Monthly Amamectin accumulation (g/ha) after runoff. The values include the accumulation in water runoff and in sediment yields.

6.6.3.1 Rainfall impact on pesticide accumulation

Rainfall was the most important factor promoting hydrological activities in a watershed and the main factor causing variance in the MUSLE sub-model. The rainfall volume controlled the amount of runoff, sediment loss, the pesticide concentration in runoff fluxes, and also in accumulated material.

In contrast to assumptions made by Huber et al (1998), who allowed their model to run when rainfall events were higher than 10mm, this study started to run the model at 1 mm increments. This was based on the report of Chiem (1993) who discussed the high detachment capacity of soil types found in the Mekong delta.

An Minh station data (Figure 6.18) for rainfall and pesticide accumulation was extracted in order to compare these parameters (see Figure 6.19). In general, accumulated pesticides and rainfall volume fluctuated similarly and, as expected, there were two peaks of pesticide accumulation each year at the end of May and beginning of October. At the other times pesticide accumulation values seemed to be less dependent on rainfall and runoff.

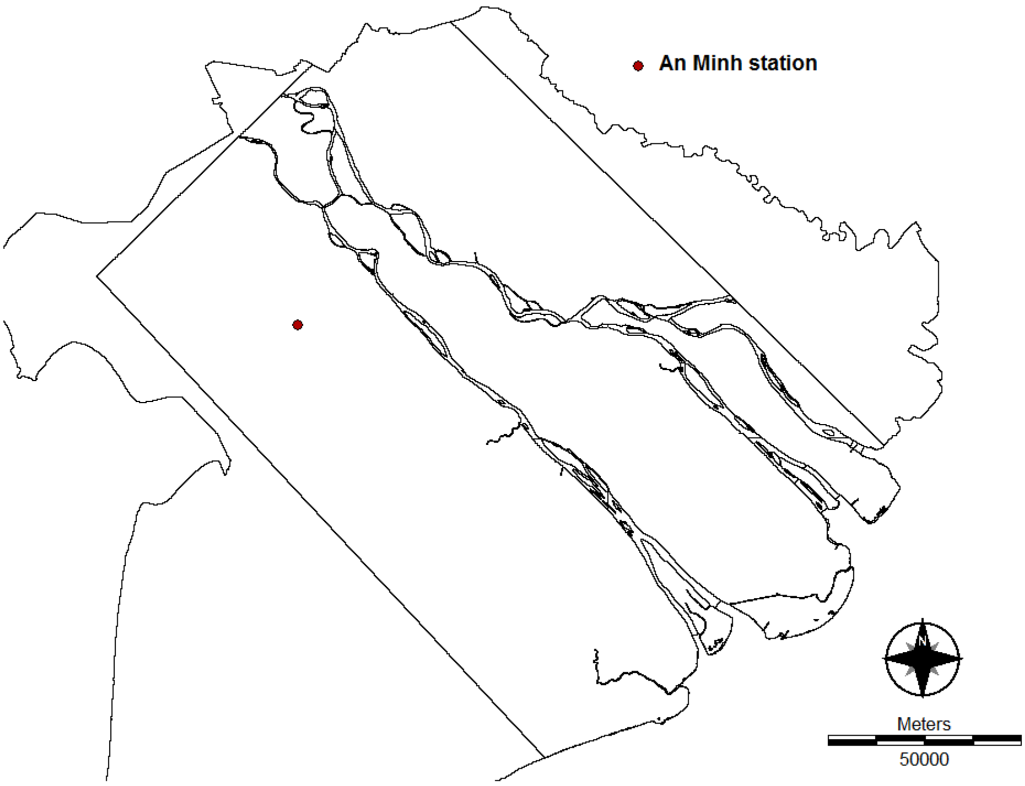


Figure 6. 18. The An Minh sample station used to extract comparative data.

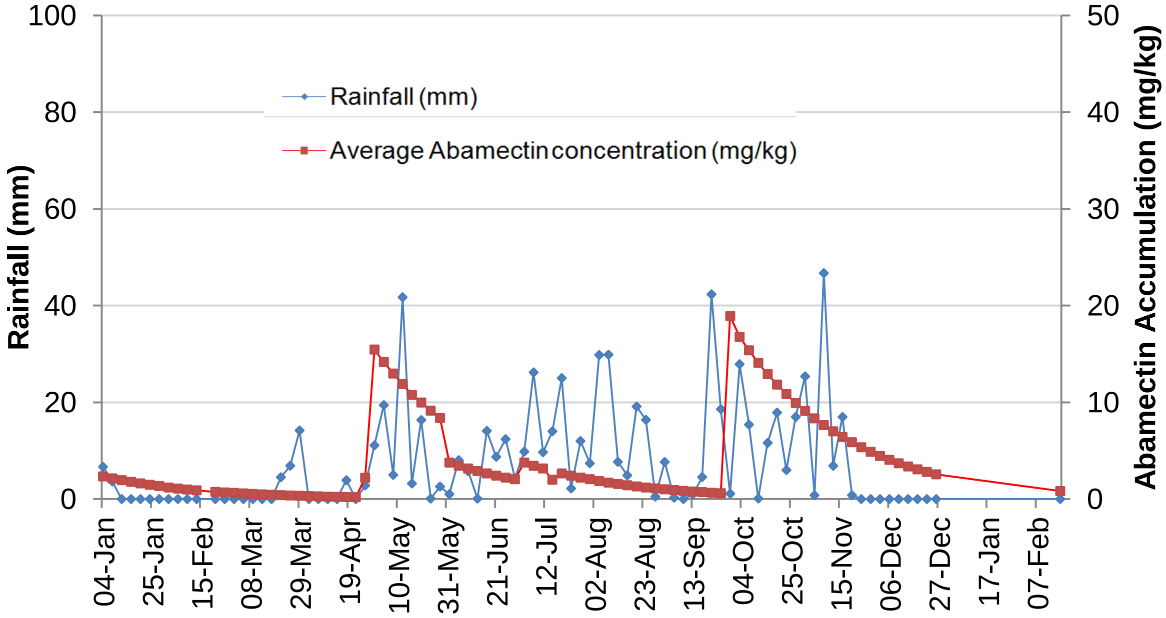


Figure 6. 19. The trend of Abamectin accumulation *(mg/kg)* compared with monthly rainfall *(mm)* at An Minh station

6.6.3.2 Half-life degradation losses and pesticide accumulation concentration

In contrast with rainfall, half-life degradation seems to have a strong effect on pesticide accumulation in each cell (Figure 6.20). This has a bigger effect on monthly pesticide accumulation than runoff

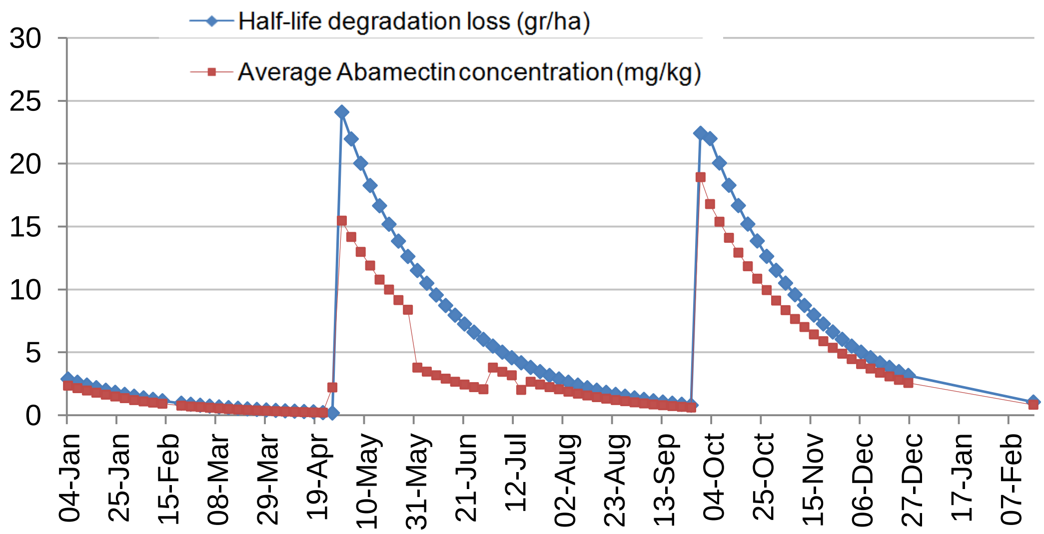


Figure 6. 20. The trend of Abamectin accumulation *(mg/kg)* compared with losses by half-life degradation *(g/ha)* at An Minh station

6.7 Potential impacts of pesticide on aquaculture sites

By using the toxicological parameters LC_{50} (96 h), LD_{50} (96 h), and EC_{50} (96 h), it is possible to reclassify potential impacts in the whole study area for the two most significant aquaculture species in the Mekong delta, Pangasius (*Pangasius hypothalmus*) and tiger shrimp (*Penaeus monodon*). The expected outcome is a fuzzy reclassification of risk areas for both species in the monthly datasets.

6.7.1 Aquaculture site classification by pesticide accumulation risk.

The pesticide risk classification uses two datasets: (1) the concentration of a specific pesticide present in water volume and (2) the values for half-loss lethal concentration (LC_{50}) of an aquaculture object.

The results from the pesticide loss and accumulation model show the cumulative quantity of pesticides in a grid-cell (mg/kg) calculated using Equations 6.11 and 6.7, The volume of water (m^3) presents in a cell is based base on the typical pond water depths of 0.5; 1.0; 1.5 and 2.0 meters and the effects of this are illustrated in the following examples.

6.7.3.1 Case 1: 0.5 m initial water depth.

In this situation, it was assumed that pond water depth was 0.5m and as each cell size was $900m^2$ (30m x 30m) therefore the volume of water per cell was ~$450m^3$ water. The classification was carried out over the whole study area with no geographical limitation by current catfish or tiger shrimp culture areas. It also was assumed that there were no differences in desorption of pesticides in different salinities. The results show the areas of highest risk occurring during May and October (Figures 6.21, 6.22). Having a higher membership function values, the riverside areas and water bodies seem to be the highest risk zones for catfish over these months. Safe areas for catfish also increased much faster than for shrimp with an LC_{50} of ~11.5 µg/l. Overall, risk areas for catfish were less than for tiger shrimp.

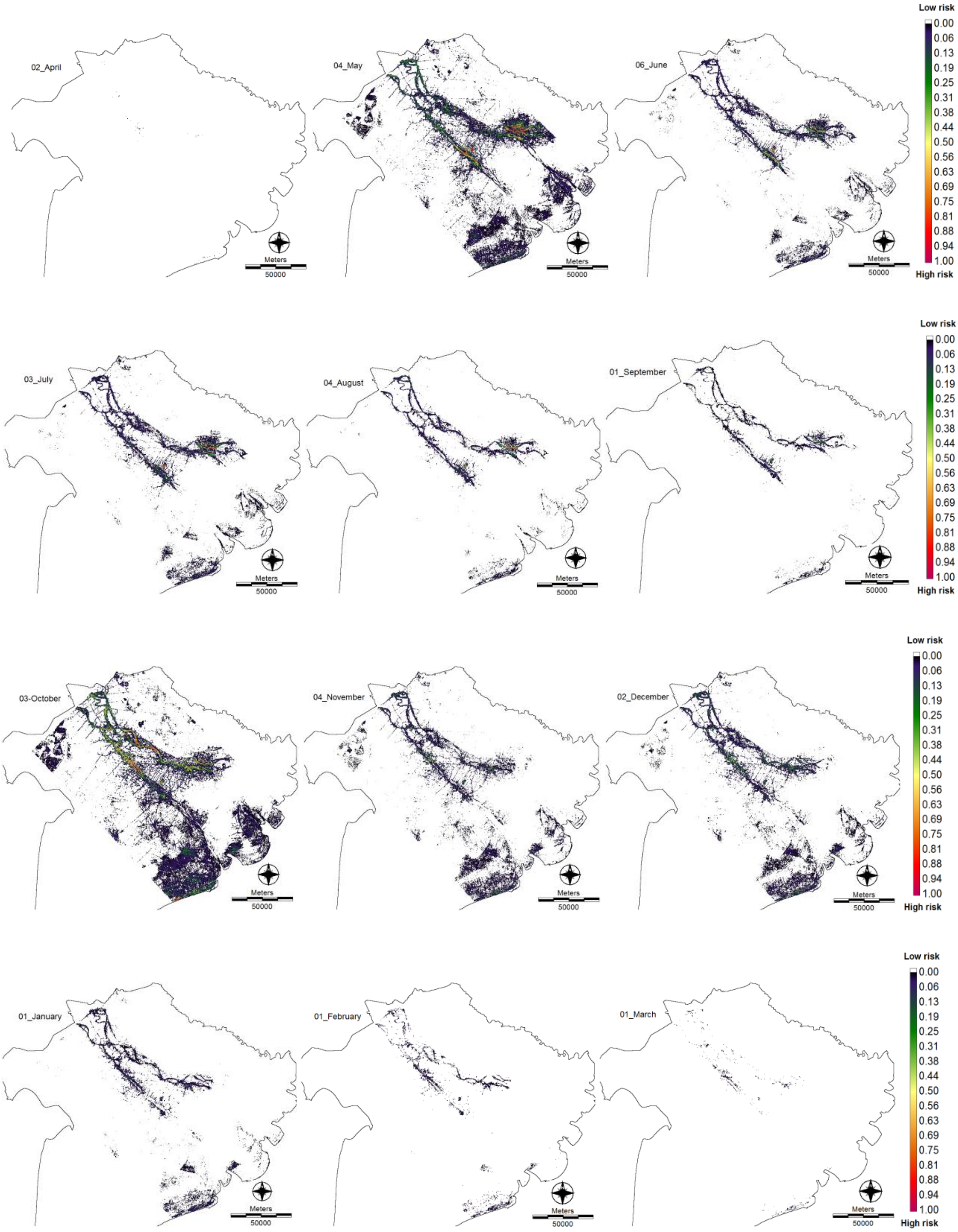


Figure 6. 21. The risk areas for catfish due to Abamectin beginning of every month with a pond depth of 0.5m.

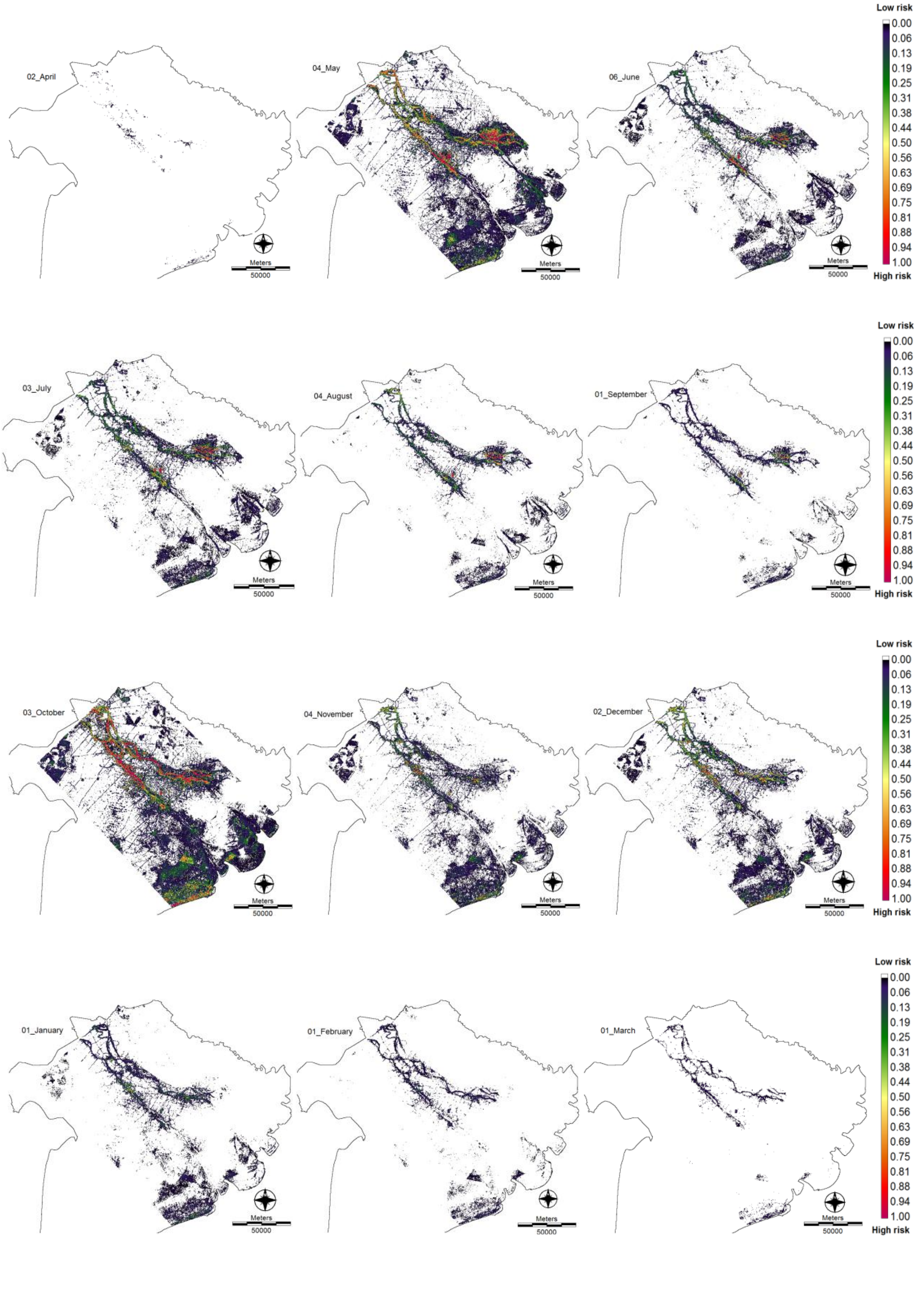
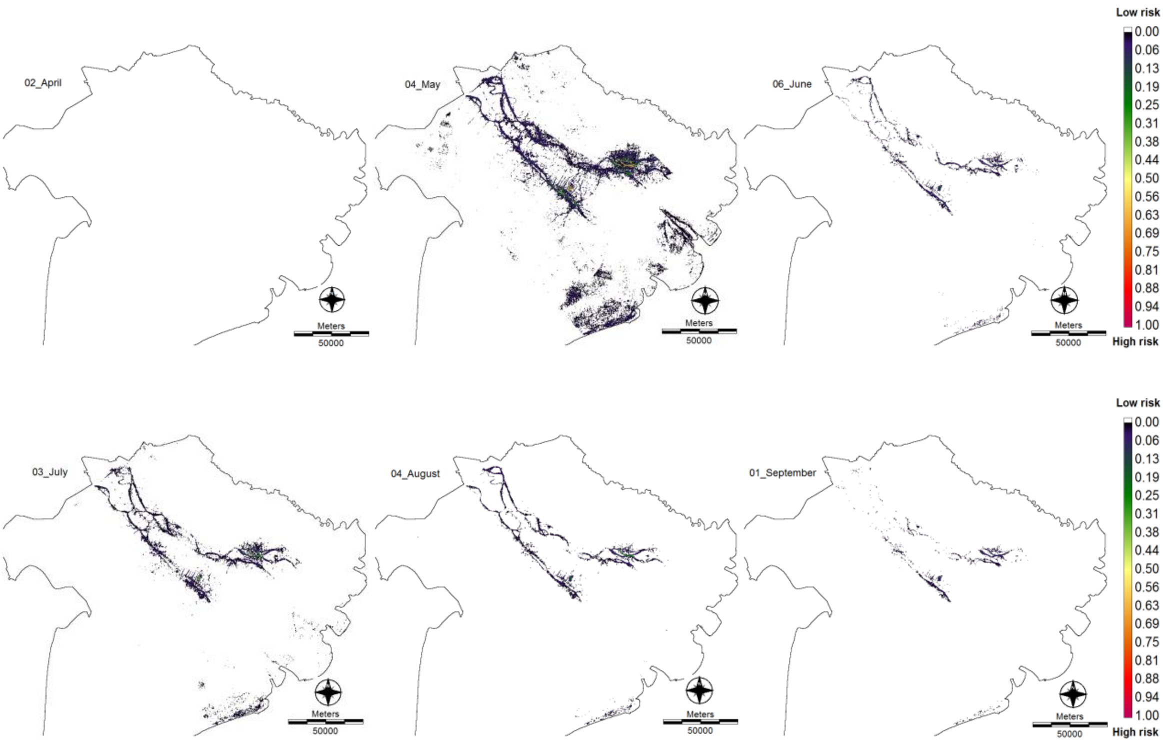


Figure 6. 22. The risk areas for shrimp due to Abamectin beginning of every month with a pond depth of 0.5m.

The membership function value (range from 0-1) is defined by the truth value under fuzzy sigmoidal function. In the reality, the lethal concentration (96hrs) causes the death of population in different percentage. It is actually known that the death rate at 100% cause by a specific value of lethal concentration will be the highest risk point (could be write LC_{100}). However, this classification considers the max risk point is at LC_{50} (at the value of lethal concentration cause 50% population loss), and the non-risk point is at zero (death rate is at zero). Therefore, the assigned values from (>0) and (<1) will also belong to the risk point, even though that lethal concentration just cause few percent of death rate in population.

6.7.3.2 Case 2: 1.0 m initial water depth.

In this case, 1.0 meter of water was assumed to be taken into the pond for aquaculture activities and the total water stored in each cell was ~900 m^3. LC_{50} values for tiger prawn and catfish were as in case 1. Other assumptions were the same as case 1. The results are shown in Figures 6.23. and 6.24. The high risk areas clearly decreased comparing to 0.5m water depth case. For catfish sites, the high risk areas in May and October were much narrower than 0.5 m depth in riverside areas. The safe areas were definitely increased (cover almost study area) from January to the end of April, whereas these situations with 0.5m water depth were from March to the end of April.



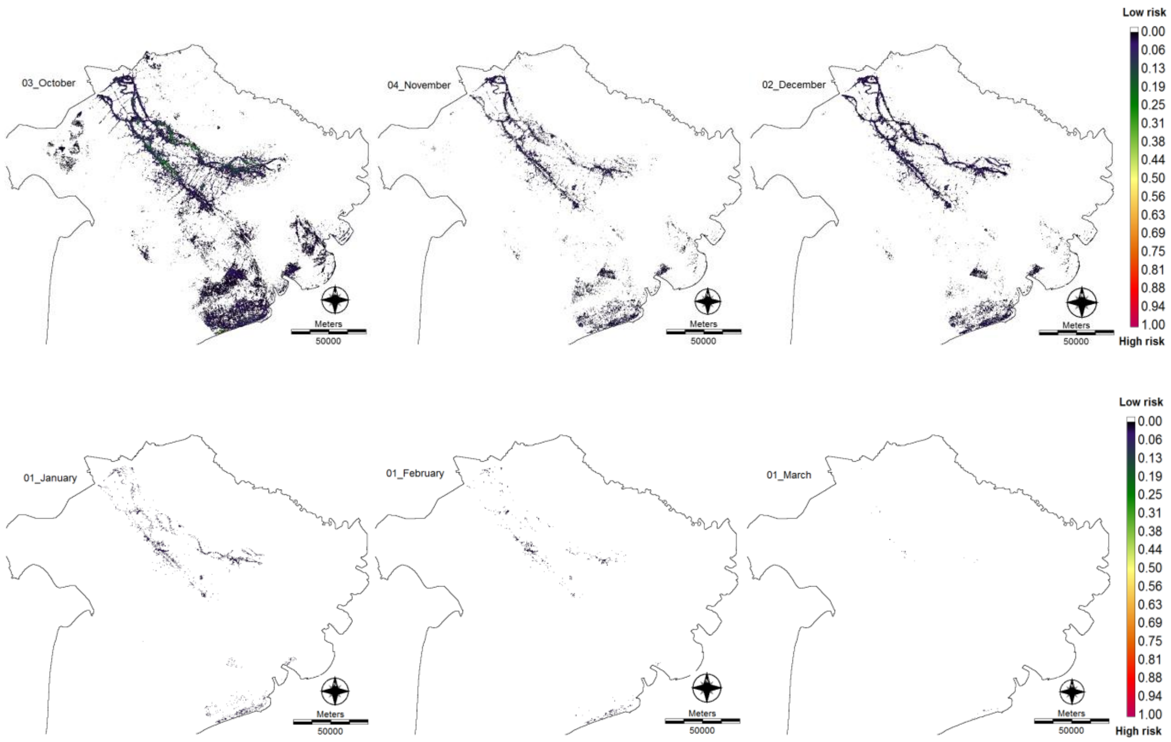
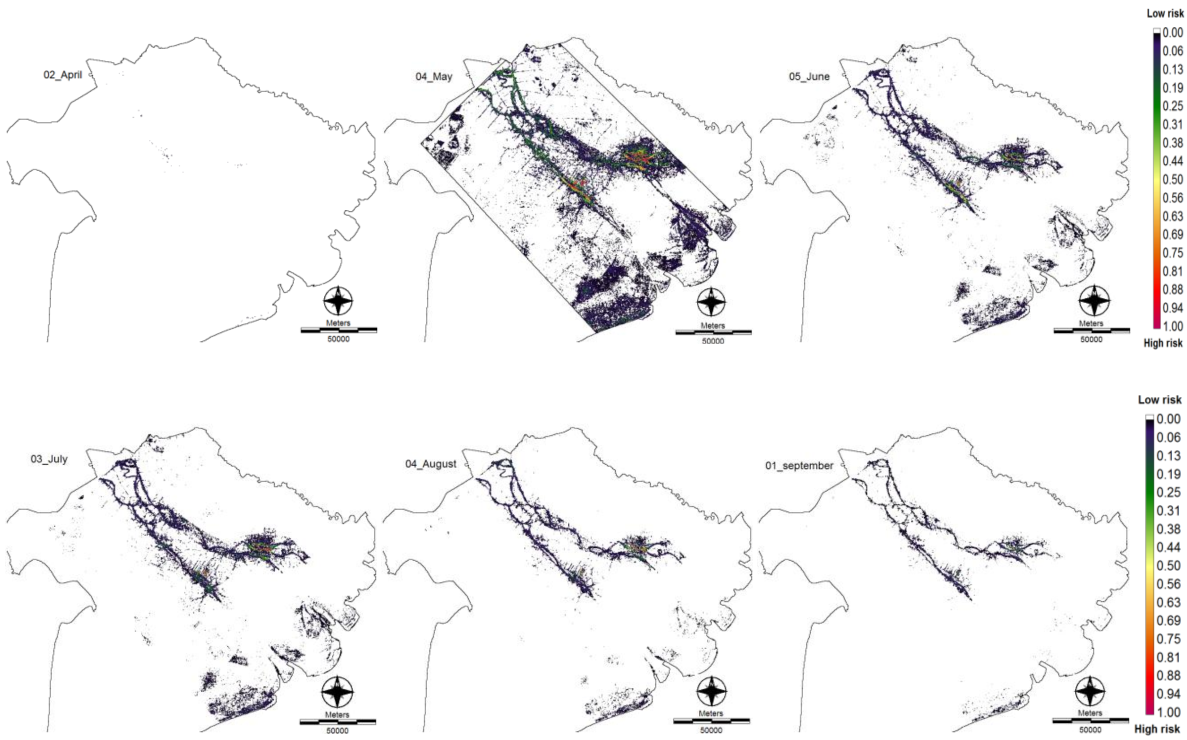


Figure 6. 23. The risk areas for catfish due to Abamectin beginning of every month with a pond depth of 1.0 m.

At the shrimp sites (figure 6.24), risk areas for tiger prawn appeared to decrease compared to 0.5 m water depth case, especially in periods from August to September, and from November to January. From the beginning of March to the end of April, safe areas for tiger shrimp were increased for the most suitable culture period.



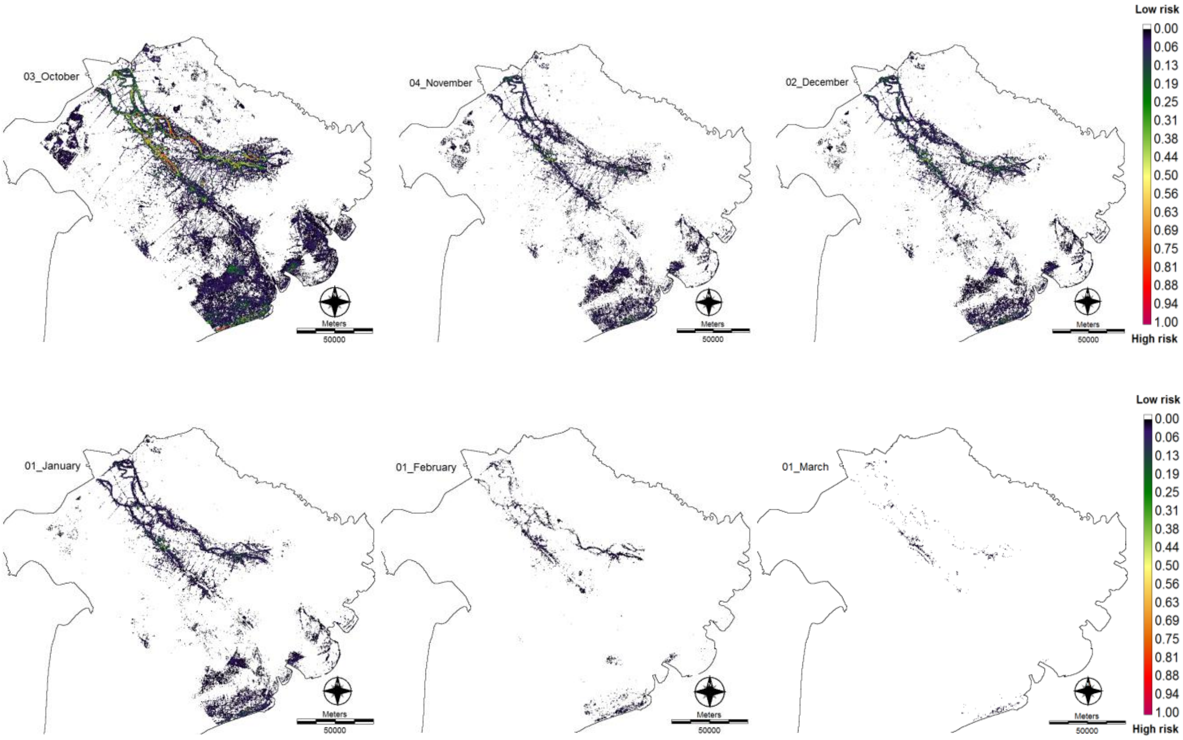
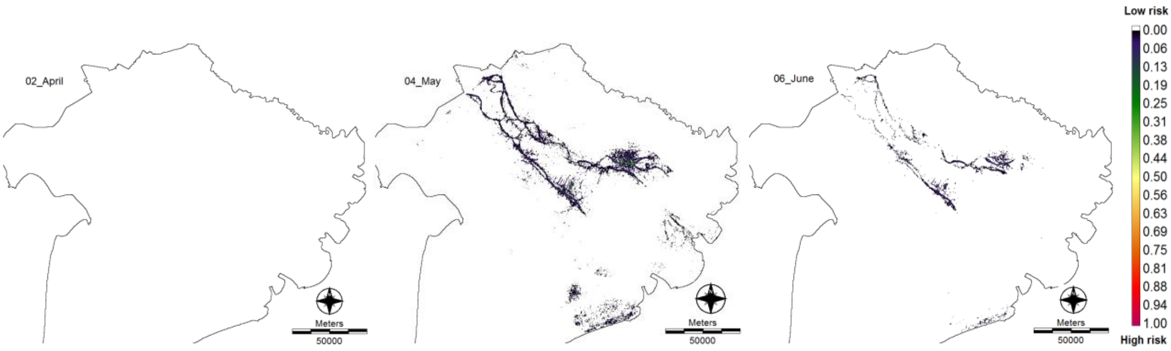


Figure 6. 24. The risk areas for shrimp due to Abamectin beginning of every month with a pond depth of 1.0 m.

6.7.3.3 Case 3: 1.5 m initial water depth.

This case assumes an initial pond water depth of 1.5 m and each cell will contain ~1350m^3. All assumptions are as in case 1. The results are shown in Figures 6.25 and 6.26. In this case, catfish was considered to be safe all year round except for two months (May and October) in very narrow areas at the riverside with a low pesticide risk.



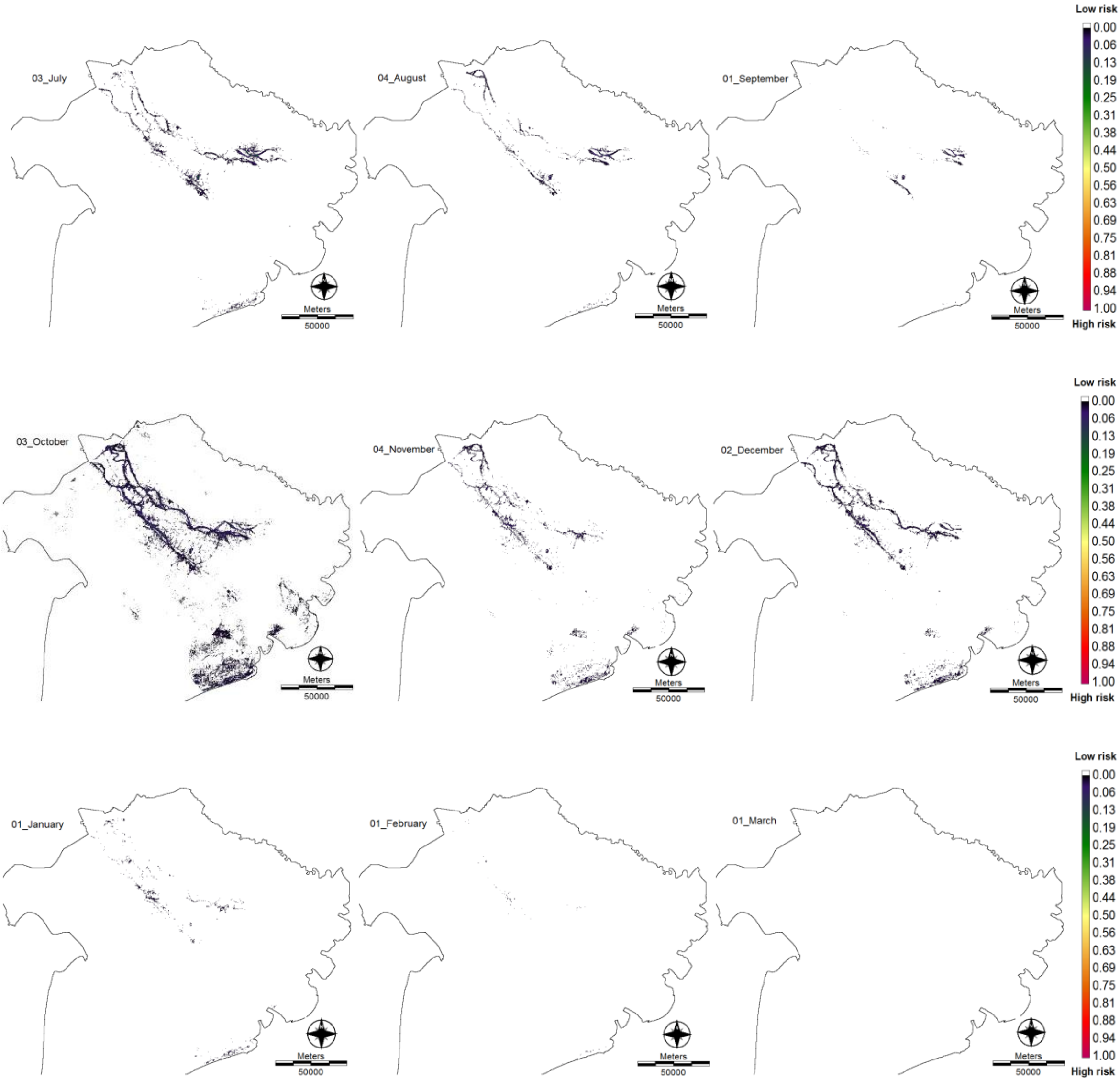


Figure 6. 25. The risk areas for shrimp due to Abamectin beginning of every month with a pond depth of 1.5 m.

Risk areas for shrimp were still present with 1.5 m water depth at the riverside and coastal provinces (Figure 6.26). However, shrimp culture was safe over the period from June to September (with only small areas at even low risk from Abamectin), and from January to the end of April. In only coastal areas consideration, 1.5m water depth indicates the largest safety culture areas for tiger prawn.

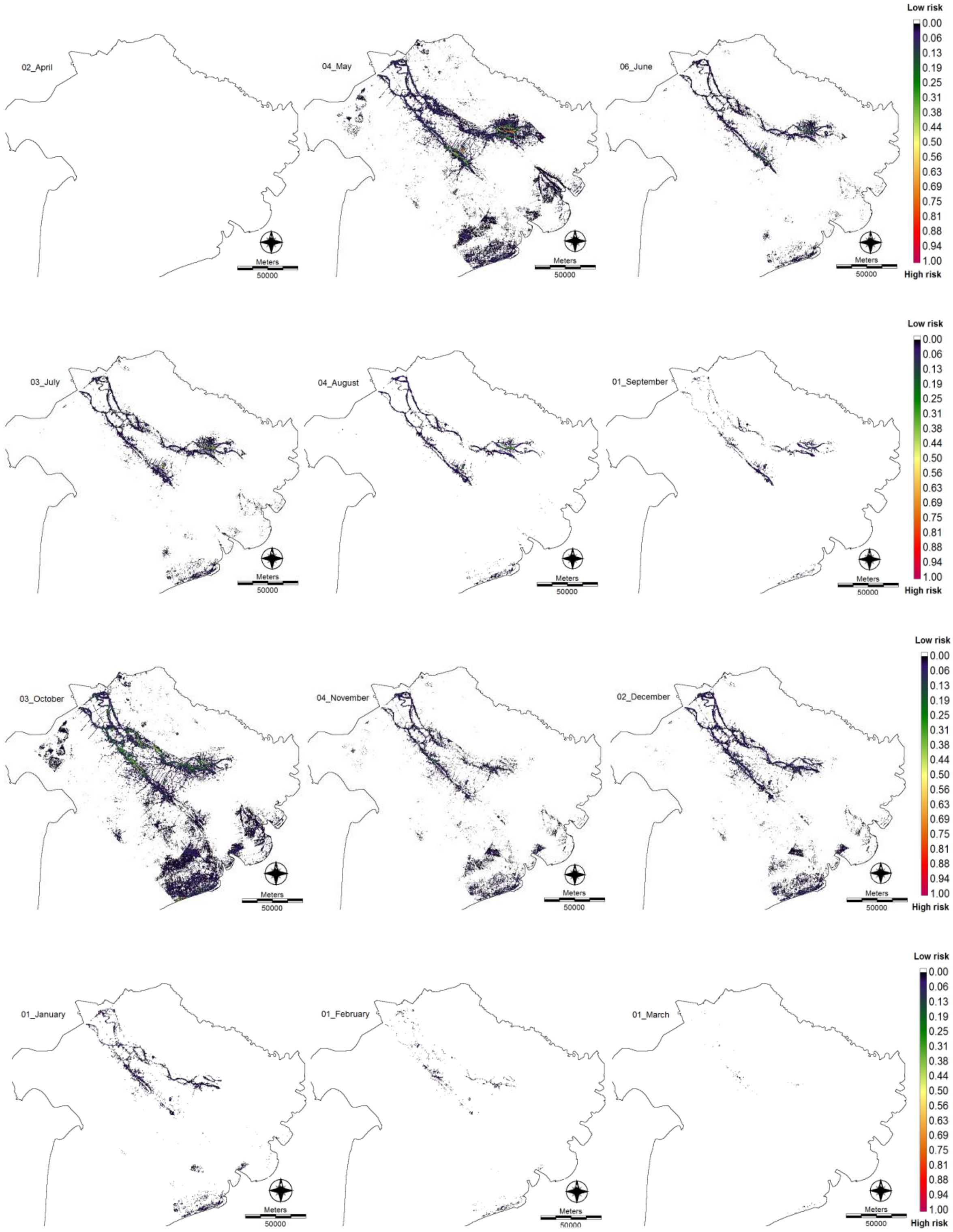


Figure 6. 26. The risk areas for shrimp due to Abamectin beginning of every month with a pond depth of 1.5 m.

6.7.*2* Impact of pesticides on potential aquaculture areas

The total areas for the assessment of risk were extracted from these case studies to show the overall area of risk and no-risk for catfish and tiger shrimp for each month. Even though Abamectin was widely used throughout the study area, those areas at risk occupy a relatively low percentage of the total areas. Figures 6.27 to 6.32 show the fluctuation in risk and non-risk areas in the Mekong delta for the three scenarios.

For catfish, areas of risk peaked in May and October at ~333000 and ~420,000 ha for 0.5m water depth (Figure 6.27); at ~136,000 and ~183,000 ha in the case of 1.0 m water depth (Figure 6.29); and only ~10,840 and ~19,000 ha in the case 1.5 m water depth (Figure 6.31). The two peaks times for areas of risk for tiger shrimp were also in May and October but were considerably higher in size at ~648,000 and ~771,000 ha with 0.5 m water depth (Figure 6.28); ~346,000 and ~446,700 ha with 1.0 m water depth (Figure 6.30); and ~185,000 and 250,000 ha with 1.5 m water depth (Figure 6.32). At water depths of 0.5 and 1.0 m, the sizes of the risk areas were relatively high, especially for shrimp culture. However, at 1.5 m water depth there was less areas of risk for catfish culture during the year, but still some small risk areas for shrimp during May and October.

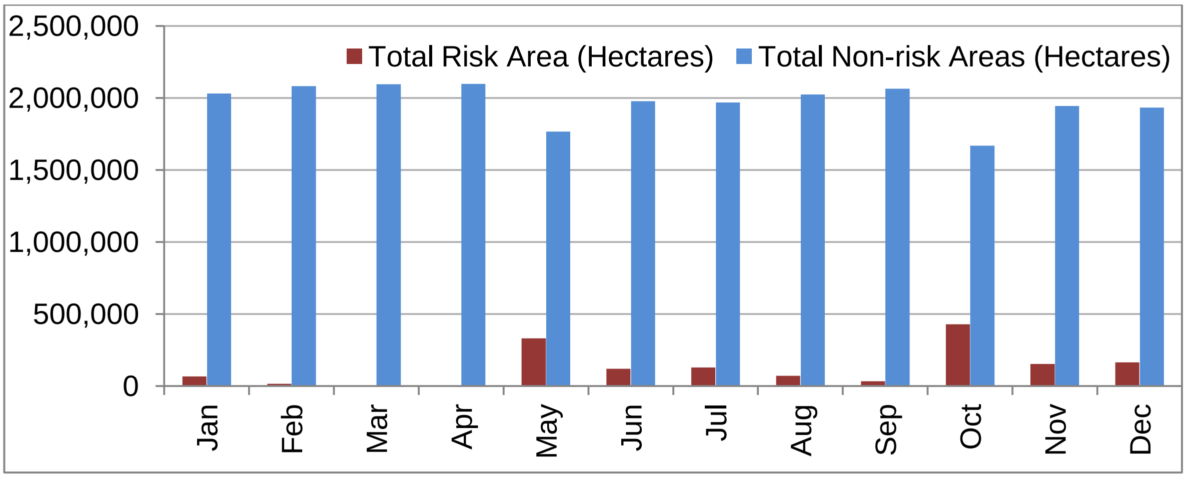


Figure 6. 27. Pesticide risk and no-risk areas of Abamectin for catfish then they were reared in 0.5 m water depth.

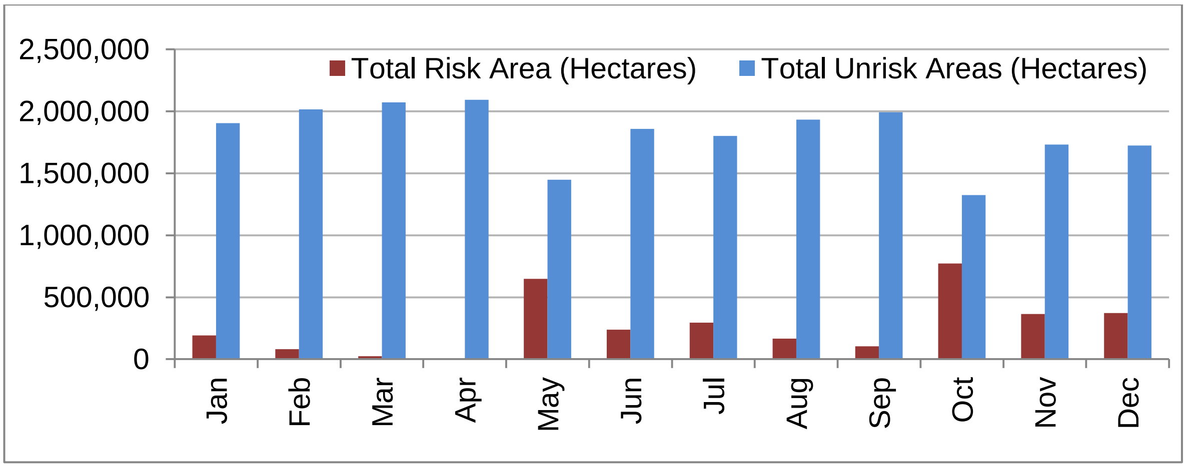


Figure 6. 28 Pesticide risk and no-risk areas of Abamectin for shrimp when they were reared in 0.5 m water depth.

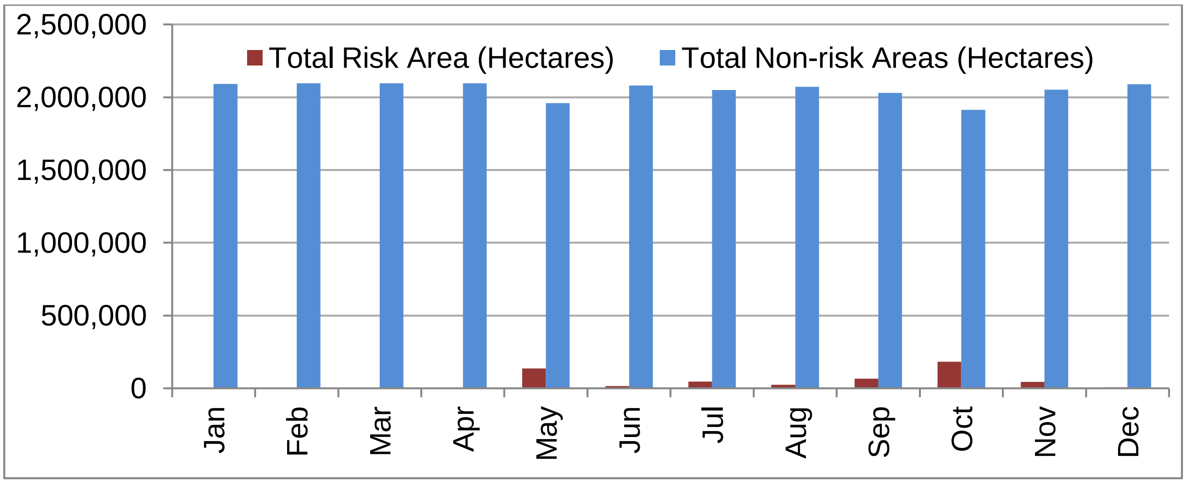


Figure 6. 29. Pesticide risk and no-risk areas of Abamectin for catfish when they were reared in 1.0 m water depth

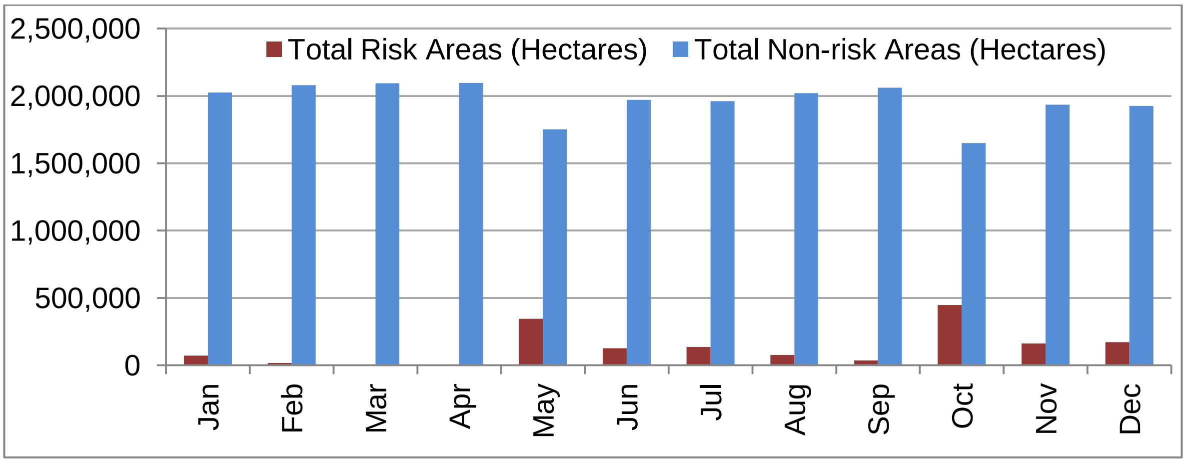


Figure 6. 30. Pesticide risk and no-risk areas of Abamectin for shrimp when they were reared in 1.0 m water depth

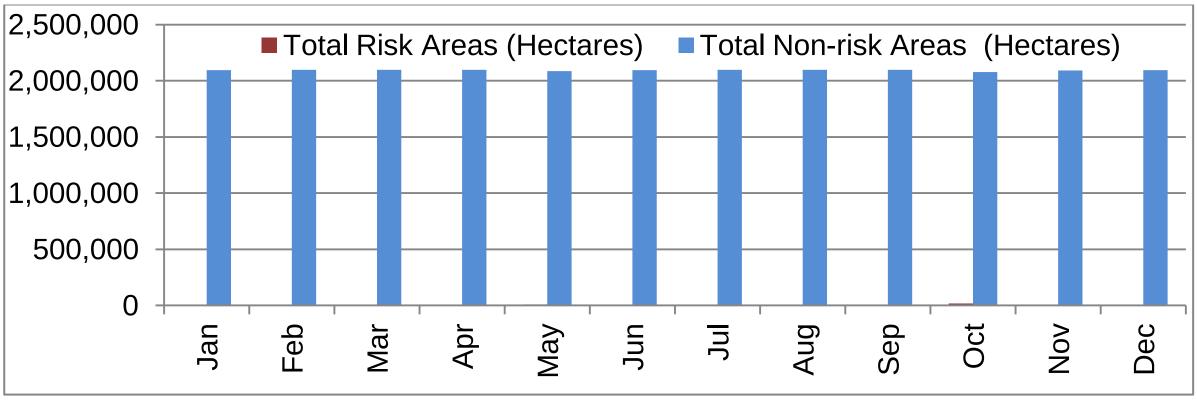


Figure 6. 31 Pesticide risk and no-risk areas of Abamectin for catfish when they were reared in 1.5 m water depth

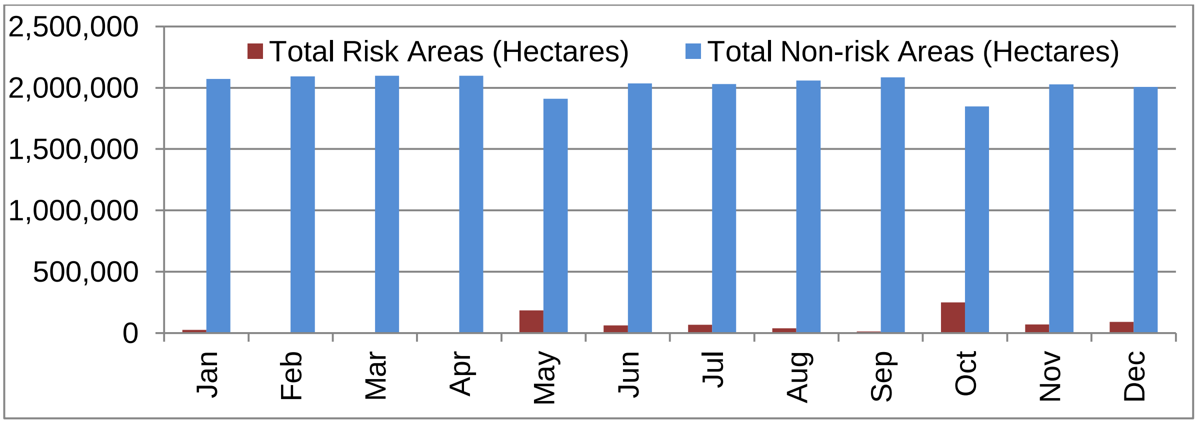


Figure 6. 32. Pesticide risk and no-risk areas of Abamectin for shrimp when they were reared in 1.5 m water depth

6.8 Discussion

The pesticide loss and accumulation model shows the feasibility of estimating and observing pesticide fate in the environment. The results from the model present the quantity of pesticides at any time under the impacts of various factors in nature during the year such as runoff, adsorption, desorption, leaching, water flow, accumulating and others. The spatial accumulation of pesticides provides significant information for policy makers and farmers and investors who seeking safe places with minimum risk factor including chemical toxicity. Integration of the model within GIS allows query of spatial information on pesticides and contributes a decision making tool when combined with the results of other datasets. Going further, this model could be easily applied to any other pesticides in any geographical area.

Pesticide loss models have been developed and applied widely to calculate pesticide losses from agricultural land at both big and small scale such as PeRM of (Li *et* *al.*,2003; Li *et al.*,2003) and AGNPS (Young *et al.*,1989). The most important factor in these models was the runoff process in which elevation was highly influential. In this study the models have been applied in the Mekong delta which differs from previous studies by being very low and flat. The highest risk areas for catfish and shrimp were found in this study at almost the same places where the pesticides had been highest applied and occurred along the riverside and coastal zones. This is also the reason why monitoring stations have been set up at these areas to collect the data on pesticide concentration in soil and water samples (Carvalho *et al.*,2008; Minh *et al.*,2007). In general, risk areas of Abamectin for both catfish and tiger prawn were not large enough to effect the development of culture of these two species under current application regimes.

Some models have been developed to estimate pesticide loss through overland flow (Holvoet *et al.*,2008; Chen *et al.*,2004; Li *et al.*,2003; Huber *et al.*,1998) mainly focusing on calculating the amount of pesticide loss in runoff water. The present study clearly shows the benefit of calculating pesticide losses in both water runoff and sediment based on the adsorption and desorption of chemicals between the two different environments: soil and water. This summation of pesticide concentration in water and in sediment results in a much higher predicted accumulation of pesticide in each cell than previous studies.

The pesticide loss and accumulation model was designed for the Mekong delta where agricultural pesticides are applied throughout the year. The background of the model was based on the time scale of these agricultural chemical uses and could be set to update every 4 days or even every day depending on user modifications. Some models calculating pesticide losses based on the RUSLE equation developed by Renard et al (1987) and USLE equation by Wischmeier (1978), create results that predict totals over a whole year. By contrast, the sediment loss and pesticide loss models in this study were approached as daily events. The scale of the outcomes from this model is presented in terms of the grid cells used, rather than the watershed which has been the norm. For example, the pesticide loss models by Li (2003), Barrar (2000), and Zhang (2011) mostly concentrate on watershed scale and simulate pesticide losses at some outlets of the channel network. In general, the advantage of the present model’s approach has been a greatly improved time scale and the calculation of the results at a much more detailed spatial scale than previous studies.

Based on the pesticide fate in the environment, the pesticide loss process is very complicated in term of defining the quantities and distribution of each pesticide. During runoff losses, the duration of rainfall has not been analysed. While this factor in reality controls the magnitude of soil loss and sediment yield after every rainfall event, the present model runs over a maximum duration of 4 days which may result in over-estimation for a single event. Furthermore, leaching and evaporation were not included in the calculations. However, the structure of model has been designed to allow easy insertion of these components at a later date.

Chapter 7

Overall discussion and conclusion

7.1 General discussion

The Mekong delta is one of the largest deltas in the world. Agriculture and aquaculture are key areas for development in the past, in the present and also the future. Agriculture is the core economic activity in this region. Rice cultivation is considered as the main agricultural target which takes the advantages of rich freshwater resources derived from The Mekong River. Similarly, aquaculture in previous years started to develop in the Mekong delta despite potentially negative interactions with agriculture. According to the few projects carried out on the Mekong delta to detect the residue of persistent pesticides (Minh et al, 2007); Carvalho et al, (2008), there is clearly an issue concerning residue pesticides in the soil layer, sediment, water and biota in over the Mekong delta. This project investigated the impacts of these agro-chemicals in terms of chemical interactions, quantities and their fate in the aquatic environment.

In this project, the problem has been investigated in 4 main parts: (1) Survey the current use and distribution of pesticide in agriculture and aquaculture in the Mekong delta; (2) Modeling the soil loss erosion, sediment lost yields caused by rainfall to evaluate the quantities of pesticide existing in cumulative sediments; (3) Modeling the runoff to evaluate pesticide volume concentrate in cumulative water; (4) A fuzzy classification was used to define the risk areas for specific aquaculture targets.

7.1.1 Pesticide use in the Mekong delta

The advantage of the survey on this project is the geographical location approaches for every interview. Every sample has its own geo-coordinate. Therefore, each sample brings two types of data, the spatial data and pesticide information. Several surveys have been done in the Mekong delta between 1996-2007 (Nguyen Huu Dung *et al.*,1999), from 1999-2000 (Berg, 2001) and latest in 2004 by World Bank (2012a) which normally used the sampling methods without recording specific geographical locations of the farms surveyed. This project carried out sampling methodology which geo-sampling approach, information on pesticide quality and quantities, land-use, soil types, number of crops have been conducted. With coordinate recorded, users would be able to achieve more accurate information in whole area instead of normally using a traditional sampling method selecting a small concentrated areas (a village or a hamlet) as a typical location for the survey.

Although 334 farms were surveyed the total area approached ~20,000km^2. On average, 1 sample represented up to ~59,000 hectares of crop land. However, the compensation for this is the homogenous culture system in the Mekong delta. Total large areas in the central were used for rice cultivation which nearly homogenous about technique, time of cultivation and pesticide application, time of harvest, and type of chemicals use. It will be similar for the other types of land-use.

The average amount of pesticides applied in a hectare was found to be higher than those in the past few years. Results shown in figure 4.13 and 4.14 reveal the mean pesticide uses in 2008 at the rate of ~2.5kg/ha a.i while only ~1.01; ~1.8 and ~2.16kg/ha a.i were found in 1996, 1999 and 2004 respectively. The higher concentration of pesticides found, the higher potential risk to aquatic organisms. However, in total 96 pesticide types was found, there was not any of them belonging to the Group II (WHO, 2006), while previous pesticide data in the survey during 1996 and 1999 revealed a large number of pesticide (especially insecticides) belonged to Group Ia and Ib which are considered the top mortality affects to aquatic animals. In term of the toxicity level and residue impacts, it revealed a good sign for environmental issues and aquaculture development. It also indicated that farmers understood the long persistent risk of pesticides. However, the increase of pesticide quantities applied per hectare also indicated there is little certainty about the stable development of seafood production in term of quantity and quality in the Mekong delta.

Using the mean values of pesticide application per hectare, there is unlikely to be lethality in reared fish, but there may be a residue in flesh.

Pesticide survey in this study provided information on pesticide use in the Mekong delta for target users. The improvement of this survey compared to several in 1999, 2000, 2004 and 2006 (mentioned in chapter 4) is the geo-information which helps to illustrate the spatial distribution of a specific pesticide in whole area. Information and database created for each pesticide’s contribution to pesticide profiles in the Mekong delta. This supports environmentalists, policy makers and aquaculture investors in the decision making process.

7.1.2 Soil loss and sediment yields in the Mekong delta

Soil and sediment type were the basis for pesticide attachment and transport by the moving of soil particles in the environment. Soil erosion and sediment loss model was built on the method of MUSLE developed by William and Berndt (1977), which is different from soil erosion equations of some other previous authors, as it replaces rainfall factor for yearly runoff data with storm event data. From this, results are presented in daily data which is more detail and it could be linked to other models by time series or longitudinal dataset. Except the runoff factor, other component factors such as *K,C,P,LS* were based on the root modification from Wischmeier and Smith (1978) which many authors apply to their specific condition. Although the concept of the equation was an equal contribution to sediment loss, applying to the Mekong delta also found the differences among their contribution in different places where model was applied (discussed in chapter 6).

An aim of this project was to set up a time series model to stimulate soil erosion and sediment yield loss for every surface grid cell. Therefore, MUSLE was considered as the most appropriate solution for the Mekong delta to predict sediment yield in any places where they have available rainfall distribution. Although there is no better model than MUSLE used for this study, the accuracy of this model is still relatively précised (Lim *et al.*,2005), especially when integrating the model into GIS, the results expose the detail in quantities of sediment volume loss and accumulation. In each factor, there were many sub-components which required calibration by the user. Therefore for the model to be accurate, enhancement was required and the user must be explicit about the natural properties, land-use and land treatment, and hydrology condition in the areas applied to the model (Ha, 2009).

Soil type characteristics, land-use control runoff, and discharge processes where important model parameters. Soil type on the majority of hydrology processes related to leaching, infiltration, and absorption of water when runoff. Soil texture data and permeability in the study area revealed hardly any runoff capacity, which may lead to reduced soil erosion, especially for the soil with high clay content (up to ~75% in some places) and widely distributes in low land areas (used for paddy fields). In addition, land-use in the Mekong delta can be resistant to runoff depending on the soil depth and area of cover of vegetation canopy. Clearly knowing these two main factors will create potential approaches to manage runoff and erosion in every specific place at a regional scale.

Although MUSLE could be applied in any place with enough data requirement, but sediment loss and accumulation in the Mekong delta is not clearly displayed. Slope factor is mentioned as an important affect on the quantity of soil loss and accumulation (Van Remortel, Maichle and Hickey, 2004; Di Stefano, Ferro and Porto, 2000; Liu, Nearing, Shi and Jia, 1999). For different events, the distribution of soil or sediment loss will be easy to recognize especially when combining the parameters to display in a GIS system (Zhang.Z *et al.*,2009).

Accumulated sediment ranged from ~1066.42 tonne/ha/year at hilly areas to ~150.15 tonne/ha/year in wet paddies. Areas in the riverside and near the channels got relatively high at ~230 tonne/ha/year. In these areas, total accumulation could affect to the water quality for aquaculture especially some species sensitive to suspended sediment in water. In the negative impacts, the contribution of ~230 tonne of sediment per hectare existing in the pond may result in the increase of investment for aquaculture as fisherman have to pay a fee to deal with the sedimentation brought from sediment loss and accumulation processes.

7.1.3 Pesticide accumulation over the Mekong delta

Aquatic environment and aquaculture are always considered less important than agriculture development which still be promoted by the government development policies. It has been stated that the pesticide loss and accumulation was calculated and mathematical modelled. This model can be applied for any type of pesticides with difference places.

In the 8 land-use types in the Mekong delta, pesticide use was more effective for short growing time cash crop and vegetable areas than for areas of paddies. Compared with total usage in both seasons, apparent direct pesticide loss was not as great as previously measured at up to 40% or a maximum of 80%, (cited by (Holvoet, SeuntjensmK, Mannaerts, De Schepper, and Vanrolleghem, 2007)).

The accumulation was basically calculated by the consideration on the period runoff of the fluxes containing water, sediment and other substances. Although SWAT (Soil and Water Assessment Tool) is considered as a powerful tool to modeling the hydrology especially runoff process on grid cell system. However, the principle and equations constructed in SWAT were also derived from curve number method (CN method) (USDA-SCS, 1986) which can be integrated to other hydrological model as a component. Therefore this study applied the CN method to integrated directly on Macro modeller function together with other component models such as MUSLE The highest pesticide accumulation in 2008 in the Mekong delta was in May, June, July, August, October and November. The result of accumulation depended on two main components; the actual applications over a year and degree hydrology activities such as rainfall, runoff, soil loss and soil accumulation. Two main applications in May and October coincidentally happen in rainy season (one at the beginning and another at the end). That explains why pesticide accumulation peaks at the same time as the pesticide inputs. Although the Mekong delta had a rich rainfall leading strong runoff and sediment loss, the fluctuation of pesticide accumulation quantities were still affected more by the loss from half-life degradation than from the impact of hydrology processes.

7.1.4 Pesticide impacts to aquaculture

The purpose of modeling for this project was to find the state of temporal and spatial distribution of risk areas caused by pesticides.

Risk sites caused by Abamectin toxicity for catfish at 0.5 water depth culture appear at riverside areas. However, actual high risk areas for catfish only appear in May, Jun, Jul and Oct, Nov, Dec. That means at 0.5 m water depth, the best time for catfish culture ranged from Aug to end of Sep, and from Dec to the end of Apr next year. Although suitable sites were illustrated by many other parameters (larvae quality and environmental parameters), the pesticide toxicity in long term still potentially impact on health and survival rate of catfish.

The model was constructed based on the calculation of concentration of pesticide in water body (of the ponds), the model did not include volume of pesticide existing in bottom soil layers. Those amounts are capable to release into water body by desorption processes during the production cycle.

Spatially, the risk areas concentrate in the river and river sides of the Mekong rivers in the middle distance of river length (e.g, see in Figure 6.21) within the delta. That means at 0.5m water depth, catfish cultures still have potential risk caused by accumulated pesticide, especially in riverside areas. In the actual condition, some catfish rearing sites currently overlap with risk area location created by this study (Figure 7.1).

The pesticide risk sites results for shrimp at 0.5m water depth show large areas of acute toxicity for tiger shrimp. These high risk areas concentrate on the months: from

May to Oct, and Dec. Safe culture for tiger shrimp in the Mekong delta just can be seen in Jan to end of Apr

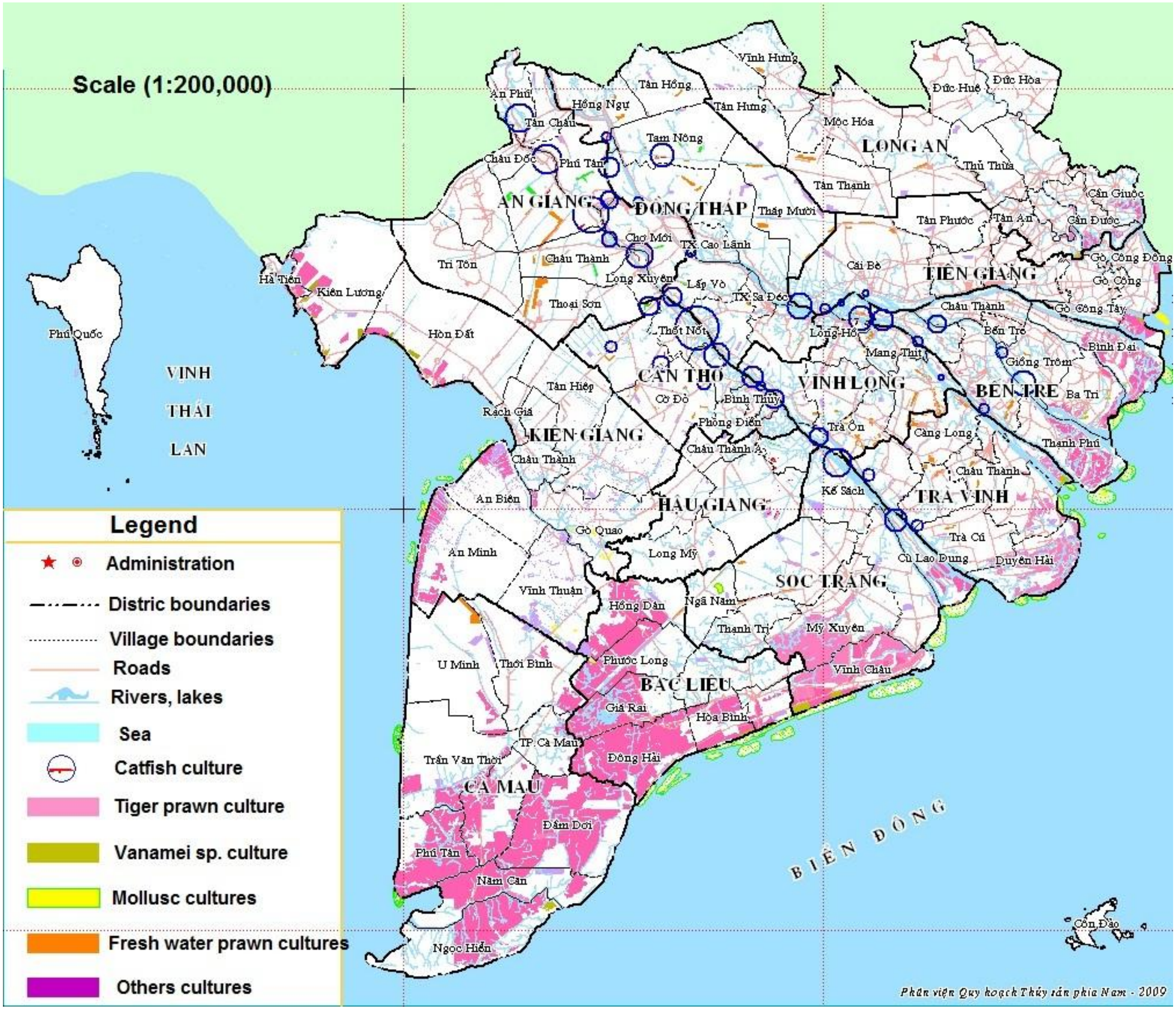


Figure 7. 1. Aquaculture distribution in the Mekong delta (2009).

(Source: Southern Sub-Institute of Aquaculture, 2009)

However, the results reveal on 0.5 m water depth there were little real problems for shrimp culture by pesticide toxicity. Normally, shrimp culture in the Mekong delta located following the salt intrusion areas, especially when strongly developed in coastal areas. Whereas the risk maps for tiger shrimp reveal the high risk areas in riverside at the middle of the main rivers within the delta. Except in May and Oct, there was a minor area in coa stal zones in Soc Trang province got value 1 (the death point) (see figure 6.22). So, if it is based on the salinity distribution map (Figure 7.2), the risk areas caused by Abamectin for shrimp cultures will be in period of May to July, and from Oct to Dec. Other months in year could be considered as suitable time for shrimp farming due to the risk areas in these periods allocated in inland areas or fresh water areas where fishermen could not culture *Penaeus* species.

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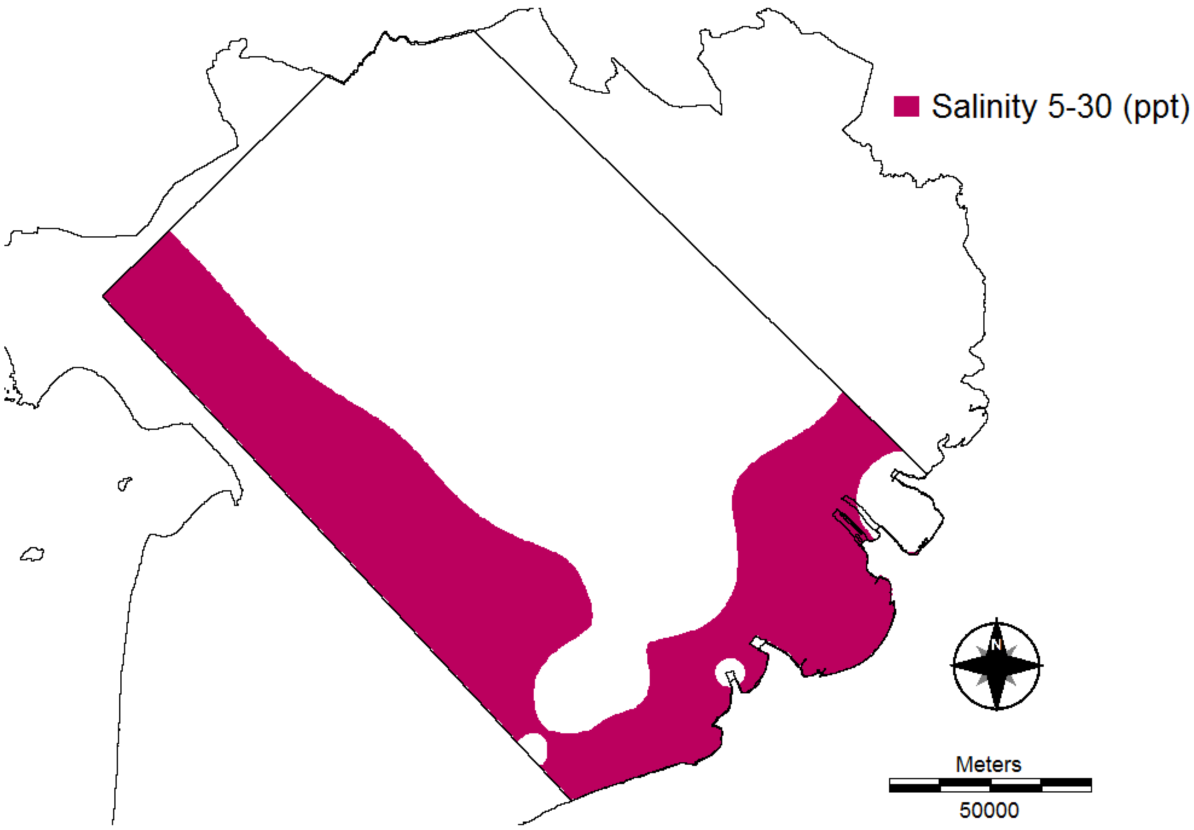

Figure 7. 2 . Salinity map. The red areas gain salinity intrusion from 5 to 30ppt which is considered as the salinity fluctuation for tiger shrimp cultures.

Source (RIA2, 2005)

For a culture pond depth of 1.0m, catfish culture could be affected (but did not reach the LC_{50} death point) in May and Oct. While tiger shrimp cultures, at 1.0 to 1.5m water depth, showed some minor areas of impact to the survival rates (at death point of LC_{50} values) in coastal areas only in May and Oct. At other times it was considered safe in these areas for tiger prawn.

The results indicate that with a specific amount of input pesticide used in agriculture, the fisherman could avoid the risk caused by toxicity impact on aquaculture rearing objects by applying this model. In specific case on this project, shrimp cultures could be avoid to the risk of Abamectin toxicity by increase the water depth in culture ponds over 1 m. Although this conclusion still depends on various factors related to environmental parameters and health conditions of the species reared.

Due to the limitation of studying time, the model results could not be validated. However, the validation could be carried out by field measurements in different points. A number of random points will be selected across the study area with geo-coordinate to aid users approach those in real location to ensure the results from the model are representative. Data on rainfall, soil erosion and accumulation, pesticide use and pesticide accumulation (under the concentration in soil and water) will be collected to confront with the values derived from modeling. It is noticed that the model can run the update with new dataset of rainfall and pesticide application. Therefore in temporal aspect, the system to take samples for validation data will be set up prior the model running.

Even though the model has not been validated, it provides a methodology to stimulate the relation between pesticide input to the environment and the lethal risk to aquaculture through mathematical modeling integrated with GIS. The results are presented under a raster database. The model is an open code which could be linked to other models. In further modeling, the most useful model for aquaculture is the site selection for a specific species, and then this model will be one of the parameter risk indication.

7.2 Conclusion and recommendation

In conclusion, the project is summarized in some issues as below:

- The pesticide survey investigated pesticide information on both quality and quantity in 2008-2009. Combining several survey carried out in 2000 (Nguyen Huu Dung et al, 1999), 2004 (World Bank, 2012b), these cover the trend of pesticide using in the Mekong delta in 2000s. The survery supplied most basic information for regional management and development. The advantages of this survey is integrate pesticide data on a geo-coordinate system which could present the pesticide distribution in GIS.
- The trend of pesticide use in the Mekong delta was strongly changed, especially when Vietnam it owns producing agro-chemical for internal use. Therefore, this survey data will be soon outdated. So, it need to replaced by further survey.
- The modeling soil loss and sediment accumulation is a typical model for low and flat land, the model is suitable for calculate soil loss in the delta areas. Factors in soil loss equation was calibrated based on the description of MUSLE (Modified Universal Soil Loss Equation), and be better if users deeply know

about the study area. Data and model construction was built on the base of GIS by IDRISI software

- Application of sediment loss and accumulation model will support to users a quick and useful tool to predict sediment quantities in any area scale with a daily recorded rainfall data. The display from this model will be presented by the display system of GIS which provides an easy understand results under vectors, rasters, or tablars. The resolution raster results bring up to the viewer with a high resolution up to 30m x30m. Grid cell based calculating not only comes over the issue in watershed modeling (difficult to calibrated the parameters due to un-homogenous data in a large watershed), but also display a smooth raster image to show the sediment loss and accumulation.
- The most vulnerable areas for soil loss are concentrated in riverside, hilly and coastal areas. While two ideal factors affected to runoff and sediment loss, but the feasible factor used to controle sediment loss is landuse and farming practices or shorten land tilling. In this roject, the sediment loss model was designed to adapt with the longitudinal data, therefore the model can be applied to modeling for continuity years in the future.
- The pesticide loss and accumulation model has been develope by four submodel including pesticide distribution, soil loss and accumulation, runoff and direct loss in grid cell concept. The model built as a mathematical model integrated GIS to enhance the results
- The results of pesticide accumulation model were used for fuzzy classification to find the potential risk areas for tiger shrimp and catfish. Fuzzy model reveals the concentration of risk areas is main ly in riverside and coastal areas where current catfish and tiger shrimp are culturing. Majority of non-risk areas were classified when tiger shrim and catfish was culture at 0.5, 1.0 and 1.5m of water depth. The model provide a potential methodology to find the trilateral relation between pesticide use in agriculture, the hydrology process and risk area for specific aquaculture species.

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