Workshop on Sustainable Management of
Mae Klong River Basin, Thailand
Bangkok, October 12, 1999

Forest Situations in the Mae Klong River Basin Analyzed by Remotely Sensed Data and Relationships with Suspended Sediment Yield

Hideji Maita
Institute of Agricultural and Forest Engineering, University of Tsukuba
Tsukuba, Ibaraki, 305-8572 Japan
Mika Kawamoto
Master's Program in Forestry, Kasetsart University
Bangkok, 10900 Thailand
Nipon Tangtham
Faculty of Forestry, Kasetsart University
Bangkok, 10900 Thailand
Shigeo Ogawa
Remote Sensing Laboratory, National Institute of Agro-Environmental Sciences
Tsukuba, Ibaraki, 305-8604 Japan
Varawoot Vudhivanich
Faculty of Engineering, Kasetsart University
Kamphaengsaen Campus, Nakhon Pathom, 73140 Thailand
Kosit Lorsirirat
Hydrology Division, Royal Irrigation Department
Dusit, Bangkok, 10300 Thailand

Abstract

This paper focuses on forest situations in the Mae Klong river basin analyzed by remotely sensed data and relationships with suspended sediment yield. The forest land ratio of the basin has remained stable at 62-65 percent during the last two decades though the ratio for all Thailand decreased rapidly from 43 percent in 1973 to 26 percent in 1993. The Lam Phachi watershed of the basin is covered with less forest (56 pct.) than the Khwae Noi (76 pct.) and Khwae Yai (79 pct.) watersheds and has considerably larger agricultural land ratio (the Khwae Noi (13 pct.), the Khwae Yai (8 pct.) and the Lam Phachi (37 pct.) watersheds). It has also roughly twice the annual mean suspended sediment concentration (540 ton/mcm) as the Khwae Noi (244 ton/mcm) and the Khwae Yai (273 ton/mcm) watersheds. In addition, the Lam Phachi watershed the most finely divided network among the three watersheds. These conditions of the Lam Phachi watershed result in the highest susceptibility to erosion. Thus soil erosion seems to be caused by agricultural activities of lowland areas as well as the forest destruction of upland areas. Therefore, from the viewpoint of soil erosion control in the Mae Klong river basin, it is necessary to protect the remaining forest in upland areas to prevent increases of sediment sources and to conserve the soil of cultivated land in lowland areas to decrease sediment sources.

Keywords: remotely sensed data, suspended sediment yield, forest land, agricultural land

1. INTRODUCTION

Soil erosion degrades soil fertility, and sedimentation due to erosion reduces river and reservoir capacities. Soil erosion and sedimentation are thus inseparable problems. According to Jantwat (1985), the annual erosion rate in Thailand ranges from 12 to 2,045 ton/km^2/year in the North, 8 to 3,874 ton/km^2/year in the Northeast, 20 to 569 ton/km^2/year in the Central Plain, 27 to 355 ton/km^2/year in the East and 30 to 1,787 ton/km^2/year in the South. The higher erosion rates thus occur in the Northeastern and Northern regions where deforestation has progressed rapidly. Therefore, special attention has been paid to soil erosion and sedimentation problems in these regions. According to Maita *et al.* (1998), the annual suspended sediment yield per unit area (1km^2), which is similar to the annual erosion rate, ranges from 55 to 210 ton/km^2/year in the Mae Klong river basin. Judging from these values, soil erosion in the basin is not so severe because the soil of steep slopes is now almost covered with forest (AIT, 1994; Tangtham, 1997). Accordingly, little attention has been paid to erosion and sedimentation problems though huge dam reservoirs are located in the basin. However, the soil of steep slopes is susceptible to erosion if vegetation cover is removed. Proper watershed management, therefore, should be practiced in the basin to prevent reducing reservoir capacities due to off-site effects of soil erosion as well as to conserve the forest. For this purpose, we should first clarify vegetation cover condition in the basin because it directly affects soil erosion.

The objectives of this paper are to analyze forest types and land cover for extensive areas of the basin using remotely sensed data, and to clarify the relationship among vegetation, watershed characteristics and suspended sediment yield as a first step to practice proper watershed management in the Mae Klong river basin.

2. STUDY AREA

The Mae Klong river drains a 30,800 km^2 basin in the western part of Thailand. Three tributaries were selected for the comparative analysis of relationships between vegetation cover and suspended sediment yield in both upstream and downstream areas of each tributary's basin. The tributaries are the Khwae Yai river, the Khwae Noi river and the Lam Phachi river. The largest of these, the Khwae Yai river drains a 11,750 km^2 watershed above its confluence with the Lam Taphoen stream, where the Srinagarind Dam reservoir with a 419 km^2 water surface is located. Khwae Noi river drains a 7,000 km^2 watershed above its confluence with the Huai Mae Kraban stream, where the Khao Laem Dam reservoir with a water surface area of 388 km^2 is located. The smallest of the three, the Lam Phachi river, drains a 2,620 km^2 watershed above its confluence with the Khwae Noi river (Fig. 1).

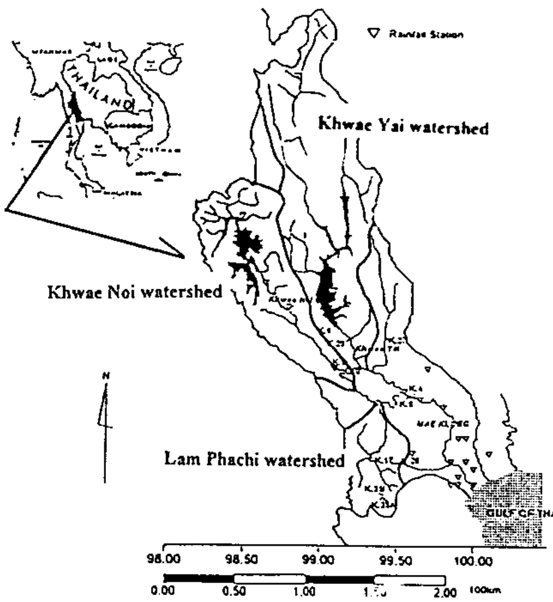


Fig. 1 Map of study area.

2.1 Geology

The mountainous area of the Mae Klong river basin is mainly underlain by sedimentary rocks of Paleozoic and Mesozoic eras such as limestone, sandstone, mud stone, shale and quartzite. The geology of these three watersheds is shown in Table 1. The Khwae Noi and the

Khwae Yai watersheds are mainly characterized by limestone of the Mesozoic era, whereas the Lam Phachi watershed is characterized by igneous rocks (Maita *et al.*, 1998).

Table 1 Geology in the Mae Klong river basin and the Khwae Noi, the Khwae Yai and the Lam Phachi watersheds.

Geology		Mae Klong (%)	Khwae Noi (%)	Khwae Yai (%)	Lam Phachi (%)
Sedimentary rock	**(Quaternary period)**	24.1	11.5	3.3	20.0
	(Tertiary period)	1.5	3.9	1.4	0.0
	(Mesozoic era)	10.4	7.8	19.6	2.8
	(Paleozoic era)	22.7	32.7	12.5	44.8
Limestone	**(Mesozoic era)**	24.9	32.4	40.6	1.0
Igneous rock	**(Mesozoic era)**	13.9	11.7	17.5	31.4
Metamorphic rock	**(Proterozoic era)**	2.5	0.0	5.1	0.0

2.2 Topography

The Khwae Noi and the Khwae Yai rivers are main tributaries in the Mae Klong river basin. After they converge at Kanchanaburi, they are renamed the Mae Klong river, which flows through the plain to the Gulf of Thailand approximately 130 km distant. The slope of the Mae Klong river flowing through the plain is 1/7,000 to 1/5,000; the slopes of the Khwae Noi and the Khwae Yai rivers flowing in hilly land areas are 1/3,000 to 1/1,000, and their slopes in the mountainous areas are more than 1/500.

The drainage pattern of the Mae Klong river basin is dendritic. Drainage system analysis revealed that the Lam Phachi river is exceeds the Khwae Noi and Khwae Yai rivers in drainage density and frequency, and their values of the Khwae Noi river is similar to the Khwae Yai river (Table 2; Maita *et al.*, 1998). It should be noted that the Lam Phachi river has the largest values because its usually high density and frequency indicate that a drainage basin has a finely divided network of streams with short length and steep slopes.

Table 2 Drainage density and frequency in the Mae Klong river basin and the Khwae Noi, Khwae Yai and Lam Phachi watersheds.

	Drainage Frequency Number				Drainage Density Length (km)		
Stream order	Khwae Noi	Khwae Yai	Lam Phachi	Stream order	Khwae Noi	Khwae Yai	Lam Phachi
1	75	160	66	1	784	1,494	429
2	24	35	16	2	296	374	174
3	7	8	2	3	114	191	82
4	2	2	1	4	157	225	61
5	1	1		5	81	145	
Total	109	206	85	Total	1,432	2,430	747
F (Streams/km^2)	0.0156	0.0175	0.0324	D (km/km^2)	0.205	0.207	0.285

2.3 Climate

The climate of the Mae Klong river basin is characterized by monsoons. The southwest wind during the wet monsoon season from May to October brings much rainfall, whereas the northeast wind during the dry monsoon season from November to April brings little rainfall (Table 3). Based on an annual mean rainfall isohyetal map of the Mae Klong river basin, the rainfall for the lower part of the basin is roughly 1,000 mm, and it increases with latitude to roughly 2,100 mm in the upper part of the basin. The rainfall also increases from east to west in the basin and ranges from 900 mm to 2,100 mm (Maita *et al.*, 1998). This rainfall pattern is mainly caused by the relationship between the location of mountain ridges west of the basin and the southwest monsoon wind with highly moist air. The Khwae Noi watershed has the greatest rainfall (1786 mm); the Lam Phachi watershed, the least rainfall (1 130 mm); and the Khwae Yai watershed, an intermediate rainfall (1416 mm)(see Table 3).

Table 3 Annual and monthly mean areal rainfall in the Mae Klong basin and the Khwae Noi, Khwae Yai and Lam Phachi watersheds.

Watershed	Annual (mm)	Apr	May	Jun	Jul	Aug	Sep (mm)	Oct	Nov	Dec	Jan	Feb	Mar
Mae Klong	1,363	76	167	179	225	216	243	187	49	5	6	15	28
Khwae Noi	1,786	92	209	290	335	327	268	177	34	5	6	18	36
Khwae Yai	1,416	78	166	182	206	229	251	160	40	5	7	16	28
Lam Phachi	1,130	63	149	108	123	142	213	217	86	10	4	14	24

The temperature of the Mae Klong river basin is higher in the upper stream and almost uniform throughout the year with little seasonal variation. For example, at the Um Phang station located in headwater regions in the high elevations of the Khwae Yai river, the annual mean temperature is 23.2°C and the monthly mean temperature varies from 18.5°C in December to 26.0°C in April. In contrast, Kanchanaburi station located in the plain of the basin has an annual mean temperature of 27.9°C, and the monthly mean temperature varies from 24.6°C in December to 31.2°C in March (AIT, 1994).

2.4 Vegetation

According to an AIT report (1994), on the Mae Klong river basin, the forest land ratio is 73% and the agricultural land ratio is 18.5%, including a sugar cane area of 7.8%, paddy field area of 3.6%, field crop area of 3.2% and an orchard area of 2.7%. However, the time these figures were estimated is not clear. Based on the estimation using the land use map published in 1972 by Department of Land Development, the forest land ratio to the whole basin was 61.7%, field crop and forest area was 22.4%, paddy field and field crop area was 4.5% and sugar cane area was 9.5% at the beginning of the 1970s (Maita *et al.*, 1998). Tangtham (1997) also reports that the forest land ratio was 53 % in 1988. As mentioned above, since information about forest and land use is not always fully accurate, their ratios should be investigated to understand present watershed conditions.

3. METHODS AND DATA

3.1 Image processing system and JERS-1 data

In order to clarify recent forest situations in the Mae Klong river basin, a software program, Imagine 8.3 (ERDAS, Inc.), was used to analyze satellite image data taken by the optical sensor (OPS) aboard Japanese Earth Resources Satellite-1 (JERS-1). Fifteen scenes (path 127 to 131 and row 273 to 278) of JERS-1 OPS data covering the Mae Klong river basin taken between January 1994 and March 1996 were selected for analysis (Fig. 2).

3.2 Analytical method and data collection

A comparative study method was selected and the data on vegetation, suspended sediment yield, rainfall, geology, topography were arranged for the Khwae Noi, the Khwae Yai and the Lam Phachi watersheds. The arranged data were then compared to clarify the relationship between vegetation cover and suspended sediment yield of the Mae Klong river basin. The rainfall, water discharge and suspended sediment yield data were monitored at many hydrological stations in the basin by the Royal Irrigation Department (RID), Electricity Generating Authority of Thailand (EGAT) and Department of Energy Development and Promotion (DEDP).

4. FOREST TYPE AND LAND COVER CLASSIFICATION

4.1 Satellite image analysis procedure

The JERS-1 OPS data were composed of eight bands in the visible, near-infrared and short wave infrared regions, and one pixel has a ground resolution of 18 m×24 m. In this study, bands one, two and three ranging from visible to near-infrared of every five pixels were used. Therefore the ground resolution of this analysis is 90 m×120 m.

4.1.1 False-color image

A false-color image was made by allotting blue to band one (visible, 0.52-0.60 μ m), green to band two (visible, 0.63-0.69 μ m) and red to band three (near-infrared, 0.76-0.86 μ m) because it is generally known that much information concerning land cover of watersheds can be extracted from images of this composition (Hasegawa,1998). In a false-color image, forest land is generally red; grass and agricultural land, bright red or pink. Paddy fields are dark blue when the water surface is visible. Bare land is whitish, and water surfaces, blackish. The red intensifies with increments of vegetation coverage and vegetation growth.

First, a preliminary false-color image was obtained using a scene of path 130 and row 276 (130/276) covering the Khao Laem Dam and the Srinagarind Dam reservoirs to examine preliminary forest types and land use. Next, a false-color composite was made from the 15 scenes by digital mosaicking. Geometric correction, which involves generating an Affine transformation model, was then performed using seven ground control points such as rivers, road intersections, and land and lake separations selected from both the image and the map (scale 1:500,000). Consequently, a false-color composite with defined coordinates was obtained as shown in Fig. 3.

	Path 131	130	129	128	127
Row 273		Jan. 2, 96			
274	Jan. 29, 94	Jan. 2, 96			
275	Jan. 29, 94	Jan. 2, 96	Mar. 29, 96		
276	Jan. 29, 94	Jan. 2, 96	Apr. 25, 94		
277		Jan. 2, 96	Apr. 25, 94	Dec. 31, 95	
278			Mar. 12, 94	Dec. 31, 95	Dec. 30, 95

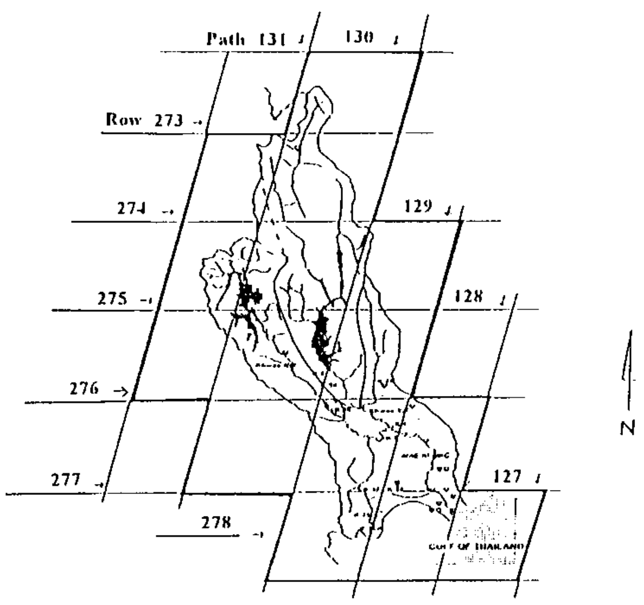
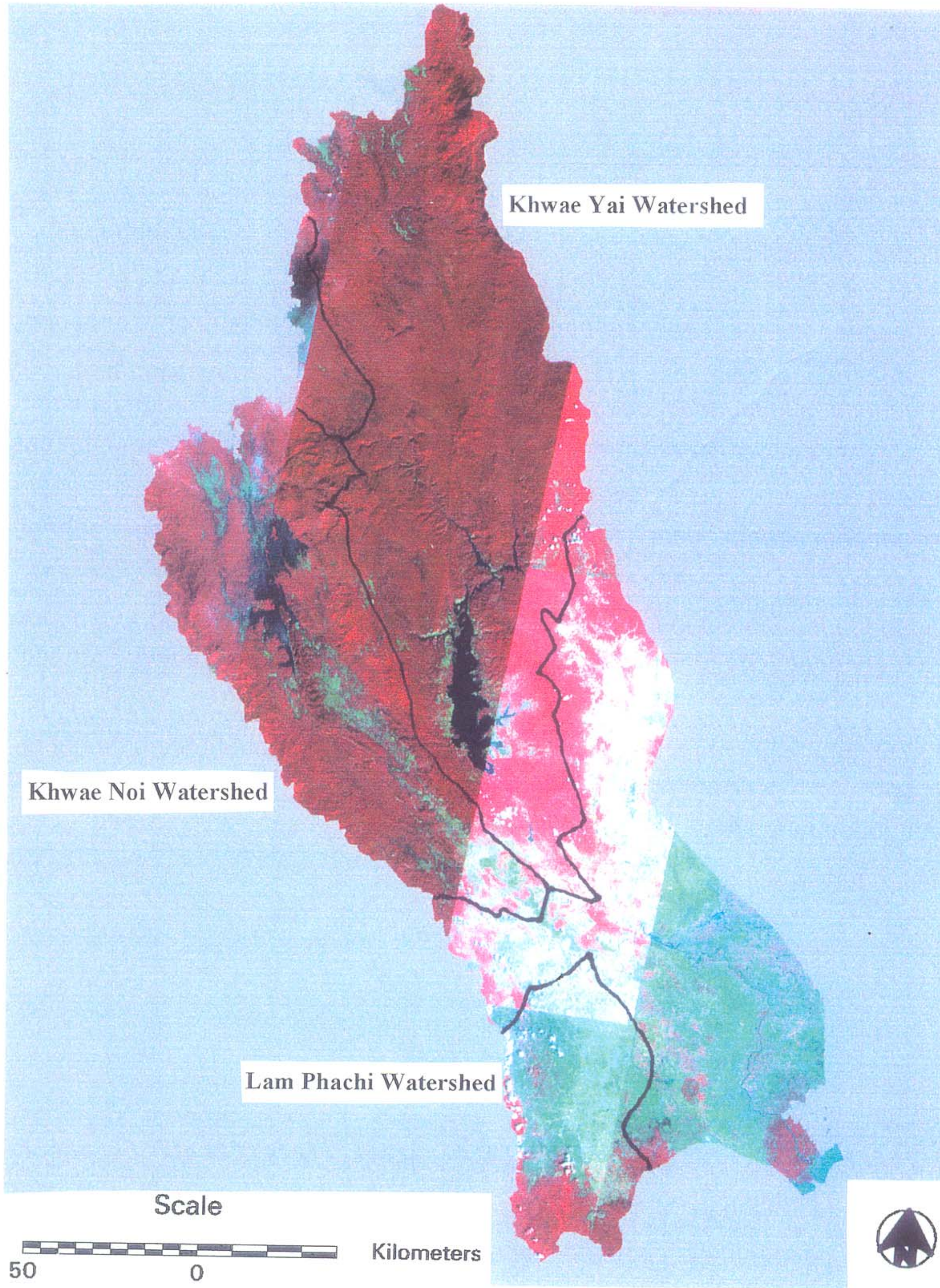


Fig. 2 Satellite image data for remote sensing.



JERS-1 data

RED : Band three (near-infrared, 0.76-0.86 μ m)
GREEN : Band two (visible, 0.63-0.69 μ m)
BLUE : Band one (visible, 0.52-0.60 μ m)

Fig. 3 False color composite of the Mae Klong river basin.

4.1.2 Ground truth data

In November 1997, we made a reconnaissance in Mae Klong Watershed Research Station (MWRS) of RFD in the upper stream of the Khwae Noi river (scene 130/276) to acquire ground truth data on forest types. We also conducted reconnaissance from downstream to upstream of the Khwae Noi river to acquire information about forest and land use situations. In September1998, we made a field investigation in the areas around Srinagarind Dam to obtain information on forests and land use by taking photos with a GPS camera. The camera can simultaneously record time, longitude, latitude and direction because it has a ground positioning system. We also checked the result of preliminary classification of the forest types for scene 130/276, as determined below (see paragraphs 4.1.3 and 4.1.4).

4.1.3 Categories

According to Suksawang (1995), forest types of MWRS can be divided into the following four categories based on their ecosystems.

a) **Mixed deciduous forest with bamboo**: This forest type is scattered all over the study site and forms about 97%of the watershed area. The dominant trees are *Xylia kerrii, Schleichera oleosa, Pterocambium cuspidata, Dillnia obovata and Croxylum indicum*. The lower story of the forest is bamboo.

b) **Dry dipterocarp forest**: This forest type is found mainly in terrace formations at the ridge top of watershed areas. The dominant trees are *Dipterocarpus* spp., *Shorea siamensis, Careya arborea, Dalbergia* spp., etc.

c) **Dry evergreen forest**: This forest type is scattered in the areas along creeks. This forest is composed of *Hopea odorata, Walsura trichostemon, Sterculia* spp. etc.

d) **Disturbed forest**: This forest type originates from subsequent burning and cultivation and is found in the gentle slope areas composed of wild banana, bamboo and some small trees.

According to the Upper Khwae Yai Project Report (1980), forest types of the head water region, which is about 140 km upstream from Srinakarind Dam, can be devided into the following five categories.

a) **Mixed deciduous forest**: This forest type is scattered all over the research site and covers 70-80% of it. The dominant trees are Teak (*Tectona grandis*), *Xylia kerrii, Pterocarpus macrocarpus, Schleichera oleos, Terminalia bellerica, Dillnia obovata* etc. The undergrowth of the forest consists of bamboo.

b) **Dry dipterocarp forest**: This forest is composed of *Pentacme sauvis, Dipterocarpus* spp., *Shorea obtusa, Pterocarpus macrocarpus, Terminalia* spp. etc.

c) **Dry evergreen forest**: This forest is composed of *Hopea ferrea, Cannarium kerrii, Hydnocarpus ilicifolius, Cedrela toona, Tetrameles nudiflora, Salmalia insignis, Milletia leucantha* etc.

d) **Moist evergreen forest**: The dominant trees are *Dipterocarpus* spp., *Hopea ferrea, Artocarpus lakoohca, Amoora polystachya, Tetramedles nudiflora, Vitex glabata, Lagerstroemia speciosa* etc.

e) **Secondary growth forest or shifting cultivation areas**: This forest type occurs as a result of the destruction of forest by shifting cultivators for growing agricultural crops. This forest type is extensively composed of grasses and small trees. Bamboo is sparsely found throughout the areas.

As mentioned above, the Mae Klong river basin is similar in forest types. Therefore, based on the previous study as well as the field investigation, the following 11 categories were selected for classifving satellite images.

a) Mixed deciduous forest. **b) Dry dipterocarp forest.** **c) Dry evergreen forest.**

d) Disturbed forest. These are based on Suksawang's forest type classification.

e) Unclassified forest. This type can not be classified in the above categories.

f) Agricultural land, including bare land.

g) Urban land. **h) Fish or shrimp ponds.** **i) Water surface.**

j) Cloud. **k) Shadow.**

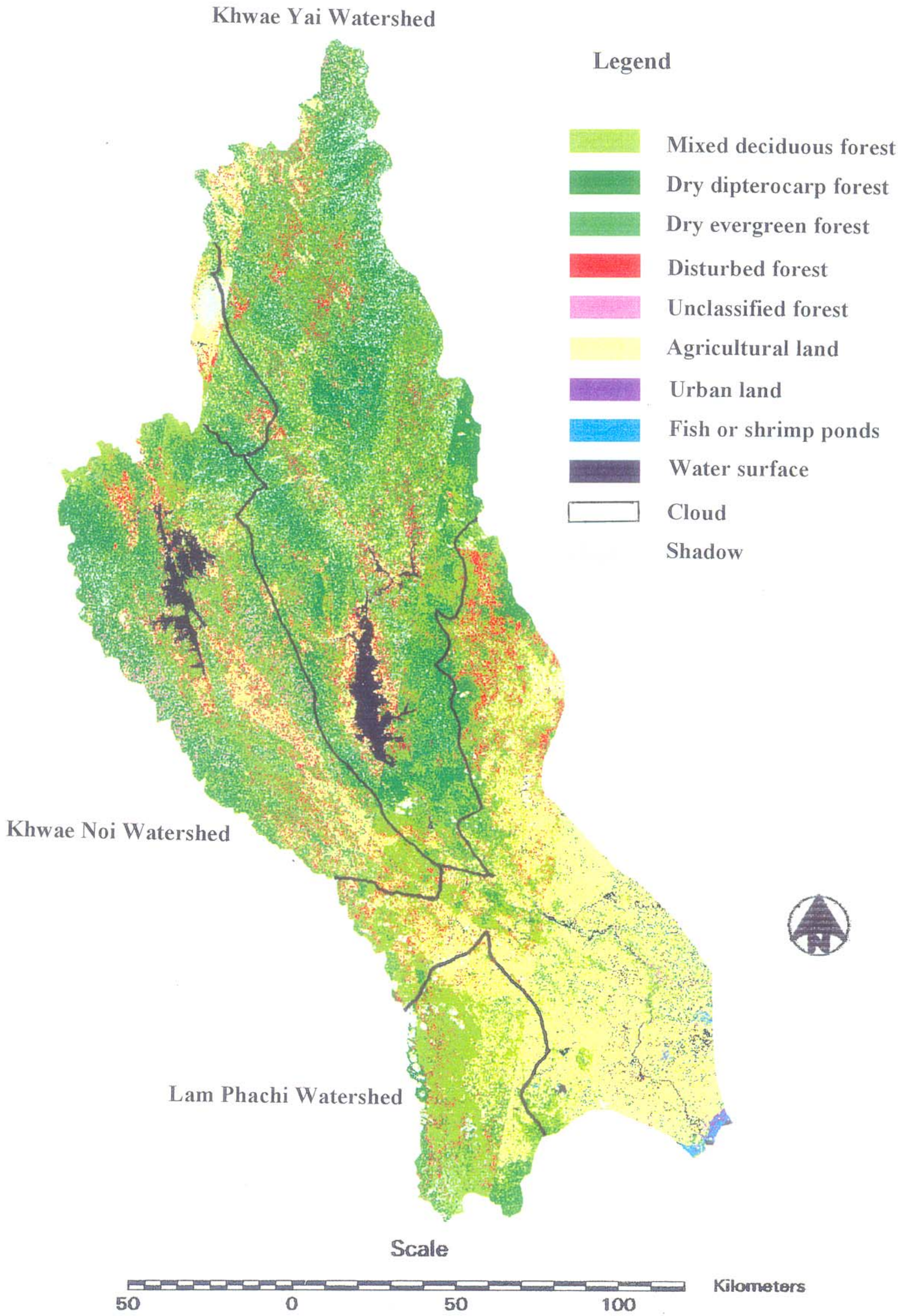


Fig. 4 Classified composite of the Mae Klong river basin.

4.1.4 Interpretation

First, an unsupervised analysis was performed for the scene of 130/276. The 40 clusters classified by this analysis, were then integrated into the 11 categories based on visual interpretation using information about the false color image and ground truth data together because there is abundant information about ground truth and forest types in this scene. Second, other scenes were also classified into 11 categories in the same way as scene 130/276. Finally, a classified composite covering all the Mae Klong river basin was obtained by digital mosaicking and geometric correction in the same way as mentioned in paragraph 4.1.1. The area of each category for the whole basin and each watershed can be calculated by a computer-aided method using the classified composite because the coordinates were defined on the composite by means of geometric correction.

4.2 Land cover and forest type classification

Figure 4 shows a classified composite covering the whole basin, and Table 4 presents the area of each forest type and land cover as well as their ratio to the basin area from 1994 to 1996 as estimated using remotely sensed data. As shown in Table 4, the forest land ratio to the whole basin area is about 65% and the agricultural land ratio, 25% in 1994 to 1996. Upland areas of the basin, therefore, are mostly covered with forest mainly composed of mixed deciduous forest and dry dipterocarp forest (Tables 4 and 5).

Table 4 Area of each forest type and land cover and its ratio to the basin area from 1994 to 1996 estimated using remotely sensed data.

Categories	Mae Klong Area (km)	Ratio (%)	Khwae Noi Area (km)	Ratio (%)	Khwae Yai Area (km)	Ratio (%)	Lam Phachi Area (km)	Ratio (%)
Mixed deciduous forest	11,484	37.2	3,041	42.5	4,651	38.7	1,216	44.7
Dry dipterocarp forest	5,299	17.2	1,417	19.8	3,329	27.7	82	3.0
Dry evergreen forest	1,847	6.0	370	5.2	925	7.7	160	5.9
Disturbed forest	1,340	4.3	411	5.7	520	4.3	63	2.3
Unclassified forest	212	0.7	164	2.3	48	0.4	0	0.0
Sub total	20,182	65.4	5,403	75.5	9,473	78.9	1,521	55.9
Agricultural land	7,553	24.5	943	13.2	992	8.3	1,017	37.4
Urban land	64	0.2	0	0.0	0	0.0	1	0.0
Fish or shrimp pond	205	0.7	0	0.0	0	0.0	1	0.0
Water surface	783	2.5	332	4.6	370	3.1	2	0.1
Cloud	193	0.6	33	0.5	27	0.2	70	2.6
Shadow	1,893	6.1	449	6.3	1,148	9.6	108	4.0
Total	30,873	100.0	7,160	100.0	12,010	100.0	2,720	100.0

It should be noted that the disturbed forest, which is often caused by shifting cultivation, is mostly along the roads and in the gentle slope adjacent to agricultural land, though its area is quite small. This means that easy access to the areas results in the disturbed forest. However, soil erosion due to the disturbed forest does not seem to be so severe because the shifting cultivation of this area was practiced in traditional way as we observed in the field investigation of November 1997 and September 1998. It also should be noted that the forest land ratio of the Mae Klong river basin has remained stable at 62-65% during the last few decades (Tables 4 and 6) in spite of the fact that the ratio for all Thailand decreased rapidly from 43.2% in 1973 to 26% in 1993 (RFD, 1994).

With regard to land cover and forest types, the Khwae Noi watershed is similar to the Khwae Yai watershed in the forest land and agricultural land ratios to the whole basin area. For the Khwae Noi watershed, these figures are 76%forest land ratio and 13%agricultural land ratio; for the Khwae Yai watershed, 79%forest land ratio, and 8%agricultural land ratio. In contrast, the Lam Phachi watershed has a 56%forest land ratio and a 37%agricultural land ratio.

Thus the Lam Phachi watershed is covered with less forest than the Khwae Noi and Khwae Yai watersheds and has a considerably larger agricultural land ratio. As for forest types, the Lam Phachi watershed is highest (80%) in the ratio of mixed deciduous forest to forest land area and smallest (5%) in the dry dipterocarp forest (Table 5).

Table 5 Ratio of each forest type to forest land area from 1994 to 1996 estimated using remotely sensed data.

Categories	Mae Klong Ratio (%)	Khwae Noi Ratio (%)	Khwae Yai Ratio (%)	Lam Phachi Ratio (%)
Mixed deciduous forest	56.9	56.3	49.1	79.9
Dry dipterocarp forest	26.3	26.2	35.1	5.4
Dry evergreen forest	9.2	6.8	9.8	10.5
Disturbed forest	6.6	7.6	5.5	4.1
Unclassified forest	1.1	3.0	0.5	0.0

Table 6 Land use at the beginning of the 1970s estimated using the land use map published in 1972 (after Maita *et al.*, 1998).

Land use types	Mae Klong Ratio (%)	Khwae Noi Ratio (%)	Khwae Yai Ratio (%)	Lam Phachi Ratio (%)
Forest	62	76	83	57
Field Crop and Forest	22	24	16	24
Paddy Field and Field Crop	5	0	0	0
Field Crop	1	0	1	0
Suger Cane	9	0	0	19
Fiber Crop, Banana, Pine apple	0	0	0	0
Orchard	1	0	0	0
Salt Pan, Shrimp and Fish Pond	1	0	0	0
Total	100	100	100	100

5. SUSPENDED SEDIMENT YIELD AND RELATIONSHIPS WITH FOREST TYPE AND LAND COVER

5.1 Relationship between the exponent of the specific suspended sediment yield equation and forest cover

A specific suspended sediment yield is defined as the annual suspended sediment yield per unit area (km^2). In general, forest cover decreases suspended sediment yield while cropland increases the yield (Fig. 5; Wark and Keller, 1963). Therefore, if upstream areas of a basin are almost covered with forest and downstream areas are dominated by agricultural land such as cropland, the exponent of the exponential equation relating specific suspended sediment yield and basin area must be positive because the agricultural land ratio of the basin increases with basin area. In contrast, if forest land of the upstream is converted to agricultural land and other land use, more sediment would be produced in the upstream areas than in the downstream areas. Because sediment production is more active in the headwater region that contains many steep slopes than in the downstream. The exponent, therefore, must be negative.

The exponent of the equation was estimated using regression analysis for the data of main basins in Thailand until 1998 and was found to be negative in some basins and positive in other basins. In order to examine the rational mentioned above more precisely, we analyzed the relationship between the exponent and the coverage ratio of remaining forest in 1988 (Tangtham, 1997) using data with a correlation coefficient 0.8 (almost $P<0.001$) (Table 7). We found that basins whose forest land ratio exceeds 40% have positive values, whereas basins whose ratio is less than 25% have negative values (Fig. 6). This appears, therefore, to be the strongest proof for interpretation of the exponent mentioned above. In addition, we should emphasize that soil erosion of a negative basin, which means the exponent is negative, is severe as compared with a positive basin, which means that the exponent is positive. Accordingly, the positive or negative state of the exponent could be a clue to consider where suspended sediment sources are in a basin and the severity of soil erosion as a whole.

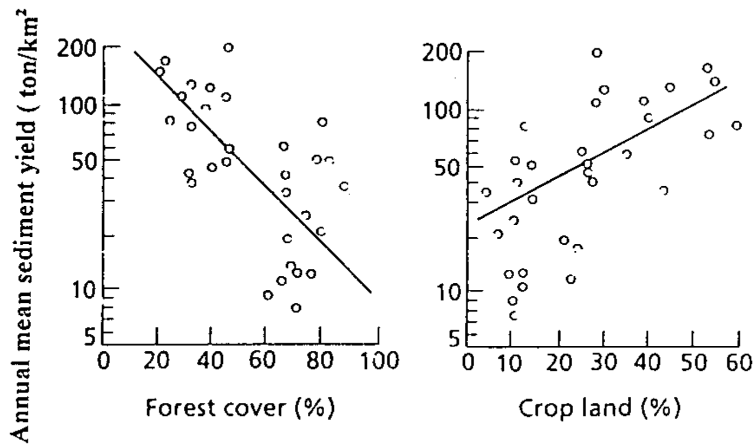


Fig. 5 Relationship between annual mean suspended sediment yield and land use established for catchments within the Potomac River basin by Wark and Keller (1963).

Table 7 Specific suspended sediment equations of main basins in Thailand.

Basin	Total Stations	Basin area (km^2)	Equation (S/A : specif. susp. sedi. yield; S : ann. susp. sedi. yield; A : basin area)	R
Mae Klong	22	67-26,441	$S/A = 21.61A^{0.223}$	0.949^{***}
Salawin	31	24-8,360	$S/A = 14.81A^{0.296}$	0.942^{***}
MeKong	44	12-419,000	$S/A = 20.20A^{0.198}$	.0.968^{***}
Kok	22	51-10,300	$S/A = 32.60A^{0.142}$	0.979^{***}
Chi	31	158-47,391	$S/A = 56.24A^{-0.011}$	0.904^{***}
Mun	35	61-117,000	$S/A = 79.72A^{-0.177}$	0.833^{***}
Ping	61	2-42,704	$S/A = 12.96A^{0.219}$	0.971^{***}
Nan	15	90-25,294	$S/A = 17.57A^{0.239}$	0.951^{***}
Pasak	8	67-14,522	$S/A = 2132A^{-0.425}$	0.804^{*}
Prachin Buri	11	45-7,502	$S/A = 60.83A^{-0.026}$	0.950^{***}
Bang Pa Kong	5	128-8,360	$S/A = 4955A^{-0.784}$	0.651
East Coast-Gulf	8	45-671	$S/A = 707.2A^{-0.322}$	0.599
Phetchaburi	4	264-2,207	$S/A = 2.203A^{0.589}$	0.925
Prachuapkhiri-khan Coast	5	93-2,370	$S/A = 7391A^{-0.785}$	0.308
Peninsula East Coast	24	11-1,638	$S/A = 30.97A^{0.146}$	0.823^{***}
Tapi	14	36-4,415	$S/A = 173.6A^{-0.086}$	0.898^{***}
Thale Sap Song Khla	8	14-1,562	$S/A = 181.6A^{-0.240}$	0.960^{***}
Peninsula West Coast	18	16-1,801	$S/A = 57.37A^{0.081}$	0.863^{***}

*** $P<0.001$ * $P<0.05$

Since the exponent of the exponential equation is positive in Mae Klong river basin, there seem to be many sediment sources in lowland areas downstream of where agricultural activity is significant. Obviously, in such a basin, it is important to conserve the soil of cultivated areas in lowlands to decrease sediment sources. Furthermore, it is necessary to properly manage the remaining forest in upland areas to prevent increasing sediment sources because the soils of steep slopes in the areas are susceptible to erosion when forest cover is removed.

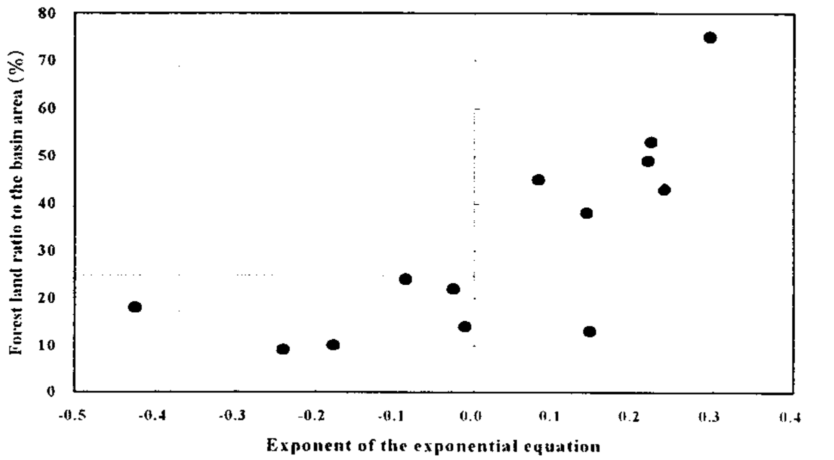


Fig. 6 Relationship between the exponent of exponential equation and forest land ratio in main basins of Thailand.

5.2 Suspended sediment yield and relationships with watershed characteristics, particularly land cover

Rainfall and land cover, particularly forest cover, directly affect soil erosion and sediment production as well as geology and topography, which determine basic watershed conditions for erosion. As shown in Table 8, the Khwae Noi watershed has the greatest mean specific suspended sediment yield, the Lam Phachi watershed, is smallest yield, and the Khae Yai watershed, a moderate yield, though their values are largely scattered. However, the amount of specific suspended sediment yield does not always correspond to the susceptibility to erosion since the susceptibility heavily depends on the amount of annual rainfall as well as basic watershed characteristics such as topography, geology, vegetation, and land use. A more sensitive index of susceptiblity to erosion is the annual suspended sediment côncentration because the concentration suggests turbidity to the same discharge. As is evident from Table 9, the Lam Phachi watershed has roughly twice the annual mean suspended sediment concentration as the Khwae Noi and Khwae Yai watersheds, though the concentration is also largely scattered. The difference of the mean concentration for the watersheds was tested statistically. The Lam Phachi watershed was found to differ from the Khwae Noi and the Khwae Yai watersheds in the mean concentration at a significance level of 0.05. The Khwae Noi watershed, however, does not differ from the Khwae Yai watershed at the same significance level. Therefore, the Lam Phachi watershed is more susceptible to erosion than the Khwae Noi and the Khwae Yai watersheds, which are similar in susceptibility to erosion.

As mentioned before (see section 2), the Lam Phachi watershed has the most finely divided network composed of short streams with steep slopes because it has the highest drainage density and frequency among the three watersheds. These topographic features might be related to igneous rocks characterizing the Lam Phachi watershed. In addition, it has the lowest forest land ratio but the highest agricultural land ratio. These conditions of the Lam Phachi watershed result in the highest susceptibility to erosion although its annual rainfall is lowest among the watersheds (Table 3). Therefore, when its annual rainfall is the same as the others, the Lam Phachi watershed may be more susceptible to erosion because rainfall is an important factor in soil erosion. However, we need the short-term rainfall data to prove this idea since rainfall intensity in a short period is more important for erosion than annual rainfall.

As for forest types, the Lam Phachi watershed has the highest (80%) ratio of mixed deciduous forest to the forest land area and the smallest (5%) ratio of dry dipterocarp forest (Table 5). However, it is now impossible to evaluate the difference of forest types with respect to soil erosion since there is not enough information about the effect of forest types on soil erosion.

Table 8 Annual mean suspended sediment yield, specific suspended yield and annual mean suspended sediment concentration in the Khwae Noi, Khwae Yai and Lam Phachi watersheds.

Watershed	Station code	Period (Fiscal year, Apr. to Mar.)	Basin area (km^2)	Annual mean susp. sedi. yield (ton)	Annual mean runoff (mcm)	Specif. susp. sedi. Yield ($ton/km^2/year$)	Annu. susp. sedi. conce. (ton/mcm)	Remark
Khwae Noi	140801	1969.71-74	2,570	1,101,550		429		3
	140802	1980	308	37,145		121		3
	141101	1973-1994	6,512	1,518,170	5,634	233	224	2
	K9	1963-1973	6,902	4,016,098	6,089	582	597	1
	K10	1965-1991	7,008	766,881	5,856	109	125	1
					Mean	254	244	
Khwae Yai	140603	1966-1971	5,530	389,772		70		3
	140604	1968-1972	351	73,806		210		3
	140903	1982	67	4,487		67		3
	140403	1979-86.88-91	4,960	615,578	3,007	124	187	2
	140201	1973-1978	5,644	912,795		162		2
	140601	1969-1975	10,500	1,870,306		178		2
	140703	1973-1974	11,352	1,759,922		155		2
	140702	1973-1976	14,037	2,580,189		184		2
	K6	1952-1972	10,001	1,792,826	4,560	179	351	1
	K20	1967-1975	11,184	1,330,359	4,452	119	281	1
	K27	1978-1985	1,921	31,717	125	17	190	1
					Mean	139	273	
Lam Phachi	K17	1978-1986	1,355	134,238	191	99	633	1
	K25	1991-1993	482	44,223	100	92	530	1
	K25A	1994-1995	250	13,367	46	53	179	1
					Mean	91	540	
Mae Klong					Mean	182	290	

mcm: million cubic meter

Remark: 1, Dtata from Royal Irrigation Department (RID)

2. Data from Electricity Generating Authority of Thailand (EGAT)

3. Data from Department of Energy Development and Promotion (DEDP)

Table 9 Annual mean suspended sediment concentration

Watershed	Mean (ton/MCM)	Stand. dev. (ton/MCM)	Range (ton/MCM)	Data
Mae Klong	290	210	17 – 1,006	116
Khwae Noi	244	211	39 - 1,006	53
Khwae Yai	273	159	62 - 768	50
Lam Pachi	540	222	14 - 790	13

mcm: million cubic meter

6. CONCLUSIONS

Forest situations from 1994 to 1996 in the Mae Klong river basin were investigated using remote sensing data. The forest land ratio to the whole basin area was found to be 65%, and the agricultural land ratio, 25%. Therefore, the upland areas of the basin are mostly covered with forest that is mainly composed of mixed deciduous forest (37% of the whole basin area) and dry dipterocarp forest (17% of the whole basin area). The forest land ratio of the Mae Klong river basin from the beginning of the 1970s to 1996 has remained stable at 62-65%, in spite of the fact that the ratio for all Thailand decreased rapidly from 43% in 1973 to 26% in 1993. This suggests that the Mae Klong river basin is one of the most precious areas protected from forest destruction in Thailand. As for recent forest situations of watersheds, the Lam Phachi watershed (forest land ratio 56%) is covered with less forest than the Khwae Noi (forest land ratio 76%) and Khwae Yai (forest land ratio 79%) watersheds. The ratio of each watershed is roughly the same as the ratio at the beginning of the 1970s. However, the recent agricultural land ratio of the Lam Phachi watershed (37%) is quite high compared with the Khwae Noi (13%) and the Khwae Yai (8%) watersheds. In regard to the recent forest types, the Lam Phachi watershed is highest (80%) in the ratio of mixed deciduous forest to the forest land area and smallest (5%) in dry dipterocarp forest . As mentioned above, the Lam Phachi watershed is substantially different from the Khwae Noi and Khwae Yai watersheds in forest situations and agricultural activities.

The following tendency was confirmed by analyzing relationship in main basins of Thailand between the exponent of the equation and the forest land ratio. On the one hand, if upstream areas of a basin are almost covered with forest and downstream areas are dominated by agricultural land, the exponent seems to be positive because the agricultural land ratio of the basin increases with basin area. On the other hand, if the forest land upstream is converted to agricultural land and other land use, more sediment would be produced in upstream areas than in downstream areas because sediment production is more active in the headwater region that contains many steep slopes than in the downstream. The exponent in this case, therefore, seems to be negative. Consequently, the sign (positive or negative) of the exponent could be a clue to consider where suspended sediment sources are in a basin and the severity of soil erosion as a whole.

The Lam Phachi watershed has the lowest forest land ratio but the highest agricultural land ratio as mentioned above. In addition, it has also the most finely divided network, composed of short streams with steep slopes, among the three watersheds. These conditions seem to cause that the Lam Phachi watershed has roughly twice the annual mean suspended sediment concentration (540 ton/mcm) as the Khwae Noi (244 ton/mcm) and the Khwae Yai (273 ton/mcm) watersheds. This means that Lam Phachi watershed result in the highest susceptibility to erosion although its annual rainfall is lowest among the watersheds. Therefore, if its annual rainfall is the same level as others, the Lam Phachi watershed may be more susceptible to erosion because rainfall is an important factor in soil erosion. However, we need short-term rainfall data to prove this idea since rainfall intensity in a short period is more important for erosion than annual rainfall.

Finally, this study clarified that the Mae Klong river basin has remained stable at 62-65% forest land ratio during the last two decades although the forest destruction has already occurred in most Thai basins. However, the Mae Klong river basin is not always free from soil erosion problems because agricultural activities of lowland areas may cause soil erosion. For example, the Lam Phachi watershed, whose agricultural land ratio is highest, is most susceptible to erosion among all watersheds in the basin. Therefore, from the viewpoint of soil erosion control in the Mae Klong river basin, it is necessary to protect the remaining forest in upland areas to prevent increases of sediment sources and to conserve the soil of cultivated land in lowland areas to decrease sediment sources. We should practice proper watershed management in the Mae Klong river basin because it is one of the most precious areas protected from forest destruction in Thailand.

ACKNOWLEDGEMENTS

This study was supported by the Tien Lo Fund for International Academic Research, University of Tsukuba. We thank staffs of RID and RFD in Thailand for providing the hydrological and forest data, and also thank the National Space Development Agency and the Ministry of International Trade and Industry in Japan for providing the JERS-1 data. Without their assistance and collaboration, the study would not have been carried out.

REFERENCES

Asian Institute of Technology (1994): Study of potential development of water resources in the Mae Klong river basin. Final report submitted to the Office of National Economic and Social Development Board, Volume 2 - Main Report.

Hasegawa, H. (1998): The ABCs of Remote Sensing. Kokon-syoin. Tokyo, Japan. 138p.

Jantawat, S. (1985): An overview of soil erosion and sedimentation in Thailand. In: Soil erosion and conservation. Soil Cons. Soc. Am., p. 0-14.

Maita, H., Nagai, T., Vudhivanich, V., Kwanyuen, B., Ngernprasertsri, S., Tangtham, N., and Lorsirirat, K. (1998): Analysis of suspended sediment yield and watershed characteristics in Mae Klong river basin. Proc. of Workshop on Sustainable Development of Agricultural Infrastructure and Organizational Management of Chao Phraya and Mae Klong Basins. p.38-56.

Royal Forest Department (1994): Forestry Statistics of Thailand 1994. Data Center Information Office of RFD. 129p.

Songtam Suksawang (1995): Thong Phaphoom Study Site. Paper presented in 'International Workshop on the Changes of Tropical Forest Ecosystems by El Nino and Others.' 29p.

Tangtham, N. (1997): Erosion and sedimentation studies and management in Thailand. Proc. of International Symposium on Hydrology and Water Resources for Research and Development in Southeast Asia and Pacific, p.16-19, organized by UNESCO and NRCT.

Upper Khwae Yai Project (1980): Environmental and Ecological Investigation. Final Report, Volume II : Main Report, Electricity Generating Authority of Thailand.

Wark, J.W. and Keller, F.J. (1963): Preliminary Study of Sediment Sources and Transport in the Potomac River Basin. Interstate Commission on the Potomac River Basin. Edgewater. Maryland, USA.