แบบจำลองการเคลื่อนที่ของตะกอนแขวนลอยและตะกอนท้องน้ำที่ปนเปื้อนแคดเมียม ในห้วยแม่ตาว ประเทศไทย

นางสาววันวิสาข์ ธาราธรรมาธิกรณ์

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TRANSPORT MODELING OF CADMIUM CONTAMINATED
SUSPENDED SEDIMENT AND BED LOAD
IN MAE TAO CREEK, THAILAND

Miss Wunvisa Tharathammathigorn

A Thesis Submitted in Partial Fulfillment of the Requirements
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วันวิสาข์ ธาราธรรมาธิกรณ์ : แบบจำลองการเคลื่อนที่ของตะกอนแขวนลอยและตะกอนท้องน้ำที่ปนเปื้อนแคดมียมในห้วยแม่ตาว ประเทศไทย . (TRANSPORT MODELING OF CADMIUM CONTAMINETED SUSPENDED SEDIMENT AND BED LOAD IN MAE TAO CREEK, THAILAND) อ. ที่ปรึกษาวิทยานิพนธ์หลัก : อ.ดร. พิเชฐ ชัยวิวัฒน์วรกุล, 108 หน้า.

งานวิจัยนี้เป็นการศึกษาการเคลื่อนที่ของแคดเมียม โดยตะกอนท้องน้ำ และตะกอนแขวนลอย ที่เกิดขึ้นในช่วงฤดูฝนและฤดูแล้ง ในห้วยแม่ตาว อำเภอแม่สอด จังหวัดตาก ตะกอน ได้แก่ ตะกอนท้องน้ำ และตะกอนแขวนลอยเป็นเป็นตัวการสำคัญในการเคลื่อนที่ของแคดเมียมที่ปนเปื้อนในห้วยแม่ตาว

ความเข้มข้นของแคดเมียมในตะกอนท้องน้ำและตะกอนแขวนลอยและขนาดของ ตะกอนท้องน้ำ ของ 10 สถานีตรวจวัดตลอดห้วยแม่ตาวได้ถูกสำรวจทั้งในฤดูฝน และฤดูแล้ง แบบจำลอง MIKE 11 ถูกนำมาใช้คำนวณน้ำท่าจากปริมาณน้ำฝน คำนวณการเคลื่อนที่แบบ 1 มิติในลำน้ำและคำนวณการเคลื่อนที่ของตะกอน จากการพัดพาของน้ำ เพราะมีความเหมาะสมกับพื้นที่ศึกษา ทั้งนี้ได้ใช้ข้อมูล ระดับน้ำที่บันทึกรายวันในช่วงเดือนพฤษภาคม 2553 ถึงกุมภาพันธ์ 2554 ในการปรับเทียบแบบจำลอง ชลศาสตร์ของลำห้วย ความน่าเชื่อถือของผลจากแบบจำลองการไหลถูกประเมินโดยใช้ค่าสัมประสิทธิ์สหสัมพันธ์ (the correlation coefficient) และรากที่สองของความคลาดเคลื่อนเฉลี่ย กำลังสอง (Root Mean Square Error) จากการคำนวณค่าทั้งสองมีค่ากับ 0.85 และ 0.06 เมตรตามลำดับ ผลที่ได้จากโปรแกรมชลศาสตร์ถูกใช้เป็นข้อมูลสำหรับโปรแกรมการเคลื่อนที่ของตะกอนเพื่อหาอัตราการเคลื่อนที่ของตะกอนท้องน้ำและตะกอนแขวนลอย สุดท้ายได้นำผลการเคลื่อนที่ของตะกอนและความเข้มข้นของแคดเมียมที่ตรวจวัดมาประเมินการเคลื่อนที่ของแคดเมียมโดยตะกอน

ผลการศึกษาพบว่าที่บริเวณท้ายน้ำ ของลำห้วยนั้น การ เคลื่อนที่ ของตะกอนท้องน้ำ โดยรวม ที่เกิดขึ้นในช่วง เดือนพฤษภาคม 2553 ถึงกุมภาพันธ์ 2554 มีค่าเท่ากับ 20.74 กิโลกรัม ทั้งนี้ การเคลื่อนที่ส่วนใหญ่เกิดขึ้นในช่วงฤดูฝน และตะกอนแขวนลอยถือเป็นกระบวนการสำคัญในการเคลื่อนที่ของแคดเมียมในห้วยแม่ตาว

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WUNVISA THARATHAMMATHIGORN: TRANSPORT MODELING OF CADMIUM CONTAMINETED SUSPENDED SEDIMENT AND BED LOAD IN MAE TAO CREEK, THAILAND.

ADVISOR: PICHET CHAIWIWATWORAKUL, Ph.D., 108 pp.

Mae Tao Creek, Mae sot district, Tak Province is contaminated with high cadmium levels. Stream sediment include bed load and suspended sediment are the main process of cadmium transport in Mae Tao Creek. This research was focused on cadmium transport via bed load and suspended sediment during the wet and dry seasons in Mae Tao Creek.

Cadmium concentration of bed load and suspended sediment and grain size distribution of bed load at 10 monitoring station along Mat Tao Creek were quantified in the wet and dry seasons. MIKE 11, suggested as an appropriate model for study area, was used to model the channel flow from amount of rainfall, one-dimensional transport in the creek, and calculate sediment transport by water flow. The time series of water depth from May 2010 to February 2011 were used to calibrate the channel flow. The reliability of hydrodynamic results was evaluated based on the correlation coefficient (CC) and root mean square error (RMSE). The CC and RMSE value obtained during this study are 0.85 and 0.06 meter respectively. The hydrodynamic results were inputted into the ST module to obtain the rate of bed load and suspended sediment transport. Finally, the sediment transport results and measured cadmium concentrations were calculated to estimate the cadmium transport in the area.

From the results, cadmium transport out of Mae Tao Creek during from May 2010 to February 2011 was approximately 20.74 kg. Moreover, the spread of cadmium contamination depended on creek discharge and mainly occurred during wet season. Moreover, suspended sediment was a dominant process of cadmium transport in Mae Tao Creek in both the wet and dry seasons.

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CHAPTER I
INTRODUCTION

1.1 Introduction

Sediment plays a significant role in the transportation of heavy metal pollutants through a river system. It can be used to assess the metal contamination in natural waters. This is because the sediment accumulated more heavy metals than the water. Sediment itself acts as a transporter and a possible source of pollution. Because of heavy metals are not permanently fixed to them. Sediment allows the metals to be released back into the water body whenever water chemical properties have changed, such as salinity, redox conditions, pH, organic chelators (Fürstner, 1985).

Cadmium was first discovered in 1817 as a by-product of zinc refining process in Germany (De Voogt, 1980). The mining wastes have not only been having adverse effects on the ecology but also human health. Heavy metals from ore processing and open-cast mine can be dispersed into the environment within a radius of 8 to 12 km. Moreover, irrigation water can take heavy metals to arable land up to several kilometers away (Kalandadze, 2003). In Thailand, the richest source of zinc is located in Mae Sot district, Tak province. Zinc mining has been in operation by several companies for more than 30 years (Simmons *et al.*, 2003). Since 1982, this area has been producing an average of 160,000 tons of zinc, which are supplied to various industries (Department of Primary Industry and Mines, 2006).

In Thailand, Mae Sot district was reported as the biggest source of zinc minerals and many mining activities were performed by several companies. (Unhalekhaka and Kositanont, 2008). Cadmium usually occurs in association with zinc ore and released as by-product of zinc mining. People have been faced with cadmium contamination in the agricultural system. Cadmium is not only found in soil surrounding the zinc mine areas but also detected in water and agricultural products (e.g., rice, garlic, and soybeans). Agricultural area, located within Phatat Pha Daeng sub-district, receives irrigation from Mae Tao Creek which passes through active mines. From extensive survey in 2001–2002, rice from this agricultural area contains cadmium concentrations from 0.05 to 7.7 mg of Cd per kg of rice. Over 90% of the rice grain samples collected had concentrations exceeding the Codex Committee on Food Additives and Contaminants (maximum level for cadmium in rice grain of 0.2 mg of Cd per kg of rice grain). From a public health perspective, an estimation of the weekly intake values ranged from 20 to 82 µg Cd per kg of body weight for rice consumption. Therefore, people in this area have confronted a significant health risk (Simmons *et al*., 2005). For this reason, in 2004, the Royal Thai Government declared prohibition of rice cultivation in this area and had to recompense for the local agriculturists about 100 million baht per year. Concurrently, the Ministry of Natural Resources and the Environment bought and destroyed 130 tons of cadmium-contaminated rice. At the same time, the mining companies agreed to provide a 1.1 million baht recompensation, even though there was no decisive evidence to indicating that the cadmium contamination came from mining activities.

As mentioned above, agricultural production in Mae Sot has been seemingly oppressed by cadmium contamination. Although the cadmium concentration is higher in soil than sediment, potential mobility of the soil is less. Mae Tao subcatchment was selected as the study area to demonstrate the processes that play significant role in transport of cadmium. This study will focus on temporal variation of hydrodynamic in order to assess the mobility of cadmium associated with the bed load and suspended sediment in Mae Tao Creek. A numerical model, MIKE 11, can simulate flow, water level and sediment transport in river (Andersen *et al*., 2006)

Therefore, MIKE 11 was used in this study to simulate the processes of cadmium contaminated transport. MIKE 11 is also capable to simulate the processes of bed sediment transport, which is expected to be the main mechanism of cadmium transport in the area.

1.2 Objectives of the study

- To demonstrate the cadmium contaminated sediment transport via bed load and suspended sediment in Mae Tao Creek, Mae Sot district, Tak province.

- To identify the processes that play significant role in the transport of cadmium in the study area.

1.3 Hypotheses

- The dominating transport process of cadmium contaminated sediment in Mae Tao Creek varies due to the dynamic change of hydrological characteristics.

1.4 Scope of study

- The study focuses on total cadmium accumulated in bed load and suspended sediment.

- Bed load and suspended sediment samples were collected from ten stations of field surveys and analyzed triplicate at the laboratory

- Bed load and suspended sediment samples were collected and analyzed two times to determine the effects of both the wet and dry seasons.

- Topography and metrological data were reviewed from the government sectors.

- Comparisons between the transport processes of bed load and suspended sediment were made to identify the most significant process of cadmium transport.

- The study use MIKE 11 model to simulate the hydrodynamic system and sediment transport in Mae Tao Creek.

- The model will be verified with the observed water depth that was record daily at station 1 and station 4.

1.5 Expected outcome

The accumulated cadmium transfer values due to sediment transport during both the wet and dry seasons are expected.

CHAPTER II
THEORETICAL BACKGROUNDS
AND LITERATURE REVIEWS

2.1 The study area

The study area is located in Mae Sot district, which contains zinc and the largest zinc mine of the country. It also has been agricultural producing area.

2.1.1 Location

Mae Sot district, Tak province, which located on the Thai-Myanmar border, is hidden in mountainous area. The study area is situated between 16° 42’47” N latitude and 98° 34’ 29” E longitude; it is approximately 11 km southeast of Mae Sot and about 500 km north of Bangkok. Mae Sot contains 10 sub-districts: Mae Sot, Mae Ku, Phawo, Mae Tao, Mae Kasa, Tha Sai Luat, Mahawan, Dan Mae La Mao and Phra That Pha Daeng. Mae Sot is characterized as a tropical savanna. There are three seasons: summer, from March to May; the rainy season, from June until October; and winter, from November through to February (Kaowichakorn, 2006).

2.1.2 Hydrology

Mae Sot can be divided into seven subcatchments, namely, Luang Creek, Pong Creek, Mae Tao Creek, Mae Ku Creek, Mae Ku Luang Creek, Phak La Creek and Mae Paen Creek, which are shown in Figure 2.1 Streams in the area are mostly running westwards to the low land areas and discharged into Mae Moei River (Kaowichakorn, 2006). The drainage in the study area is dendrite pattern, which is characterized by the distribution streams resembling the veins of a leaf. This agricultural area is customarily influenced by the floods occurring during the rainy season (Maneewong, 2005).

Mae Tao Creek, approximately 25 kilometers long, flows through and directly receives runoff from the zinc deposit. The sediment that discharges to hill slopes, foothills, and alluvial plains are eroded from country rocks and the soil cover of the hilly area including the areas where zinc is located. The alluvial plain, which contains many villages, is normally used for growing agriculture. The creek moves westward and supplies the Mae Moei River (Maneewong, 2005). At the same time, some mining activity areas of the Padaeng Industry Public Company Limited take part in the Mae Tao subcatchment area (Srisathit, 2004).

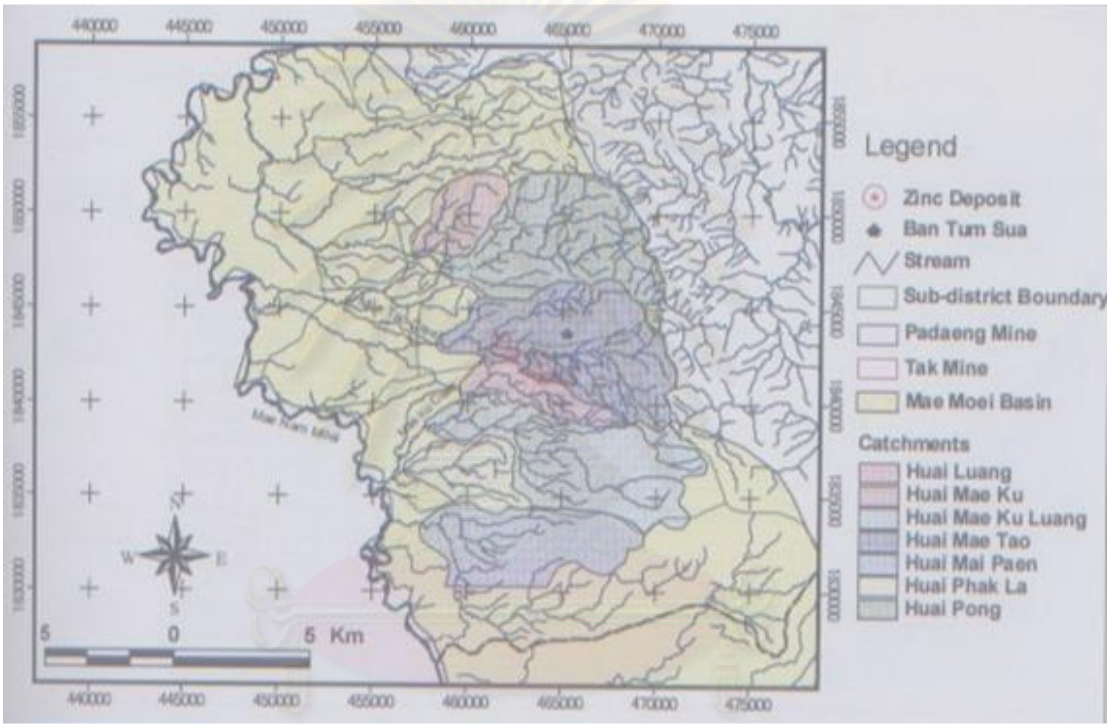


Figure 2-1 Seven sub-catchments belonging to Mae Moei Basin of Mae Sot area (Kaowichakorn, 2006)

2.2 Cadmium (Cd) and its environmental impacts

Cadmium is a soft, silvery-white, lustrous, but tarnishable metal with an oxidation state of +2. It has a melting point of 320.9 °C and boiling point of 765 °C and a relatively high vapor pressure Moreover, its environmental behavior resembles that of zinc, and it therefore occurs naturally in almost all zinc ores by isomorphous replacement. Cadmium is a relatively rare element, and generally present at an average concentration of about 0.15-0.2 mg/kg in the earth crust. It is a cumulative toxic element with a biological half-life in the human body of 16-33 years (WHO, 1982). Cadmium exists everywhere in nature (the air, water, soil, and foodstuff). It is not naturally found in its pure state but is usually present in association with other elements, such as oxygen, sulfur, or chlorine. The solubility of cadmium in water is influenced by the pH of the water: high acidity in water can be dissolved cadmium from sediment-bound (Ghinwa and Volesky, 2009).

Cadmium most generally present in small quantities associated with zinc, copper, and lead ores, such as greenockite (CdS) and sphalerite (ZnS), it is mainly gained as a by-product in treatment process of zinc copper and lead ores. Carbonaceous shales, formed under the reducing condition, are sedimentary rock types that normally contain high cadmium contents. Cadmium is used largely in rechargeable nickel-cadmium batteries, pigments, stabilizers in plastics, and protective plating for metals (Plachy, 2001).

The need to determine the cadmium levels in suspended matter and sediments in order to assess the degree of contamination of a water body has been identified. The concentration of cadmium in unpolluted fresh water is generally less than 0.001 mg/L; the concentration of cadmium in seawater averages about 0.00015 mg/L. (Ghinwa and Volesky, 2009). In general, cadmium is released into the environment about 25,000 tons per year. About half of this cadmium is released into the rivers by the weathering of rocks and some cadmium is released into air through forest fires and volcanoes. Additionally, the mining of zinc and lead ores, and manufacturing of phosphorus fertilizers have been the main sources of industrial cadmium emissions to the environment (Oliver *et al*., 1994). Sources of cadmium emission to soil are shown in Table 2-1.

Table 2-1 Sources of cadmium emission to soil (ICdA, 2010)

Categories	**Activities**
Inputs to agricultural soils	Atmospheric deposition
	Sewage sludge application
	Phosphate fertilizer application
Inputs to non-agricultural soils	Iron and steel industry
	Non-ferrous metals production
	Fossil fuel combustion
	Cement manufacture
Depositions in controlled landfill	Disposal of spent cadmium-containing products
	Non-cadmium containing products, which may contain cadmium impurities
	Naturally-occurring wastes

Cadmium in the environment is a great source of concern due to its toxic effects to animals and humans. Cadmium that accumulates in plants is not toxic to them, yet it is toxic to the animals eating the plants. It is especially harmful to humans because humans have longevity and it accumulates the organs (Tudoreanu and Phillips, 2004). The long-term consumption of cadmium in contaminated food may result in chronic and acute human cadmium diseases. The effects of accumulated cadmium intake can also manifest as high blood-pressure, liver disease, and nerve or brain damage. Symptoms of acute effects include pulmonary edema, headaches, nausea, vomiting, chills, weakness, and diarrhea (Nogawa and Kido, 1993). Chronic effect known as "Itai-Itai" in Japan is specifically associated with a form of osteomalacia, a proximal tubular renal dysfunction (Tohyama *et al*., 1982).

In Thailand, Hazardous Substances Acts, B.E. 2535 (1992) classified cadmium as the third category of hazardous substances. The owners of the hazard substances that are produced, imported, exported have to request for permit from The Department of Industrial Works. The standards of cadmium concentration in the environment are shown in Table 2-2

.

Table 2-2 Cadmium concentration in Water Quality Standards, Thai environmental regulations (PCD**,** 2009)

Surface Water Quality Standards	Standard of cadmium concentration (mg/m3)
Hardness ≤ 100 mg/L of CaCO3	5
Hardness > 100 mg/L of CaCO3	50
Coastal Water Quality Standards	5
Groundwater Quality Standards	3
Ground Water Quality Standards for Drinking Purposes	0-10
Drinking Water Quality Standards	0-10
Bottled Drinking Water Quality Standard	5
Appropriated Water Quality Criteria for Aquatic Living	1
Industrial Effluent Standards	30
Water Characteristics Discharged into Irrigation System	30
Water Characteristics Discharged into Deep Wells	100

2.3 Information on cadmium in Mae Sot district

The dominant agricultural products in Mae Tao are paddy rice and soybeans. The agricultural area of over 3000 hectares receives irrigation water from Mae Tao Creek, which passes through a zinc deposit zone (Simmons *et al*., 2009) (see Table2-3). Rice samples from household storage were detected. The average cadmium concentration in rice samples was 1.33 mg Cd/kg rice, which 91% of rice samples exceeded Codex Committee on Food Additives and Contaminants of 0.2 mg Cd/kg rice (Padungtod *et al*., 2006). The soil in the study area was found to contain cadmium concentrations in the range of 0.5 to 280 mg Cd /kg soil, while the normal Thai background concentrations are between 0.002 to 0.141 mg Cd /kg soil (Simmons *et al*., 2009). Thereby, the Thai Investigation Level for cadmium is 0.15 mg Cd /kg of soil (Zarcinas *et al*., 2004).

Table 2-3 Measured parameters of the contaminated area in Mae Sot (Simmons *et al.*, 2009)

Parameter	Measured values	Unit
Soil pH	5.4 to 7.68	-
Organic carbon remaining	1.86 ± 0.0168	%
Clay content	15.5 to 46.8	%
DTPA-extractable cadmium concentration	0.494 to 31.92	mg/kg

Department of Pollution Control reported a significant difference of cadmium concentration in sediments sampled along Mae Tao Creek (Table 2-4). The results showed that that cadmium contamination in Mae Tao Creek could be affected from zinc mining activity.

Table 2-4 Cadmium concentration found in sediment of Mae Sot district Mae Tao Creek by Department of Pollution Control (2004) (Padungtod *et al*., 2006).

Location along Mae Tao Creek	Cd concentration in sediment (mg Cd/Kg soil)
Tham Sue village (creek origin)	0.5
Zinc mining area	82 – 326
Small dam near Zinc mining area	80 – 104
Towards the end of creek	44 – 63

Maneewong (2005) found that bed load and suspended sediment from Mae Tao Creek contained the higher concentrations of cadmium than those of Mae Ku Creek and Nong Khieo Creek, as show in Table 2-5. In the study, cadmium and zinc in the water samples could not be detected by ICP, while the Department of Water Resource proved that the cadmium level in the water from the study area was lower than the standard level. The results revealed that cadmium and zinc in the study area were not in their soluble forms, due to the natural pH of the water is about 7.0-8.5. The soluble forms of cadmium decrease as a water pH increase.

Table 2-5 Average total concentrations of cadmium, zinc, and their ratios in bed load and suspended sediment from Mae Tao Creek, Mae Ku Creek, and Nong Khieo Creek (Maneewong, 2005)

Creek	Total Cd concentration (mg/kg)	Total Zn concentration (mg/kg)	Average ratio of Cd:Zn
Suspended sediment			
Mae Tao	18.27	7,767.14	0.0023
Mae Ku	7.75	7,722.99	0.001
Nong Khieo	6.32	6,232.97	0.1
Bed load			
Mae Tao	37.11±0.33	1,231.47±10.76	0.03
Mae Ku	7.99±0.01	316.55±3.66	0.025
Nong Khieo	5.67±0.10	63.08±0.84	0.9

Karoonmakphol and Chaiwiwatworakul (2010) measured cadmium concentration in bed load from Mae Tao Creek. Cadmium concentration at station 5, 9 and 10, represents cadmium at upstream part of Mae Tao left, Mae Tao right, Mae Tao Creek (main) respectively, indicated that cadmium cloud exist naturally in very low concentration. However, the concentration at station 6 and 4 signified that cadmium concentration increase through the zinc mine area. Station1, located downstream of the Mae Tao subcatchmant, has the highest cadmium concentration (see Table 2-6).

Furthermore, from the 7,697 persons surveyed in Mae Sot, 54.4% had urinary cadmium levels > 2 μg/g creatinine, which 4.9% were between 5 and 10 μg/g creatinine and 2.3% were > 10 μg/g. In persons without excessive exposure to cadmium, urinary cadmium excretion is usually < 2 μg/g creatinine (Department of Health and Human Services, 1999). Consequently, people may face possible renal damage and urinary calculus caused by their consumption of cadmium contaminated rice and water over a long period of time (Swaddiwudhipong *et al*., 2007).

Table 2-6 Average total concentrations of cadmium bed load from Mae Tao Creek (Karoonmakphol, 2009)

Station	Northing (m)	Easting (m)	[Cadmium concentration in bed load (mg of cadmium per kg of sediment)
1	1843017	457998	33.93± 1.35
2	1843330	459400	13.34±0.74
3	1843034	461274	06.07±0.12
4	1843110	461376	28.79±9.46
5	1843286	461438	LD
6	1842870	462046	15.05±1.21
7	1842718	465638	01.12±0.04
8	1842750	466937	01.45±0.28
9	1842559	467228	01.35±0.39
10	1842736	467088	LD

*LD = lower than detection limit of the Flame atomic absorption spectroscopy

2.4 Model Selection

Hydrologic models represent actual hydrologic systems. They can be used to predict hydrologic responses and study the function and interaction among the various components (Brooks *et al*., 1991). The goal of hydrologic modeling are to estimate the distribution and movement of surface water, underground water, the water's quantity stored in the soil and in water system and their exchange. Changes in rates and quantities over time of the components can also be estimated (Dingman, 2002).

The suitable model was selected based on the following considerations: the required model outputs important to the project; the hydrologic processes that can estimate the desired outputs adequately; the available input data; and the price limitations as defined by the investment in the project (Cunderlik, 2003).

MIKE 11 is a fully dynamic, unsteady models, with highly accurate hydraulic modelling methods (Kamel, A.H., 2008). It can used as a tool for detail analysis, desige, management and operation for complex chanel system. MIKE 11 also provide a complete and effective desige environment forengineering water resource and planning application. For this reasons, MIKE 11 model was chosen to applied in this study.

2.5 MIKE 11 model

MIKE 11 is a commercial engineering software package developed at the Danish Hydraulic Institute (DHI). It can represent phenomena in a river system including weirs, gates, bridges, and culverts, as it contains basic modules for hydrodynamics, sediment transport, rainfall-runoff, advection-dispersion, and water quality.

MIKE 11 performs one-dimensional dynamic modeling. MIKE 11 sloved the Saint Venant equations (using kinematic, diffusive or fully dynamic, vertically integrated mass and momentum equations), which can be computed numerically between all grid points at specific time intervals for a given boundary condition. The hydrodynamic module (HD), which is the core of MIKE 11, employs an implicit, finite difference computation of unsteady flows in rivers. In MIKE 11, a network configuration depicts the rivers and floodplains as a system of interconnected branches. Water levels (h) and discharges (Q) are calculated at alternating points along the river branches as a function of time. It operates on basic information from the river and floodplain topography to include man-made features and boundary conditions (Kamel, A.H., 2008).

Figure 2-2 Channel section with computational grid (Kamel, A.H., 2008)

Due to the 'Saint Venant' equation which simulating the unsteady flows in branched and looped river networks. The solutions to the equations are based on the following assumptions

- The water is incompressible and homogeneous
- The slope at the bottom is small, thus the cosine of the angle it makes with the horizontal may be taken as 1
- The wave lengths are large compared to the water depth, assuming that the flow everywhere can be assumed to flow parallel to the bottom
- The flow is sub-critical occurs when the actual water depth is greater than critical depth. Subcritical flow is dominated by gravitational forces and behaves in a slow or stable way.

There are two main modules for simulating sediment transport in channel system including advection-dispersion module (AD), which is proper for cohesive sediment such as silts and clays, and Sediment transport module (ST), which is suitable for non- cohesive sediment such as gravels and sands.

2.6 Unified Soil Classification (USC) System

The Unified Soil Classification (USC) System is a soil classification system used in engineering and geology disciplines to describe the properties of a soil based on the laboratory results of the grain size particles, the amounts of the various sizes and the characteristics of the very fine grains. The Unified Soil Classification (USC) System is represented by a two-letter symbol made up of the letters as stated below: (ASTM D 2487)

Prefix:

- G = Gravel
- S = Sand
- M = Inorganic Silt
- C = Inorganic Clay
- O = Organic Silt or clay
- Pt = Peat

Suffix:

- W = Well Graded
- P = Poorly Graded
- M = Silt
- C = Clay
- H = High plasticity; Liquid Limit > 50%
- L = Low plasticity; Liquid Limit ≤ 50%

Table 2-7 Unified Soil Classification (USC) System (from ASTM D 2487)

Major Divisions			**Group Symbol**	**Typical Names**
Course-Grained Soils More than 50% retained on the No. 200 sieve	**Gravels** 50% or more of course fraction retained on the No. 4 sieve	Clean Gravels	GW	Well-graded gravels and gravel-sand mixtures, little or no fines
			GP	Poorly graded gravels and gravel-sand mixtures, little or no fines
		Gravels with Fines	GM	Silty gravels, gravel-sand-silt mixtures
			GC	Clayey gravels, gravel-sand-clay mixtures
	Sands 50% or more of course fraction passes the No. 4 sieve	Clean Sands	SW	Well-graded sands and gravelly sands, little or no fines
			SP	Poorly graded sands and gravelly sands, little or no fines
		Sands with Fines	SM	Silty sands, sand-silt mixtures
			SC	Clayey sands, sand-clay mixtures
Fine-Grained Soils More than 50% passes the No. 200 sieve	**Silts and Clays** Liquid Limit 50% or less		ML	Inorganic silts, very fine sands, rock four, silty or clayey fine sands
			CL	Inorganic clays of low to medium plasticity, gravelly/sandy/silty/lean clays
			OL	Organic silts and organic silty clays of low plasticity
	Silts and Clays Liquid Limit greater than 50%		MH	Inorganic silts, micaceous or diatomaceous fine sands or silts, elastic silts

		Group Symbol	Typical Names
		CH	Inorganic clays or high plasticity, fat clays
		OH	Organic clays of medium to high plasticity
Highly Organic Soils		PT	Peat, muck, and other highly organic soils

2.7 Literature Review

Cadmium

The problem on cadmium contamination in Mae Sot district, Tak province was studied by many researchers (Zarcinas *et al*., (2003), Maneewong (2005), Simmons *et al*., (2005), Unhalekhaka, and Kositanont (2008)). Zarcinas *et al*., (2003) determined that the concentrations ranged from 0.5 to 284 mg/kg soil for cadmium and 100 to 8,036 mg/kg soil for zinc. Rice grain sampled from 524 fields contained cadmium concentrations ranging from 0.05 to 7.7 mg/kg. Over 90% of the rice grain samples contained cadmium concentrations higher than 0.2 mg/kg, which is the proposed maximum permissible (MP) level for rice grain by the Codex Committee on Food Additives and Contaminants (CCFAC). The research was confirmed the presence of significant public health risks associated with Cadmium intake by the local communities. Simmons *et al*., (2005) found that high concentrations of cadmium and zinc accumulated in the rice grain and soil was associated with the irrigation supply to fields. The cadmium and zinc concentrations of the soil in the area exceeded the EU standard maximum permissible level. Maneewong (2005) collected 28 bed loads, 11 suspended sediments, and 11 water samples from Mae Tao Creek, Mae Ku Creek, and Nong Khieo Creek (the control site). The results revealed that cadmium and zinc in the study area were not in their soluble forms, due to the natural pH of the water is about 7.0-8.5. The study also reported that cadmium in bed load and suspended sediment from Mae Tao Creek contained mostly extractable forms. Therefore, the distribution of cadmium is occur via bed load and suspended sediment. Unhalekhaka, and Kositanont (2008) studied cadmium distribution in Mae Tao Left creek, Mae Tao creek, Mae Ku creek and Nong Khiao creek. The results recommend that cadmium source be at the upstream of Mae Tao creek (8.45 mg/kg soil) then causing the cadmium accumulation downstream (22.5 mg/kg soil).

MIKE 11 Model

Several studies have been conducted using the MIKE 11 model in different regions. Cheng, F. (2005) used MIKE 11 to study the short-term changes in channel geometry, bed level profile and their relations with the sediment transport after dam removal at St. John Dam, north central Ohio, USA. The researcher suggested that MIKE 11 predicts reliable in both hydrodynamic and sediment transport results. The hydrodynamic module simulated that water level in the reservoir continued to decrease at upstream and increased immediately at downstream after the removal. The hydrodynamic model also simulated the attenuation of the wave generated from the dam removal, which the peak of the flood wave was retarded. Moreover, the total of sediment distributed out from the reservoir after 10 months of removal was approximately 5×10^5 m^3. The bed level profile after dam removal shown that The bed level downstream of the dam showed a 20 cm aggradations at 1.8 km below the dam and bed level increase average of 10 cm increase from the dam to 2.1 km downstream. Bed level does not change at further downstream. In addition, sensitivity analysis was tested on sediment grain size of 0.5 mm and 1 mm using Engelund and Hasen's model. The results indicated the model was strongly dependent on sediment grain size, which the smaller grain size has higher capability to transport than the bigger size. Tarakemeh *et al.*, (2007) employed MIKE 11 to investigate the contaminant transport of Acid Rock Drainage on Dee River, Mount Morgan mine, Australia. Simulation was done with different weather condition to assessed management options to minimize the risk of uncontrolled discharge into natural waterways. Kamel (2008) developed MIKE 11 model to simulated flow in the Euphrates River in Iraq. Available data are cross-sections, flow and stage hydrograph in a time series format from field measurements. The study explained that the flow simulated by MIKE 11 gave credible results due to the stage hydrograph evaluated from MIKE 11 consistently matched with the observed stage hydrograph. Moreover, The MIKE 11 model was checked the accuracy by comparing with the Uday model, which was used for the same cross sections and period. The simulated of the shape of the hydrograph, peak flow can be interpreted the MIKE 11 model gives better results. Karoonmakphol and Chaiwiwatworakul (2010) evaluated the movement of cadmium contamination caused by bed sediment transport in Mae Tao creek, Mae Sot district, Thailand. The researchers implemented the MIKE SHE coupled with MIKE 11 for determining the water depth, water discharge and sediment transport for the year 2009. Bed load in Mae Tao Creek was classified using the grain size distribution method as composed primarily of sand-sized particles. The transport of bed load sediment was described by the Meyer-Peter and Muller model. The total sediment transport at the downstream area in 2009 was equal to 24.522 m^3, 99.77% occurred in wet season and 0.23% take place in dry season. The researchers also computed cadmium transport due to bed load transport in Mae Tao creek that was mainly occurs during storm events. Approximately 1.599 kg of cadmium was transport out from Mae Tao creek during 2009.

CHAPTER III

METHODOLOGY

3.1 Data collection

The data required for the MIKE 11 include river geometry, time series of water level and metrological data of the study area. The required data input was supplemented from filed observation and other secondary sources provided from government departments.

3.1.1 Topography

The plan of the Mae Tao creek network was abstracted from 1:50,000 digital data map which belong in the map sheet 4742III of series L7018, edition 1-RTSD (Figure B-1, Appendix B). Elevation in the study area ranges from 200 to 950 m as shown in Figure 3-1. The river geometry was defined by inserting the river cross-sections at ten stations of the Mae Tao Creek.

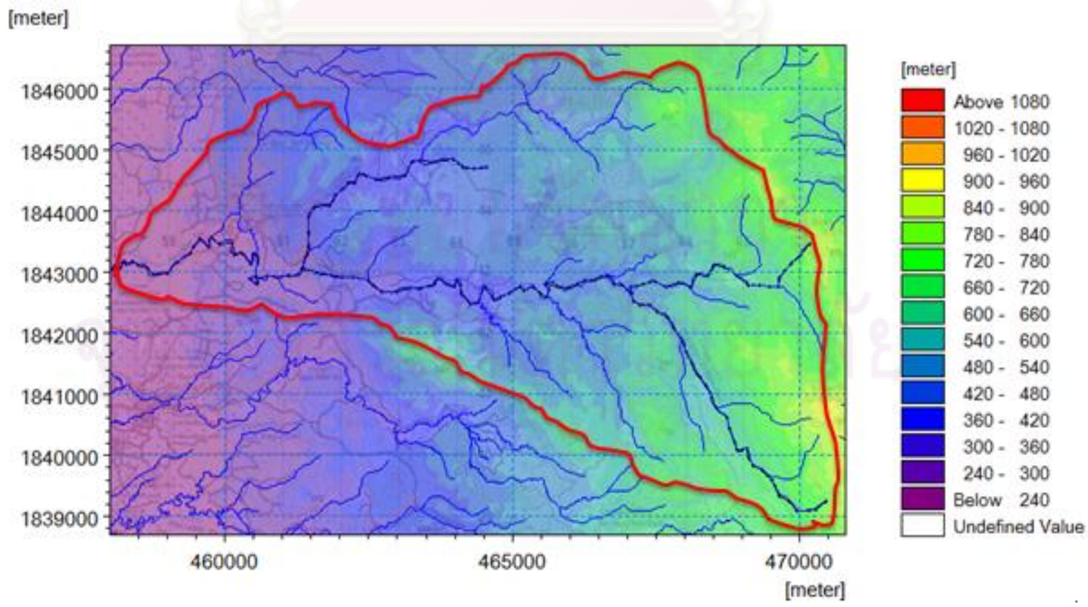


Figure 3-1 Topography of Mae Tao Creek area

3.1.2 Meteorological data

Evaporation and precipitation of Mae Tao watershed were obtained from Mae sot meteorological station, the Thai Meteorological Department (TMD). Mae sot meteorological station located at Tha Sai Luat Subdistrict, Mae sot District UTM Easting: 457098, UTM Northing: 1841791.

3.2 Filed observation

Ten sampling stations along Mae Tao Creek were designated to represent various anthropogenic uses of the creek water, particularly agricultural and mining uses. Figure 3-2 shows location of the selected stations along Mae Tao Creek. Station 1 is located at the downstream. Station 3 receives converged water from Station 4, which is located downstream from the second mine (abandoned mine), and Station 5, which receives water from Mae Tao Left. Station 6 is located between two zinc mines. Station 7 is located before entering zinc deposit area. Station 8 receives water from Station 9 and Station 10. Station 9 and Station 10 represented Mae Tao Right and upstream of the main Mae Tao creek respectively. The positions of each station are shown in Table 3-1.

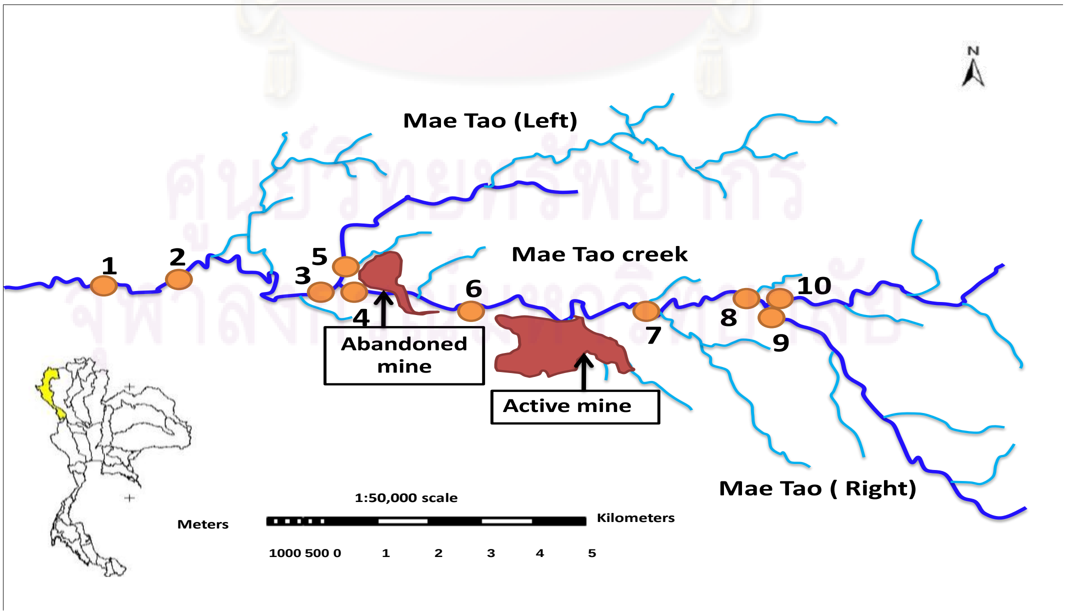


Figure 3-2 The 10 stations along Mae Tao Creek and the two zinc mines.

Table 3-1 Positions of the ten observation stations along Mae Tao Creek

Station	Easting	Northing
1	457998	1843017
2	459400	1843330
3	461274	1843034
4	461376	1843110
5	461438	1843286
6	462046	1842870
7	465638	1842718
8	466937	1842750
9	467228	1842559
10	467088	1842736

3.2.1 Sample collection

Two sample groups (bed load and suspended sediment) were collected for the investigation along Mae Tao Creek.

Bed load: Sample from the top layer (0-5 cm) of sediment was collected in a polyethylene container. Then, the water and sediment was mixed and allowed to drain so that as much of the water as possible was removed (Maneewong, 2005).

Suspended sediment: Two liters of water was collected at the center of the stream to represent the suspended sediment and water supplied throughout the area and all the stations. The top of polyethylene container was turn to upstream direction, the disturbance of bad load do not adulterate in the bottle. Then, the two liters of water was filter using a pre-weighed filter paper (GFC WATTMAN) combined with a vacuumed pump. The residue retained on the filter was placed in a Petri dish (Maneewong, 2005).

3.2.2 Flow measurement

The velocity-area method is the most common method for estimating stream flow. The velocity is the change from place to place along the stream; the stream flow becomes slower at the sides and bottom, and faster on the surface. In field measurements, accuracy is accomplished by measuring the mean velocity and flow cross-sectional area of many augmentations across a channel. This method consists of measuring both the area of the cross-section of the flow stream at a certain point (A) by dividing the area into many sections with constant intervals, and the average velocity of the flow in that cross-section (V). The flow rate is then calculated by multiplying the area of the flow by its average velocity. The wide interval (W) depends on the width of the cross section and surveying time as shown in the following figure.

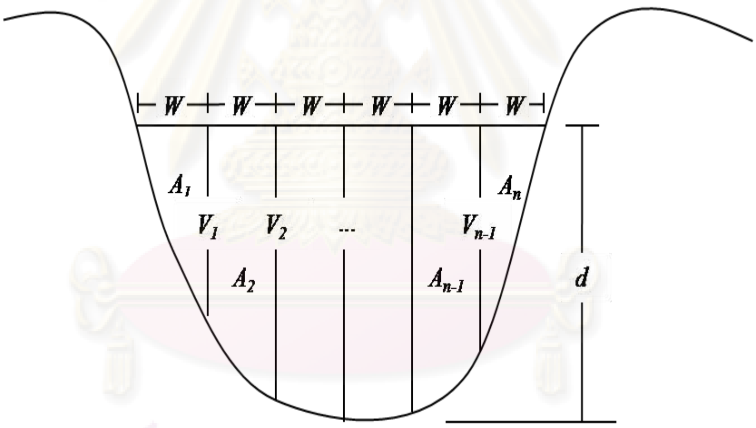


Figure 3-2 The area-velocity method

A) Instruments

The following instruments were used:

- Propeller type current meter
- Automatic leveler
- 3-4 m staff gauges
- Measuring tape
- Pegs

B) Methods

Velocity measurement

At each divided section of a cross-section, the water depth of each section was determined. Then, the measuring level and mean velocity equations based on the water depth at each measuring point was selected from Table 3-1. A propeller current meter was set at certain measuring levels to calculate the average velocity of each section. The amount and level for the velocity measurements will depend on the depth of the water at that section (see Table 3-2).

Table 3-2 The relationship between the depth of water, the velocity measuring level, and the mean velocity of the section. (Leewatchanakul, 1998)

Depth of water at each measuring point (m)	Measuring level from water surface (m)	Mean velocity in the section (m/s)	
< 0.60	0.6D	$V_{0.6D}$	(3.1)
0.60 – 1.00	0.2D and0.8D	$\frac{V_{0.2D}+V_{0.8D}}{2}$	(3.2)
3.05-6.10	0.2D, 0.6D and 0.8D	$\frac{V_{0.2D}+2V_{0.6D}+V_{0.8D}}{4}$	(3.3)
> 6.10	surface, 0.2D, 0.6D, 0.8D and bottom	$\frac{V_s+3V_{0.2D}+2V_{0.6D}+3V_{0.8D}+V_B}{10}$	(3.4)

D = flow depth (m)

V_B = water velocity at 0.3 m above bottom (m/s)

V_S = water velocity at 0.3 m below the surface (m/s)

$V_{0.2D}$ = Water velocity at 0.2 times the depth from water surface (m/s)

$V_{0.6D}$ = Water velocity at 0.6 times the depth from water surface (m/s)

$V_{0.8D}$ = Water velocity at 0.8 times the depth from water surface (m/s)

Cross section surveying method

For obtaining the physical data of the stream, cross-section surveying has been selected to be used for hydrological surveying. The cross-section area was used for stream changing analysis, hydraulic design, and the like.

Surveying of the cross sections will start at the known leveling point. The depth of cross section was measured at constant intervals of width for analyzing and plotting the cross-section area of each section before combining all cross-section areas. Thus, the flow rate and average velocity of the cross section was calculated by the following equations:

$$A = A_1+A_2+A_3+\ldots+A_i \tag{3.5}$$

$$Q = A_1V_1+A_2V_2+A_3V_3+\ldots+A_iV_i \tag{3.6}$$

$$V_{av} = \frac{Q}{A} \tag{3.7}$$

where

A	=	total cross-section area	(m^2)
Ai	=	area of section i	(m^2)
Vi	=	water velocity of section i	(m/s)
V_{av}	=	average velocity of the cross-section	(m/s)
Q	=	water discharge	(m^3/s)

3.2.3 Water depth

Water depth at Station 1 was used as downstream boundary condition, while another water depth data at Station 4 were used for model calibration.

A) Instruments

The following instruments were used:

- Vertical staff gauge
- Bench mark
- Tilting dumpy level
- Booking

B) Methods

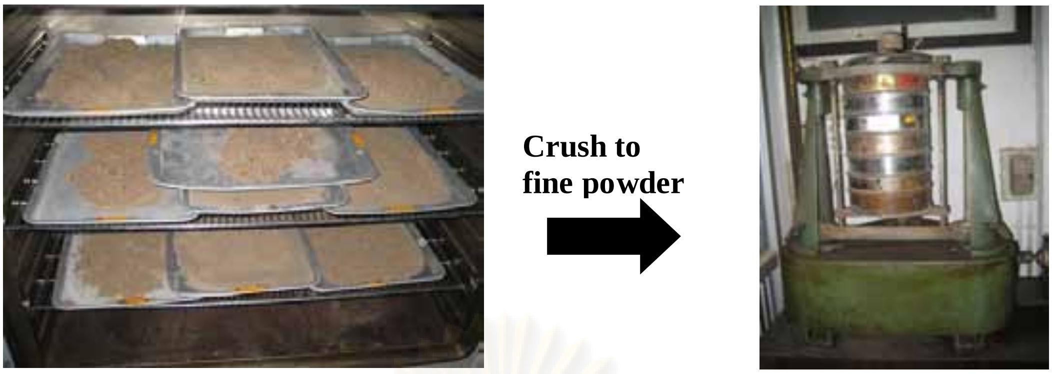
Staff gauge, which is a vertical graduated marker, established to visually estimate the water depth at Station 1 and Station 4. The water depth was daily record from these two Stations. At Station 1, record three times (8 a.m., 1 p.m., 5 p.m.). At Station 4, record two times (8 a.m., 5 p.m.)

Figure 3-3 Vertical staff gauges setup at Station 1 and Station 4

3.3 Filed measurement

3.3.1 Sample preparation

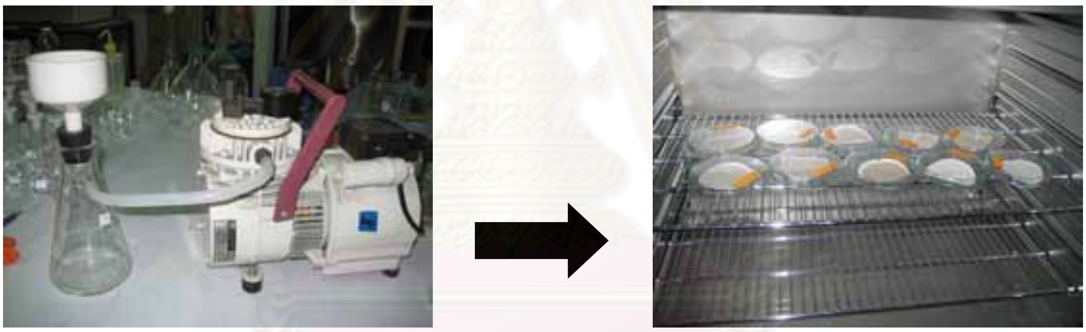
Bed load: Take the samples to the laboratory as soon as possible. Each sample was sets in a tray and dehydrates at 105 °C for 24 hours. After that, the samples are allowed to cool to room temperature. The dehydrated sediment is crush to a fine powder using a mortar and pestle before being analyzed.



Dry at 105 °C for 24 hours **Grain size distribution**

Figure 3-4 Sample preparation procedures for bed load

Suspended sediment: The residue retained on the filter dehydrates in an oven at 60 °C for 24 hours. After that, the suspended sediment was weighted.



2 liters of water filtered with filter paper and vacuum pump **Dry at 60 °C for 24 hours**

Figure 3-5 Sample preparation procedures for suspended sediment

3.3.2 Grain size distribution

The grain size distribution was determined following ASTM C136-06, the "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates" and ASTM D422-63, the "Standard Test Method for Particle-Size Analysis of Soils."

A) Instruments

- Sieves (No. 3/4”, 3/8”, 4, 10, 20, 35, 65, 100, 150 and 200)
- Automatic shaker
- Weighing apparatus
- Cleaning implements

B) Method

The sediment from each station was weight after being dehydrated and grinded up. Each selected sieve (No. 3/4”, 3/8”, 4, 10, 20, 35, 65, 100, 150, and 200) also weigh. The sieves, ranked by their mesh numbers, were placed onto the automatic shaker. The mesh was stack from smallest to largest; in other words, the smallest mesh (mesh no. 200) is at the bottom. The sample fills to the top of the sieve set and cover with the sieve lid. After allowing the shaker shake for around 30 min, each sieve and sediment sample was weigh. The total weight of the sediment after sieving must check by comparing it with the total weight of the sample before sieving. If the sediment loses more than 2% of its weight, the experiment was repeated because the disappearance of that much sediment would seem too high. If the sample passing sieve No. 200 is more than 10%, hydrometer analysis was preformed to acquire results that are more accurate.

C) Data Analysis

The retained weight of the sediment, percent passing, percent retained, cumulative percent retained, coefficient of uniformity and coefficient of curvature are calculate from the following equations:

$$\text{Cumulative Percent Retained} = \sum (\text{Percent Retained of all larger mesh sieve}) \quad (3.8)$$

$$\text{Percent passing} = 100\% - \text{Cumulative Percent Retained of that sieve mesh} \quad (3.9)$$

3.3.3 Soil Classification

Classifications of the sediment from each station use the Unified Soil Classification (USCS) method (ASTM D2487). Sieve No. 200 used as a tool for classify each sediment as coarse-grained soil or fine-grained soil. If the percent of the sample passing sieve No. 200 is less than 50%, the sample classified as having coarse-grained particles, such as gravel (G) or sand (S). If the percent of the sample passing sieve No. 200 is more than 50%, the sample classified as having fine-grained particles, for example, inorganic silt (M), inorganic clay (C), organic silt or clay (O), or peat (Pt). The coarse-grained particles classified by the coarse fraction (CF), which is the ratio defined by the following equation

$$CF= \frac{C}{F} = \frac{\text{\% coarser than 4-mesh sieve}}{\text{\% coarser than 200-mesh sieve}} \qquad (3.10)$$

If the CF is less than 50%, the sample was classified as sand (S), but if the CF is greater than 50%, the sample will classify as gravel (G)

The fine-grained were categorized using the plasticity chart shown in Figure 3-6, which is a plot of the plasticity index (PI) with regards to the liquid limit (LL). Meanwhile, the A-line was determined by the equation below.

$$PI = 0.73\ (LL-20) \qquad (3.11)$$

If the ratio between the LL and PI is under the A-line, the sample is classified as inorganic silt (M) or organic silt or clay (O). If the ratio between the LL and PI is above the A-line, the sample was classified as inorganic clay (C).

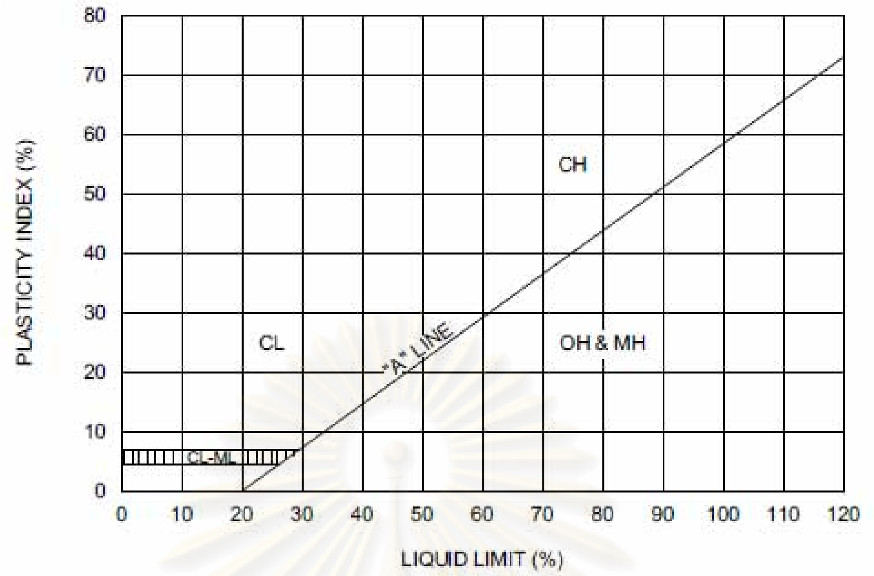


Figure 3-6 Plasticity chart and the A line (ASTM D 2487)

3.4 Total Digestion

3.4.1 Bed load (EPA method 3051):

A) Materials and Instruments

- Microwave Digestion system: Mileston Ethos SEL
- 65% Nitric acid
- Hydrochloric acid
- Standard cadmium concentration
- Deionized water
- Whatman disc filter paper No. 5
- PTFE vessels and covers
- FLAAS sample vessels
- Polyethylene bottles
- Sieve No. 65
- Weighing apparatus

- Flame atomic absorption spectroscopy (FLAAS)
- Glassware and others

  Note: All laboratory glassware and plasticware was first cleaned with deionized water and then with 10% nitric acid for at least 2 hours prior to being rinsed again with deionized water before use.

B) Methods

Digestion

The dehydrated sediment of each station is put through a sieved (65-mesh sieve). Around 0.5 g (±0.01 g) of sediment is place in each of the PTFE vessels along with 9 ml of 65% nitric acid and 3 ml of hydrochloric acid. The vessels are covered with Teflon covers. The vessels then place into a microwave system at 170 ±5 °C for 8 minutes, and remain at 170 °C for another 7 minutes, after which time they cooled down to room temperature. Each cooled sample filter using No. 5 Whatman disc filter paper into a volumetric flask. The filtered solution further dilutes to adjust the volume to 50 ml before place into a polyethylene bottle. The sample then ready to be analyzed by Flame Atomic Absorption Spectroscopy.

3.4.2 Suspended sediment (EPA method 3050B):

A) Materials and Instruments

- Hot plate
- 65% Nitric acid
- Hydrochloric acid
- 30% Hydrogen peroxide
- Standard cadmium concentration
- Deionized water
- Whatman disc filter paper No. 41
- GFAAS sample vessels

- Polyethylene bottles
- Weighing apparatus
- Graphite furnace atomic absorption spectrometry (GFAAS)
- Glassware and others

  Note: All laboratory glassware and plasticware was first cleaned with deionized water and then with 10% nitric acid for at least 2 hours prior to being rinsed again with deionized water before use.

B) Methods

Digestion

The filtered paper plus residual is weight. Then 10 ml of 1:1 nitric acid mix with the slurry and the sample cover with watch glass. Heat the sample to 95 ± 5 °C for 10 to 15 minutes without boiling. After the sample cools down, add 5 ml of the nitric acid concentration; then cover the sample and refluxes for 30 minutes. If brown fumes generate, indicating the oxidation of the sample by nitric acid, this step was repeated with the continual addition of 5 ml of the nitric acid concentration until no brown fumes generate. The solution allows to evaporate to approximately 5 ml without boiling or heat at 95 ± 5 °C without boiling for 2 hours. After allowing the sample to again cool, 2 ml of water and 3 ml of 30% hydrogen Peroxide mixed along with 1 ml of 30% Hydrogen peroxide at a warm temperature until the generated sample's appearance remained unchanged. Heat the sample until the volume reduces to about 5 ml or heat at 95±5 °C without boiling for 2 hours. Then, 10 ml of hydrochloric acid added and reflux at 95 ±5 °C for 15 minutes. Then, the digestate fill through Whatman No. 41 filter paper (or equivalent) and collect the filtrate in a 25 ml volumetric flask. Make to volume of 25 ml and the solution was analyzed by (GFAAS).

3.5 Cadmium distribution

To investigate the distribution of the cadmium concentration that accumulated in different size of bed load, bed load from wet season samples were sieved with sieve No. 65, 100, 150 and 200 (0.231- mm, 0.150- mm, 0.100- mm and 0.075-mm mesh openings respectively).

A) Instruments

- Sieves (No. 65, 100, 150 and 200)
- Automatic shaker
- Weighing apparatus
- Cleaning implements

B) Methods

The sieves were ranked from smallest to largest and placed onto the automatic shaker. The sample fills to the top of the sieve set and cover with the sieve lid and shake for around 30 min. Then, bed load samples that remain on each were digest follow EPA method 3051. Cadmium concentration were calculate by weighted average in which each quantity to be averaged is assigned a weight.

3.6 Sensitivity analysis

Parameters and processes that play significant role in hydrodynamic model were determined by sensitivity analysis. The methodology of sensitivity analysis followed Lenhart *et al.* (2002) method. Sensitivity index (I) was calculated to express the model parameter sensitivity as shown in Eq. (3.12). It is a ratio between relative changes of model output affected from change of model parameter.

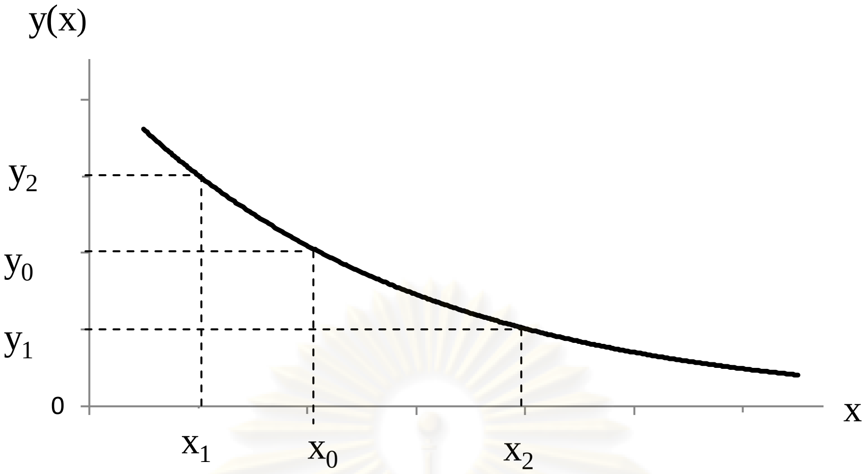


Figure 3-7 Representation of relative between output y and parameter x

$$I = \frac{(y_2 - y_1)/y_0}{2\Delta x/x_0} \tag{3.12}$$

$$x_1 = x_0 - \Delta x \tag{3.13}$$

$$x_2 = x_0 + \Delta x \tag{3.14}$$

Where	I	=	sensitivity index (dimensionless),
	x_0	=	initial value of parameter$x$,
	y_0	=	model output calculates with x_0,
	y_1	=	model output calculates with x_1, and
	y_2	=	model output calculates with x_2,

After sensitivity index of parameter was calculated, the parameter sensitivity was ranked into four classes as shown in Table 3-3.

Table 3-3 Sensitivity classes (Lenhart *et al.*, 2002)

Class	**Sensitivity index (I)**	**Sensitivity**
I	$0.00 \leq \lvert I\rvert < 0.05$	Small to negligible
II	$0.05 \leq \lvert I\rvert < 0.20$	Medium
III	$0.20 \leq \lvert I\rvert < 1.00$	High
IV	$\lvert I\rvert \geq 1.00$	Very high

In this research, the sensitivity of water discharge and velocity to changes in the parameters was analyzed. The parameters used (x) that were used for sensitivity analysis consists of;

- The bed resistance
- The surface and the root zone parameters
- The ground water parameters

The parameters affecting water discharge and velocity were studied. The Δx was assumed equal to 50 percentage of parameter x for every parameter except for the bed resistance. The bed resistance used x_1 equal to 0.025 and x_2 equal to 0.045, which is the minimum and maximum value of Manning's n values for small, natural streams (top width at flood stage < 30 m respectively (Chow, 1959). The output (y) are accumulated discharge and average velocity in August 2010 due to the highest precipitation occurred in this month for estimate the effect of parameters change to water discharge and velocity respectively.

Parameters used in the surface and the root zone are described below (DHI 2009b,c)

- **Maximum water content in surface storage (Umax).**

Represents the cumulative total water content of the interception storage (on vegetation), surface depression storage and storage in the uppermost layers (a few cm) of the soil. Moisture intercepted on the vegetation as well as water trapped in depressions and in the uppermost, cultivated part of the ground is represented as surface storage. Umax denotes the upper limit of the amount of water in the surface storage. The amount of water in the surface storage is continuously diminished by evaporative consumption as well as by horizontal leakage (interflow). When there is maximum surface storage, some of the excess water will enter the streams as overland flow, whereas the remainder is diverted as infiltration into the lower zone and groundwater storage. Typically, values are between 10 - 20 mm.

- **Maximum water content in root zone storage (Lmax)**

Represents the maximum soil moisture content in the root zone, which is available for transpiration by vegetation. The soil moisture in the root zone, a soil layer below the surface from which the vegetation can draw water for transpiration, is represented as lower zone storage. Lmax denotes the upper limit of the amount of water in this storage. Moisture in the lower zone storage is subject to consumptive loss from transpiration. The moisture content controls the amount of water that enters the groundwater storage as recharge and the interflow and overland flow components. Typically, values are between 50 – 300 mm.

- **Overland flow runoff coefficient (CQOF)**

Determines the division of excess rainfall between overland flow and infiltration. Values range between 0.0 and 1.0 When the surface storage spills, i.e. when U > Umax, the excess water gives rise to overland flow as well as to infiltration. Overland flow runoff denotes the part of the excess water that contributes to overland flow. It is assumed to be proportional to the excess water and to vary linearly with the relative soil moisture content, L/Lmax, of the lower zone storage.

$$QOF = \begin{cases} CQOF \frac{L/Lmax - TOF}{1 - TOF} Pn & \text{for } L/Lmax > TOF \\ 0 & \text{for } L/Lmax \leq TOF \end{cases} \tag{3.15}$$

where

QOF	=	the overland flow
CQOF	=	overland flow runoff coefficient ($0 \leq CQOF \leq 1$)
Pn	=	the excess water
TOF	=	the threshold value for overland flow ($0 \leq TOF \leq 1$)

- **Time constant for interflow (CKIF)**

Determines the amount of interflow, which decreases with larger time constants. Values in the range of 500-1000 hours are common. The interflow contribution, QIF, is assumed to be proportional to the moisture content and to vary linearly with the relative moisture content of the lower zone storage.

$$\mathrm{QIF} = \begin{cases} (\mathrm{CKIF})^{-1} \frac{\mathrm{L/Lmax} - \mathrm{TIF}}{1 - \mathrm{TIF}} \mathrm{U} & \text{for } \mathrm{L/Lmax} > \mathrm{TIF} \\ 0 & \text{for } \mathrm{L/Lmax} \leq \mathrm{TIF} \end{cases} \tag{3.16}$$

where

QIF	=	the interflow contribution
CKIF	=	the time constant for interflow
U	=	the moisture content
TIF	=	the root zone threshold value for interflow ($0 \leq \mathrm{TIF} \leq 1$)

- **Time constants for routing overland flow (CK1, 2)**

Determines the shape of hydrograph peaks. The routing takes place through two linear reservoirs (serial connected) with the same time constant (CK1=CK2). High, sharp peaks are simulated with small time constants, whereas low peaks, at a later time, are simulated with large values of these parameters. Values in the range of 3 – 48 hours are common. The interflow is routed through two linear reservoirs in series with the same time constant CK12. The overland flow routing is also based on the linear reservoir concept but with a variable time constant.

- **Root zone threshold value for inter flow (TIF)**

Determines the relative value of the moisture content in the root zone (L/Lmax) above which interflow is generated.

The Ground Water parameters are described below (DHI 2009b,c).

- **Root zone threshold value for ground water recharge (Tg)**

Determines the relative value of the moisture content in the root zone (L/Lmax) above which ground water recharge is generated. The main impact of increasing TG is less recharge to the ground water storage. Threshold value range between 0 and 70% of Lmax and the maximum value allowed is 0.99. The amount of infiltrating water G recharging the groundwater storage depends on the soil moisture content in the root zone

$$G=\begin{cases}(Pn\text{-}QOF)\,\frac{L/Lmax\text{-}TG}{1\text{-}TG}\,U & \text{for } \; L/Lmax > TG \\ 0 & \text{for } \; L/Lmax \le TG\end{cases} \tag{3.16}$$

where

G	=	the amount of infiltrating water
TG	=	the root zone threshold value for groundwater recharge ($0 \le TG \le 1$)

- **Time constant for routing base flow (CKBF)**

Can be determined from the hydrograph recession in dry periods. In rare cases, the shape of the measured recession changes to a slower recession after some time. To simulate this, a second groundwater reservoir may be included.

- **Specific yield for the ground water storage (Sy)**

Should be kept at the default value except for the special cases. This may be required in riparian areas, for example, where the outflow of ground water strongly influences the seasonal variation of the levels in the surrounding rivers. Simulation of ground water level variation requires values of the specific yield Sy and of the ground water outflow level GWLBF0, which may vary in time. The value of Sy depends on the soil type and may often be assessed from hydro-geological data, e.g. test pumping. Typically, values of 0.01-0.10 for clay and 0.10-0.30 for sand are used.

$$BF=\begin{cases}(GWLBF0\text{ -}GWL)\; Sy\; CKBF^{-1} & \text{for } \; GWL \le GWLBF0 \\ 0 & \text{for } \; GWL > GWLBF0\end{cases} \tag{3.17}$$

where

BF	=	base flow
GWL	=	the groundwater table depth

- **Maximum ground water depth causing base flow (GWLBF0)**

The parameter GWLBF0 can be interpreted as the distance between the average ground level of the catchment to the water level of the river. Due to the variation in the river water level throughout the year GWLBF0 can be given a significant

3.7 MIKE 11 (DHI,2009a, 2009b, 2009c)

Simulations divided into two steps. Firstly, the hydrodynamic in Mae Tao Creek was simulated using MIKE 11 hydrodynamic model. The model was calibrated with the observed water level. Secondly, the sediment transport module was utilized for simulating sediment transport results by inputting the hydrodynamic results.

1) Hydrodynamics module

There are two significant equation series in the hydrodynamics module, namely the continuity equation and momentum equation.

(A) Continuity equation

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{3.18}$$

where

A	=	cross-section area	(m^2)
Q	=	Discharge	(m^3/s)
q	=	Lateral inflow per unit width	(m^2/s)
x	=	distance	(ms)
t	=	time	(s)

The continuity equation at grid point j time step $n + \frac{1}{2}$

$$\frac{\partial A}{\partial t} \approx \frac{A_j^{n+1} - A_j^n}{\Delta t} \tag{3.19}$$

$$\frac{\partial Q}{\partial x} \approx \frac{\left(\frac{Q_{j+1}^{n+1} + Q_{j+1}^{n}}{2}\right) - \left(\frac{Q_{j-1}^{n+1} + Q_{j-1}^{n}}{2}\right)}{\Delta x_j + \Delta x_{j+1}} \tag{3.20}$$

where

Δt	=	time difference between time step n and $n+1$	(s)
Δx	=	distance between point j and $j-1$	(m)

(B) Momentum equation

$$\frac{\Delta M}{\Delta t} = \frac{\Delta(M \cdot U)}{\Delta x} + \frac{\Delta P}{\Delta x} - \frac{F_f}{\Delta x} + \frac{F_s}{\Delta x} \tag{3.21}$$

$\frac{\Delta M}{\Delta t}$	represents	Momentum	=	Mass per unit length · velocity
$\frac{\Delta(M \cdot U)}{\Delta x}$	represents	Momentum flux	=	Momentum · velocity
$\frac{\Delta P}{\Delta x}$	represents	Pressure force	=	Hydrostatic Pressure
$\frac{F_f}{\Delta x}$	represents	Friction force	=	Force due to bed resistance
$\frac{F_s}{\Delta x}$	represents	Gravity force	=	Contribution in x-direction

There are four main momentum equation selections: kinematic wave, diffusive wave, fully dynamic wave, and higher order fully dynamic wave.

- Kinematic wave

This option is suitable for steep rivers, while both backwater effects and tidal flows are not applicable. Thus, the momentum flux and pressure force terms are ignored.

$$\frac{\Delta M}{\Delta t} = -\frac{F_f}{\Delta x} + \frac{F_s}{\Delta x} \tag{3.22}$$

- Diffusive wave

This option is applied for relatively steady backwater effects and slowly propagating flood waves. However, tidal flows are not considered. Thus, the momentum flux term is ignored.

$$\frac{\Delta \mathrm{M}}{\Delta \mathrm{t}} = \frac{\Delta \mathrm{P}}{\Delta \mathrm{x}} - \frac{\mathrm{F_f}}{\Delta \mathrm{x}} + \frac{\mathrm{F_s}}{\Delta \mathrm{x}} \tag{3.23}$$

- Fully dynamic wave

This option suitable for fast transients, tidal flows, rapidly changing backwater effects, and flood waves.

$$\frac{\Delta M}{\Delta t} = \frac{\Delta (M \cdot U)}{\Delta x} + \frac{\Delta P}{\Delta x} - \frac{F_f}{\Delta x} + \frac{F_s}{\Delta x} \tag{3.24}$$

- Higher order fully dynamic wave

Finally, this option is very similar to the fully dynamic wave option but is more specific for steep channels.

$$\frac{\Delta M}{\Delta t} = \frac{\Delta (M \cdot U)}{\Delta x} + \frac{\Delta P}{\Delta x} - \frac{F_f}{\Delta x} + \frac{F_s}{\Delta x} \tag{3.25}$$

2) Sediment transport

The sediment transport module was added on, once the hydrodynamic model was calibrated.

(A) Sediment continuity equation

The major equation for erosion, deposition, and transport of the non-cohesive sediment module is the sediment continuity equation, which is used for predicting bed level changes.

$$\frac{\partial S}{\partial x} + (1-\varepsilon)w \cdot \frac{\partial z}{\partial t} = 0 \quad (3.26)$$

$$s = \left(q_b + q_s\right)w \quad (3.27)$$

where

S	=	sediment transport rate	(m^3/s)
t	=	time	(s)
w	=	channel width	(m)
x	=	longitudinal co-ordinate	(m)
z	=	bed level	(m)
ε	=	sediment porosity	(-)
q_b	=	bed load transport rate	(m^3/s)
q_s	=	suspended sediment transport rate	(m^3/s)

(B) Van Rijn model

In the van Rijn transport models, three modes of particle motion are distinguished: (1) rolling and/or sliding particle motion, (2) saltating or hopping particle motion, (3) suspended particle motion. According to the relative magnitudes of the bed shear velocity and the particle fall velocity. When the bed shear velocity exceeds the fall velocity then sediment is transported as both suspended and bed load. Bed load is considered to be transported by rolling and saltation and the rate is described as a function of saltation height. The suspended load is determined from the depth-integration of the product of the local concentration and flow velocity. The reference concentration is determined from the bed load transport.

Bed Load (Rijn, 1984a)

$$q_b = u_{bs}\delta_b c_b \tag{3.28}$$

where

q_b = bed load transport rate

u_{bs}, = the product of particle velocity

δ_b = saltation height

c_b = the bed load concentration

Expressions for the particle velocity and saltation height were obtained by numerically solving the equations of motion applied to a solitary particle. These expressions are given in terms of two dimensionless parameters which are considered to adequately describe bed load transport.

$$D_* = d_{50}\left[\frac{s-1}{v^2}g\right]^{\frac{1}{3}} \tag{3.29}$$

$$T = \frac{\left(u'_g\right)^2 - \left(u'_{f,cr}\right)^2}{\left(u'_{f,cr}\right)^2} \tag{3.30}$$

where

D_* = the dimensionless particle diameter

D_{50} = the diameter of which 50% are finer

u'_g = the bed shear velocity, related to grains

$u'_{f,cr}$ = Shields critical bed shear velocity

T = transport stage parameter

u'_g = defined so that the influence of bed forms is eliminated since form drag does not contribute to bed load transport given by:

$$u'_g = \frac{\sqrt{g}}{C'}u \tag{3.31}$$

where

u = the mean flow velocity

C' = Chezy's coefficient related to skin friction, expressed as:

$$C' = 10\log\left(\frac{R}{3d_{90}}\right) \tag{3.32}$$

where

R = the hydraulic radius (or resistance radius) related to the bed

$3d_{90}$ = considered to be the effective roughness height of the plane bed

The following expressions were determined for particle velocity and saltation height by applying the equations of motion to a solitary particle:

$$\frac{u_{bs}}{u'_f} = 9{+}2.6\log(D_*){-}8\,\frac{\theta_c}{\theta}^{0,5} \tag{3.33}$$

where

u_{bs} = the mean flow velocity

This expression was determined by expressing the computed particle velocity as a function of flow conditions and sediment size (D_*). A particle mobility, u_{bs}, was then defined as:

$$\frac{u_{bs}}{[(s-1)gd]^{0,5}} = 1.5T^{0,6} \tag{3.34}$$

An expression for the saltation height, δ_b, is given by:

$$\frac{\delta_b}{d} = 0.3D_*^{0,7}T^{0,5} \tag{3.35}$$

An expression for the bed load concentration, c_b, is obtained from a rearrangement of Equation (3.22):

$$c_b = \frac{q_b}{u_{bs}}\delta_b \tag{3.36}$$

Extensive analysis of flume measurements of bed load transport yielded the following expression for the bed load concentration:

$$\frac{c_b}{c_0} = 0.18\,\frac{T}{D_*} \tag{3.37}$$

where

c_0 = the maximum bed concentration.

Combining Equations (3.34), (3.35) and (3.36) gives the following expression for bed load transport:

$$\frac{q_b}{\sqrt{(s-1)gd_{50}^3}} = \frac{0{,}0537^{2{,}1}}{D_*^{0{,}3}} \tag{3.38}$$

or from Equation :

$$q_b = \frac{0{,}0537^{2{,}1}}{D_*^{0{,}3}} \tag{3.39}$$

This relationship is valid for particles in the range 0.2 to 2.0 mm.

Suspended load (Rijn, 1984b**)**

This method is based on the computation of a reference concentration determined from the bed load transport. Thus the reference concentration (c_a) is described as a function of the dimensionless particle diameter D_* and transport stage parameter T :

$$D_* = d_{50}\left[\frac{(s-1)g}{v^2}\right]^{\frac{1}{3}} \tag{3.40}$$

$$T = \frac{(u'_g)^2(u'_{f,cr})^2}{(u'_{f,cr})^2} \tag{3.41}$$

where

u'_g = the bed shear velocity related to the grains

$u'_{f,cr}$ = the critical bed shear velocity

The reference concentration is defined for a reference level (a) below which all sediment is considered to be transported as bed load. The reference level is approximated by:

$$a = 0.5H \tag{3.42}$$

where

H = the (known) bed form height

$$a = k \tag{3.43}$$

where

k = the equivalent sand roughness when the bed form dimensions are unknown or a minimum value of

$$a = 0.01D \tag{3.44}$$

where

D = water depth

The reference concentration is defined from :

$$q_b = c_b u_{bs} \delta_b = c_a u_a a \tag{3.45}$$

where

c_b = the bed concentration,

u_{bs} = the velocity of bed load particles

δ_b = the saltation height

u_a = the effective particle velocity at reference level a. It is expressed as:

u_a = αu_{bs}

From an examination of flume and field data, the best agreement between measured and computed concentration profile for all data was obtained for $\boldsymbol{\alpha_2}$ = 2.3 (Rijn, 1984b**)**. Combining this value with the expressions for δ_b and c_b (as functions of D_* and T) the following expression is obtained:

$$c_a = 0{,}0015 \frac{d_{50}}{a} \frac{T^{1.5}}{D_*^{0.3}} \tag{3.46}$$

The representative particle size of suspended load is generally finer than that of bed load. Van Rijn relates this particle size, d_s to the d_{50} and geometric standard deviation, σ_s, of the bed material:

$$\frac{d_s}{d_{50}} = 1 + 0{,}011(\sigma_s - 1)(T - 25) \text{ for } T < 25 \tag{3.47}$$

in which σ_s is given by:

$$\sigma_s = 0{,}5\left(\frac{d_{84}}{d_{50}} + \frac{d_{50}}{d_{16}}\right) \tag{3.48}$$

This d_s value is then used to calculate fall velocity according to equation:

$$w = \begin{cases} \frac{1}{18}\frac{(s-1)gd^2}{v} & for\ \ d < 0{,}1\, mm \\ \frac{10v}{d}\left\{\left[1 + \frac{0{,}01(s-1)gd^3}{v^2}\right]^{0{,}5} - 1\right\} & for\ \ 0{,}1\, mm \le d \le 1{,}0\, mm \\ 1{,}1[(s-1)gd]^{0{,}5} & for\ \ 1{,}0\, mm < d \end{cases} \tag{3.49}$$

The threshold for the initiation of suspension can be determined from the actual flow conditions. Using the overall bed shear stress u_f the criterion implemented in the van Rijn model becomes:

$$\frac{u_f}{w} = \frac{u}{d_s}, \text{for } 1 < d_s \le 10 \tag{3.50}$$

and

$$\frac{u_f}{w} = 0,4, \text{for } 10 < d_s \tag{3.51}$$

In describing the suspended load transport, van Rijn defines a suspension parameter Z which expresses the influence of the upward turbulent fluid forces and the downward gravitational forces. Z is defined as:

$$Z = \frac{w}{\beta \kappa u'_f} \tag{3.52}$$

where

u_f = the overall bed shear velocity

K = von Karman's constant

β = a coefficient related to the diffusion of sediment particles

An expression for β was derived as:

$$\beta = 1 + 2\left[\frac{w}{u'}\right]^2 \text{ for } 0,1 < \frac{w}{u'_f} < 1 \tag{3.53}$$

Many factors affect the suspension parameter *Z*, e.g. volume occupied by particles, reduction of fall velocity and damping of turbulence. These effects are grouped into a single correction factor *y*, which is used to define a modified suspension number *Z* as shown:

$$Z' = Z + \psi \tag{3.54}$$

ψ was found to be a function of the main hydraulic parameters:

$$\psi = 2,5\ \left[\frac{w}{u'_f}\right]^{0.8} \left[\frac{c_a}{c_0}\right]^{0.4} \tag{3.55}$$

where

c_0 = the maximum bed concentration (found to be 0.65)

The suspended load(q_s) is found as the integral of the current velocity (*u)* and the concentration of suspended sediment (c):

$$q_s = \int_a^D cudy \tag{3.56}$$

where

a = the thickness of the bed layer which can be approximated by 2 *d*

d = the grain diameter (mm)

D = the flow depth (m)

The current velocity u at a distance y above bed level is described by the logarithmic velocity profile:

$$u = 2{,}5u'_f ln\left(\frac{30y}{k}\right) \tag{3.57}$$

Where

u'_f = the friction velocity and the equivalent sand roughness

k = 2.5 d

The concentration is calculated in accordance with the concentration profile:

$$c = c_a\left(\frac{D-y}{y}\frac{a}{D-a}\right)^z \tag{3.58}$$

where

c = concentration of suspended sediment (at y above bed)

c_a = the concentration at the bed

D = depth of water (m)

y = distance from bed level (m)

Z = the Rouse number: $z = w/(0.4u'_f)$

w = the settling velocity of the suspended material

By combining the expression describing the velocity and concentration profiles (Equations (3.54) and (3.45)) with the expressions for Z and y (Equations (3.51) and (3.52)) van Rijn derived the following expression:

$$q_s = FuDc_a \tag{3.59}$$

in which F is given by:

$$F = \frac{\left[\frac{a}{D}\right]^{Z'} - \left[\frac{a}{D}\right]^{1.2}}{\left[1-\frac{a}{D}\right]^{Z'}[1{,}2-Z']} \tag{3.60}$$

(C) Additional equations

Relative density or specific gravity of sediment

$$\frac{\rho_{sediment}}{\rho_{water}} \tag{3.61}$$

where

$\rho_{sediment}$	=	density of sediment	$(\mathrm{kg/m^3})$
ρ_{water}	=	density of water	$(\mathrm{kg/m^3})$

3.8 Evaluation

The sediment transport data simulated from the models and cadmium concentration in the bed load and suspended sediment were calculated to evaluate cadmium transport rate in the stream sediment (mg/d) using the equation below.

$$\text{Cadmium transport rate} = [(S_{bd} \times \rho_{bd}) \times [Cd]_{bd}] + [(S_{ss} \times \rho_{ss}) \times [Cd]_{ss}] \tag{3.62}$$

where

S_{bd}	=	bed load transport rate	$(\mathrm{m^3/d})$
S_{ss}	=	suspended sediment transport rate	$(\mathrm{m^3/d})$
ρ_{ss}	=	density of suspended sediment	$(\mathrm{kg/m^3})$
ρ_{bd}	=	density of bed load	$(\mathrm{kg/m^3})$
$[Cd]_{bd}$	=	cadmium concentration in bed load	(mg/kg)
$[Cd]_{ss}$	=	cadmium concentration in suspended sediment	(mg/kg)

CHAPTER IV

RESULTS AND DISCUSSTION

4.1 Field observation results

4.1.1 Hydraulic conditions

The hydraulic conditions along Mae Tao Creek are presented in Table 4-1. The flow measurement results were computed using the area-velocity method, while the cross-section profile of each station is displayed in Figures A-1 to A-10, Appendix A.

From field observation, Mao Tao Creek were found two connection points as shown in Figure 3-2. First connection point was Station 8, which connect between Station 10 (main creek of Mae Tao) and Station 9 (Mae Tao Creek (Right)). Another point was Station 3, which connect between Station 4 (main creek of Mae Tao) and Station 5 (Mae Tao Creek (Left)). Mention for discharge balancing, water discharge at Station 8 was approximately equal to summation of water discharge from Station 9 and Station 10. Similarly, water discharge at Station 3 was proximately equal to the total discharge at Station 4 and Station 5. However, water flow at Station 5 does not occurred on the date of observation. The water discharge at Station 4 was lower than Station 6; this may have been cause by the supply of water for agricultural irrigation was take place between Station 6 and Station 4. The weather during the observation period was sunny with cloudy periods

Precipitation in the catchment varies substantially in terms of timing and amount. Most of the precipitation in the Mae Tao Basin generally occurs from May to October. During the simulation period (May 2010 to February 2011), the average daily precipitation value was 6.2 mm, and the maximum daily value of 104.8 mm was recorded on July 1st. Meanwhile, the average daily evaporation amount was 4.7 mm, and the maximum daily amount of 12.6 mm was record on July 2nd. Precipitation and evaporation rates from January 2010 to February 2011 are presented in Appendix C.

Table 4-1 Flow measurement results from the 10 stations

Station	Date surveyed	Water depth (m)	Channel width (m)	Cross-section (m^2)	Average velocity (m/s)	Water discharge (m^3/s)
1	5 April 10	0.200	6.40	0.81	0.169	0.137
2	5 April 10	0.250	8.60	1.42	0.151	0.215
3	6 April 10	0.400	8.15	1.77	0.089	0.157
4	6 April 10	0.300	7.10	2.01	0.084	0.168
5	6 April 10	-	-	-	-	0
6	7 April 10	0.750	9.20	4.72	0.072	0.341
7	6 April 10	0.200	7.70	0.62	0.466	0.289
8	6 April 10	0.250	3.80	0.59	0.439	0.256
9	6 April 10	0.200	3.10	0.61	0.203	0.124
10	6 April 10	0.300	3.10	0.73	0.184	0.134

Note: There was no flow at Station 5

4.1.2 Water quality results

The pH of water affects metal solubility: the higher the pH, the lower the metal solubility. The values of water pH at all of the stations were slightly alkali (pH = 7.86 to 8.35 in the dry season and 7.99 to 8.44 in the wet season). This type of condition enhances the present of insoluble form of cadmium, thus hindering its distribution throughout the body of water (Waite and Moral, 1984). The pH values of water samples from the ten stations in both the wet and the dry season are presented in Table 4-2.

Table 4-2 The water pH at each station in the study area

Station	pH Wet season	pH Dry season
1	8.27 ± 0.01	8.09 ± 0.00
2	7.99 ± 0.01	8.07 ± 0.00
3	8.31 ± 0.02	8.14 ± 0.04
4	8.44 ± 0.00	7.93 ± 0.02
5	8.02 ± 0.05	8.03 ± 0.04
6	8.34 ± 0.01	8.35 ± 0.00
7	8.26 ± 0.01	8.29 ± 0.00
8	8.24± 0.12	8.22 ± 0.00
9	8.32 ± 0.01	8.17 ± 0.01
10	8.24 ± 0.01	8.25 ± 0.01

4.2 Laboratory results

4.2.1 Total cadmium and zinc in the bed load

Ten bed load samples were collected from Mae Tao Creek during each of the two seasons. Then, these samples were prepared for total cadmium and zinc analyses based on EPA method 3051. Subsequently, all solution samples were measured by flame atomic absorption spectroscopy (FLAAS). Tables 4-3 and 4-4 show the analytical results from the dry and wet seasons respectively.

The average cadmium concentration in the bed load ranged from 0.90 to 38.83 mg of cadmium per kg of bed load in the dry season and 1.54 to 25.14 mg of cadmium per kg of bed load in the wet season. The average zinc concentrations in the bed load were ranged from 80.10 to 3,140.56 mg of zinc per kg of bed load in dry season and 24.62 to 2,694.03 mg of zinc per kg of bed load in wet season. The heavy metal distribution compared during the wet and dry seasons show a similar trend. Cadmium and zinc distribution increased after pass through the first mine, which made evident by concentration measured at Station 7 and Station 6. In addition, the cadmium concentrations continued to increase through to the second mine, which was revealed by the cadmium concentration in the bed loads of Station 6 and Station 4.

Table 4-3 The Cd and Zn concentrations in the bed load in April 2010 (dry season)

Dry season					
Station	**Total Cd concentration (mg of Cd per kg of sediment)**	**SD**	**Total Zn concentration (mg of Zn per kg of sediment)**	**SD**	**Cd/Zn Ratio**
1	28.51	± 4.35	821.11	±11.71	0.035
2	32.44	± 7.98	2,781.11	±50.74	0.012
3	38.83	± 4.10	3,140.56	±44.42	0.012
4	30.94	± 3.79	2,763.33	±46.93	0.011
5	3.19	± 0.06	164.83	±3.59	0.019
6	12.10	± 0.78	755.42	±30.23	0.016
7	1.19	± 0.08	91.89	±8.30	0.013
8	0.90	± 0.05	101.00	±11.88	0.009
9	1.24	± 0.07	84.10	±2.86	0.015
10	1.69	± 0.40	80.10	±5.63	0.021

Table 4-4 The Cd and Zn concentrations in the bed load in October 2010 (wet season)

Wet season					
Station	**Total Cd concentration (mg of Cd per kg of sediment)**	**SD**	**Total Zn concentration (mg of Zn per kg of sediment)**	**SD**	**Cd/Zn Ratio**
1	17.36	± 4.31	1,735.28	±111.78	0.010
2	18.29	± 3.42	1,335.31	±215.28	0.014
3	11.08	± 1.92	184.85	±12.42	0.060
4	25.14	± 5.33	2,694.03	±103.7	0.009
5	5.40	± 0.36	79.57	±6.01	0.068
6	13.76	± 1.41	1,332.68	±86.80	0.010
7	1.54	± 0.17	26.01	±3.35	0.059
8	1.54	± 0.08	24.62	±1.6	0.062
9	1.54	± 0.15	37.40	±2.66	0.041
10	1.55	± 0.06	52.60	±9.4	0.029

4.2.2 Total cadmium and zinc in suspended sediment

Suspended sediment was collected and filter from two liter of water, dry weight of suspended sediment collated in both wet and dry seasons are presented in Appendix C. The total cadmium and zinc concentrations in suspended sediment during the two seasons were measured using EPA method 3051B. Then, the solution samples were measured by graphite furnace atomic absorption spectrometry (GFAAS), as presented in Tables 4-5 to 4-6.

The total concentrations of cadmium in all suspended sediment samples ranged from 4.40 to 62.02 mg of cadmium per kg of suspended sediment in the dry season and 1.61 to 11.00 mg of cadmium per kg of suspended sediment in the rainy season. The average zinc concentrations in suspended sediment ranged from 250.56 to 2,049.38 mg of zinc per kg of suspended sediment in the dry season and 60.37 to 491.47 mg of zinc per kg of suspended sediment in the wet season. The concentrations of heavy metals are tented to decrease towards the western lowland and alluvial plain.

Table 4-5 The Cd and Zn concentrations in suspended sediment in April 2010 (dry season)

Dry season			
Station	**Total Cd concentration (mg of Cd per kg of sediment)***	**Total Zn concentration (mg of Zn per kg of sediment)***	**Cd/Zn Ratio**
1	27.18	663.14	0.041
2	36.25	987.50	0.037
3	61.67	1,359.38	0.045
4	26.49	306.72	0.086
5	25.05	717.76	0.035
6	62.02	2,049.38	0.030
7	4.40	297.61	0.015
8	5.88	367.98	0.016
9	16.14	1,041.04	0.016
10	5.09	250.56	0.020

*One sample collection

Table 4-6 The Cd and Zn concentrations in suspended sediment in October 2010 (wet season)

Wet season					
Station	**Total Cd concentration (mg of Cd per kg of sediment)**	**SD**	**Total Zn concentration (mg of Zn per kg of sediment)**	**SD**	**Cd/Zn Ratio**
1	10.47	±0.43	89.06	±8.95	0.118
2	11.00	±1.18	103.26	±15.15	0.107
3	6.26	±1.02	88.77	±12.17	0.071
4	7.17	±1.48	183.54	±63.32	0.039
5	1.61	±0.27	60.37	±23.20	0.027
6	9.46	±2.46	242.75	±139.42	0.039
7	2.30	±1.15	214.54	±121.67	0.011
8	3.22	±0.83	279.35	±98.86	0.012
9	4.57	±0.30	491.47	±54.72	0.009
10	1.93	±0.15	148.92	±66.31	0.013

Figures 4-1 and 4-2 show the distribution of total cadmium during the wet and dry seasons in the bed load and suspened sediment respectively. Stations were numbered from downstream to upstream. The samples from Station 6 are representive of the water between the two zinc mines: the samples from Station 4, water that has passed through two zinc mines; and the samples from Station 5, water received from Mae Tao Left.

Stations 1, 2, 3, 4, located downstream, receive water that passes through the zinc mining area, and their bed load contained lower cadmium concentrations in the wet season than dry season. Moreover, the different cadmium concentration between wet and dry season at Station 3 can explain by the high flow that occurs in wet season causing dilution from Station 5. In addition, at all sampling sites, except for the ones situated upstream of the two zinc mines, the total cadmium concentration was well beyond the UK Health Protection Agency soil and sediment standard of 2 mg/kg, at pH 7. Moreover, bed load sample at the Station 3 in the dry season also exceeded the Thai standard of 37 mg/kg (PDC, 2004). While, cadmium concentrations in the bed load samples collected from stations that located at upstream part of Mae Tao Creek was close to each other between the wet and dry seasons.

The cadmium concentrations in suspended sediment that was collected in dry season were greater than wet season at every station. In the dry season, the sediment comes from creek bank and only the area nearby the creek, which are highly contaminated with Cd. While, sediment in the wet season was characterized by a high input of alluvium from the large area of watershed, this diluted and therefore reduced cadmium concentration. This is made evidence by cadmium concentration at Station 3 in wet season, which receive suspended sediment that come from Station 5, contain cadmium concentration lower than in dry season.

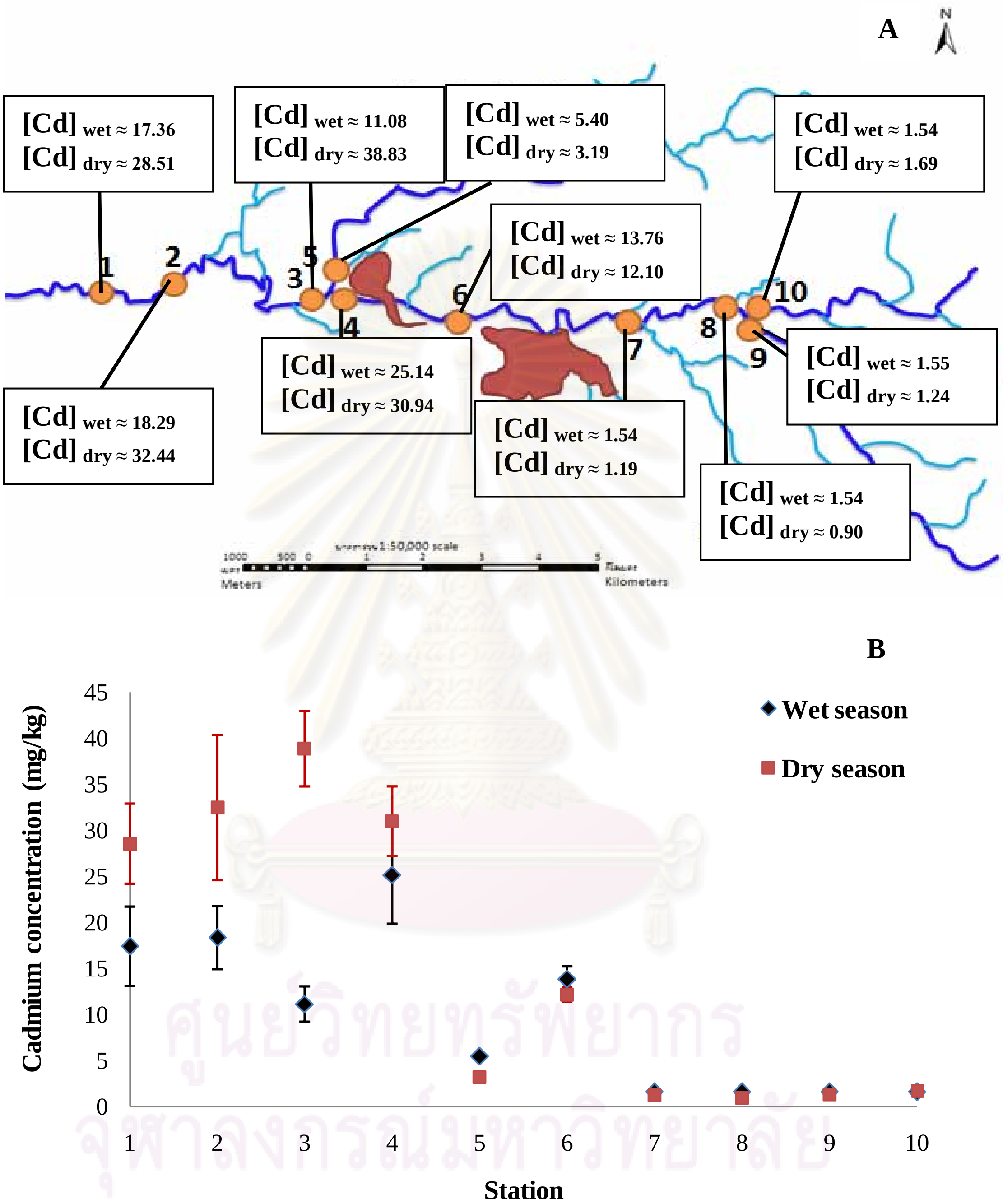
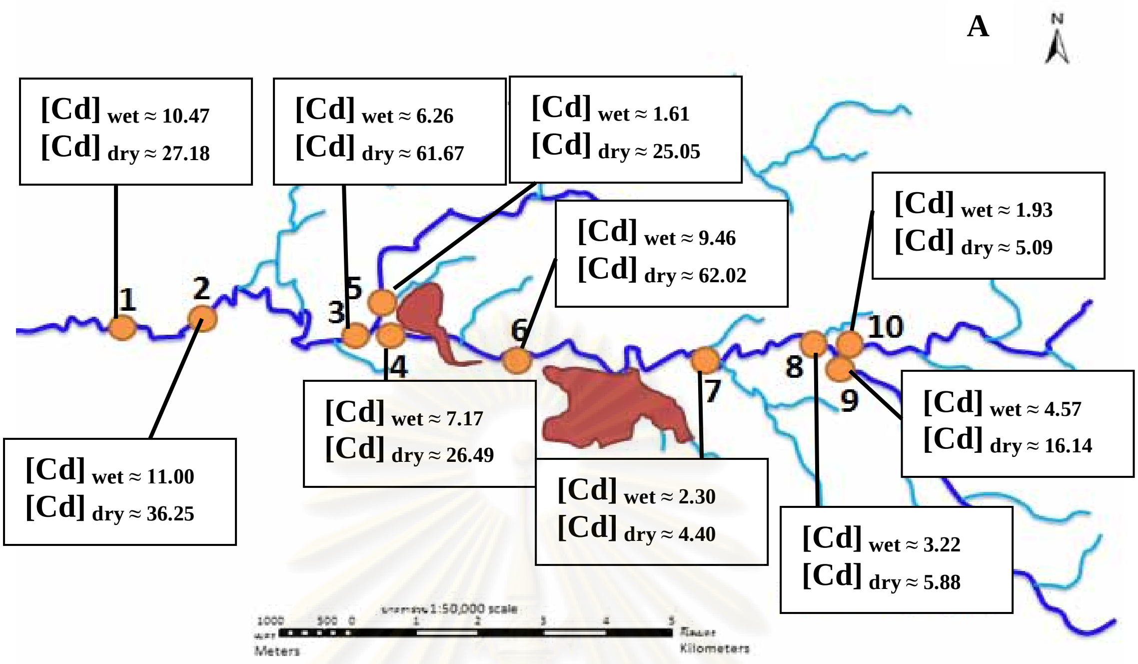


Figure 4-1 Cadmium concentration in bed load at each station in both wet and dry season (mg/kg)



B

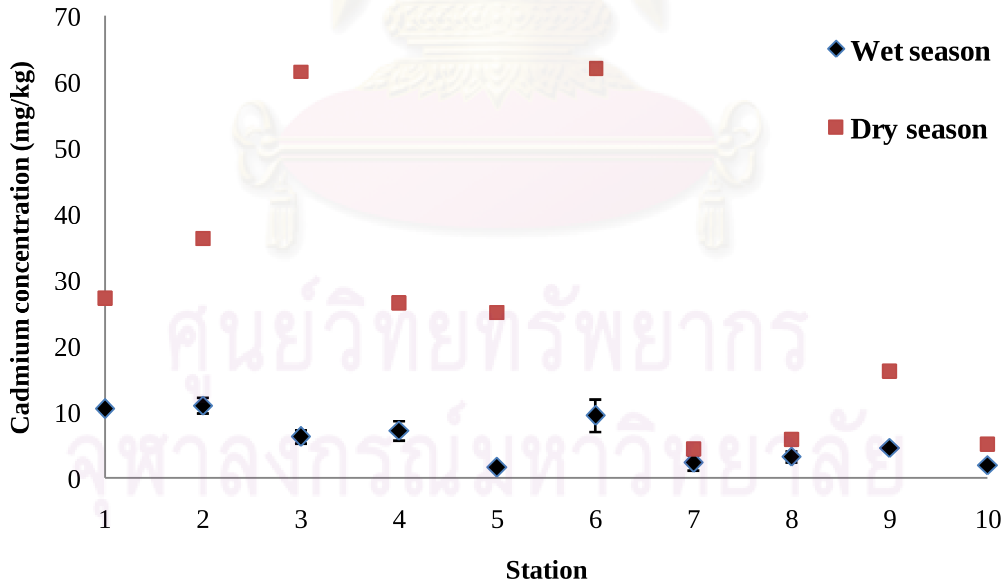


Figure 4-2 Cadmium concentration in suspended sediment at each station in both wet and dry season (mg/kg)

4.2.3 Grain size distribution

Grain size distribution was determined following ASTM C136-06 and ASTM D422-63. The mean diameter and standard deviation of the bed sediment during the dry and wet seasons at each station are respectively provided in Table 4-7 and Table 4-10.

The bed sediment capable of possible to passing through the 65-mesh sieve was used to measure the cadmium concentrations in bed sediment. This size of bed sediment was considered to the optimum size to adhere to hand (duggan *et al.*, 1985) and biggest size that can be digested. The mean diameter and standard deviation of the bed sediment that passed through a 65-mesh sieve at each station are listed in Table 4-8 (dry season) and Table 4-11 (wet season).

For sediment transport modeling, it is necessary to know the characteristics of the sediment in the creek. Therefore, bed load samples were analyzed in terms of the grain size distribution using the Unified Soil Classification method (USC). The percentage of bed load that passed through sieve No. 200 was lower than 50% at every station. Moreover, the coarse fraction (CF) was used to classify the type of bed load. The results show that the CF values were lower than 0.5 at every station. Thus, the bed sediment in the Mae Tao Creek could be categorized as sand during both the dry and wet seasons, as presented in Table 4-9 and Table 4-12 respectively.

Table 4-7 Grain-size distribution of sediment at each station (dry season)

Sieve	Mesh No.	Sieve Opening (mm)	Mean size (mm)	Weight of sediment (g)									
				Sta 1	**Sta 2**	**Sta 3**	**Sta 4**	**Sta 5**	**Sta 6**	**Sta 7**	**Sta 8**	**Sta 9**	**Sta 10**
Weight of sample before sieving				1015.19	815.55	1171.73	1136.2	791.61	922.68	791.12	823.55	682.23	897.75
1	3/4"	19.000	19.000	0.00	0.00	0.00	0.00	0.00	13.40	0.00	0.00	130.44	0.00
2	3/8"	9.500	14.250	58.94	7.88	90.68	140.56	19.95	11.19	71.19	111.72	96.27	0.00
3	#4	4.750	7.125	10.85	23.53	235.39	200.14	38.73	10.99	137.52	157.22	48.61	5.27
4	#10	2.000	3.375	110.27	47.16	191.19	159.06	159.43	18.22	152.45	138.31	51.46	22.60
5	#20	0.850	1.425	134.72	79.98	118.56	115.84	161.47	39.80	87.73	99.96	55.11	74.82
6	#35	0.500	0.675	97.55	151.09	90.70	76.79	57.93	95.28	73.33	106.74	62.98	170.14
7	#65	0.231	0.366	129.80	263.48	157.29	113.69	73.11	287.64	189.74	157.88	103.65	314.15
8	#100	0.150	0.191	106.65	130.67	72.84	82.50	55.43	173.19	47.06	29.57	44.08	116.52
9	#150	0.100	0.125	169.83	79.88	94.60	116.35	82.57	177.79	19.93	13.33	50.44	104.90
10	#200	0.075	0.088	10.49	3.98	9.33	10.61	11.56	9.22	1.21	0.02	4.21	7.57
Receiver		-	0.075	184.12	26.17	108.62	118.52	129.92	85.88	8.08	3.31	31.11	78.39
Total(g)				1013.22	813.82	1169.20	1134.06	790.10	922.60	788.24	818.06	678.36	894.36
Loss(g)				1.97	1.73	2.53	2.14	1.51	0.08	2.88	5.49	3.87	3.39
Loss (%)				0.19	0.21	0.22	0.19	0.19	0.01	0.36	0.67	0.57	0.38
% Passing Sieve No.200				18.14	3.21	9.27	10.43	16.41	9.31	1.02	0.40	4.56	8.73
Mean Diameter (mm)				1.63	0.97	3.37	3.76	1.80	0.91	3.51	4.23	6.70	0.55
S.D. (mm)				3.36	1.87	4.09	4.67	2.67	2.81	4.17	4.68	7.62	0.77

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Table 4-8 Grain-size of sediment that passed through a 65-mesh sieve at each station (dry season)

Sieve	Mesh No.	Sieve Opening (mm)	Mean size (mm)	Weight of sediment (g)									
				Sta 1	**Sta 2**	**Sta 3**	**Sta 4**	**Sta 5**	**Sta 6**	**Sta 7**	**Sta 8**	**Sta 9**	**Sta 10**
Weight of sample before sieving				1015.19	815.55	1171.73	1136.20	791.61	922.68	791.12	823.55	682.23	897.75
8	#100	0.150	0.191	106.65	130.67	72.84	82.50	55.43	173.19	47.06	29.57	44.08	116.52
9	#150	0.100	0.125	169.83	79.88	94.60	116.35	82.57	177.79	19.93	13.33	50.44	104.90
10	#200	0.075	0.088	10.49	3.98	9.33	10.61	11.56	9.22	1.21	0.02	4.21	7.57
Receiver		-	0.075	184.12	26.17	108.62	118.52	129.92	85.88	8.08	3.31	31.11	78.39
Mean Diameter (mm)				0.12	0.15	0.12	0.12	0.11	0.14	0.16	0.16	0.13	0.14
S.D. (mm)				0.04	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.05	0.05

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Table 4-9 Bed sediment classification of each station by USCS (dry season)

Sieve	Mesh No.	Sieve Opening (mm)	Mean size (mm)	Weight of sediment (g)									
				Sta 1	**Sta 2**	**Sta 3**	**Sta 4**	**Sta 5**	**Sta 6**	**Sta 7**	**Sta 8**	**Sta 9**	**Sta 10**
Weight of sample before sieving				1015.19	815.55	1171.73	1136.20	791.61	922.68	791.12	823.55	682.23	897.75
1	3/4"	19.000	19.000	0.00	0.00	0.00	0.00	0.00	13.40	0.00	0.00	130.44	0.00
2	3/8"	9.500	14.250	58.94	7.88	90.68	140.56	19.95	11.19	71.19	111.72	96.27	0.00
3	#4	4.750	7.125	10.85	23.53	235.39	200.14	38.73	10.99	137.52	157.22	48.61	5.27
4	#10	2.000	3.375	110.27	47.16	191.19	159.06	159.43	18.22	152.45	138.31	51.46	22.60
5	#20	0.850	1.425	134.72	79.98	118.56	115.84	161.47	39.80	87.73	99.96	55.11	74.82
6	#35	0.500	0.675	97.55	151.09	90.70	76.79	57.93	95.28	73.33	106.74	62.98	170.14
7	#65	0.231	0.366	129.80	263.48	157.29	113.69	73.11	287.64	189.74	157.88	103.65	314.15
8	#100	0.150	0.191	106.65	130.67	72.84	82.50	55.43	173.19	47.06	29.57	44.08	116.52
9	#150	0.100	0.125	169.83	79.88	94.60	116.35	82.57	177.79	19.93	13.33	50.44	104.90
10	#200	0.075	0.088	10.49	3.98	9.33	10.61	11.56	9.22	1.21	0.02	4.21	7.57
Receiver		-	0.075	184.12	26.17	108.62	118.52	129.92	85.88	8.08	3.31	31.11	78.39
Total(g)				1013.22	813.82	1169.20	1134.06	790.10	922.60	788.24	818.06	678.36	894.36
% Passing Sieve No.200				18.14	3.21	9.27	10.43	16.41	9.31	1.02	0.40	4.56	8.73
F = % Coarser than sieve No. 200				81.86	96.79	90.73	89.57	83.59	90.69	98.98	99.60	95.44	91.27
C = % Coarser than sieve No. 4				6.87	3.85	27.83	29.99	7.41	3.86	26.38	32.66	40.36	0.59
CF = Coarse Fraction				0.08	0.04	0.31	0.33	0.09	0.04	0.27	0.33	0.42	0.01
Stream sediment categorization				Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand

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Table 4-10 Grain-size of sediment that passed through a 65-mesh sieve at each station (wet season)

Sieve	Mesh No.	Sieve Opening (mm)	Mean size (mm)	Weight of sediment (g)									
				Sta 1	Sta 2	Sta 3	Sta 4	Sta 5	Sta 6	Sta 7	Sta 8	Sta 9	Sta 10
Weight of sample before sieving				1225.89	774.76	1721.77	1004.02	707.47	1231.77	2090.65	1274.68	1301.33	1561.05
8.00	#100	0.15	0.19	129.91	48.81	256.95	16.70	54.52	13.95	68.37	130.54	32.52	69.59
9.00	#150	0.10	0.13	78.33	152.18	341.16	16.00	70.73	10.33	33.02	62.03	14.86	70.29
10.00	#200	0.08	0.09	6.10	11.60	38.57	0.77	7.27	0.83	1.27	2.07	0.83	6.12
Receiver		-	0.08	39.69	72.17	167.54	8.17	61.56	11.81	6.70	10.67	4.98	21.90
Mean Diameter (mm)				0.15	0.12	0.13	0.14	0.13	0.13	0.16	0.16	0.16	0.14
S.D. (mm)				0.045	0.038	0.044	0.045	0.045	0.049	0.038	0.037	0.041	0.042

Table 4-11 Grain-size distribution of sediment at each station (wet season)

Sieve	Mesh No.	Sieve Opening (mm)	Mean size (mm)	Weight of sediment (g)									
				Sta 1	**Sta 2**	**Sta 3**	**Sta 4**	**Sta 5**	**Sta 6**	**Sta 7**	**Sta 8**	**Sta 9**	**Sta 10**
Weight of sample before sieving				1225.89	774.76	1721.77	1004.02	707.47	1231.77	2090.65	1274.68	1301.33	1561.05
1	3/4"	19.000	19.000	0.00	0.00	0.00	203.85	0.00	0.00	0.00	41.55	0.00	14.07
2	3/8"	9.500	14.250	33.52	0.00	0.00	302.25	0.00	9.62	0.00	44.60	34.66	139.27
3	#4	4.750	7.125	27.46	11.18	0.83	175.97	4.96	11.07	1.26	72.66	223.01	313.87
4	#10	2.000	3.375	29.97	34.99	36.66	108.67	41.73	85.80	26.00	64.06	382.20	316.62
5	#20	0.850	1.425	52.82	70.16	117.90	65.18	159.60	267.21	394.47	197.65	299.05	213.03
6	#35	0.500	0.675	158.05	137.90	190.66	48.91	182.76	559.91	957.03	145.63	155.60	187.33
7	#65	0.231	0.366	668.32	224.79	528.68	56.70	123.43	260.64	599.99	488.48	153.53	197.70
8	#100	0.150	0.191	129.91	48.81	256.95	16.70	54.52	13.95	68.37	130.54	32.52	69.59
9	#150	0.100	0.125	78.33	152.18	341.16	16.00	70.73	10.33	33.02	62.03	14.86	70.29
10	#200	0.075	0.088	6.10	11.60	38.57	0.77	7.27	0.83	1.27	2.07	0.83	6.12
Receiver		-	0.075	39.69	72.17	167.54	8.17	61.56	11.81	6.70	10.67	4.98	21.90
Total(g)				1224.17	763.78	1678.95	1003.17	706.56	1231.17	2088.11	1259.94	1301.24	1549.79
Loss(g)				1.72	10.98	42.82	0.85	0.91	0.60	2.54	14.74	0.09	11.26
Loss(%)				0.14	1.44	2.55	0.08	0.13	0.05	0.12	1.17	0.01	0.73
% Passing Sieve No.200				3.24	9.45	9.98	0.81	8.71	0.96	0.32	0.85	0.38	1.41
Mean Diameter (mm)				1.01	0.66	0.43	9.92	0.84	1.11	0.74	2.18	3.05	3.93
S.D. (mm)				2.49	1.07	0.58	6.81	0.96	1.51	0.51	4.27	2.95	4.37

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Table 4-12 Bed sediment classification of each station by USCS (dry season)

Sieve	Mesh No.	Sieve Opening	Mean size	Weight of sediment (g)									
		(mm)	(mm)	Sta 1	Sta 2	Sta 3	Sta 4	Sta 5	Sta 6	Sta 7	Sta 8	Sta 9	Sta 10
Weight of sample before sieving				1225.89	774.76	1721.77	1004.02	707.47	1231.77	2090.65	1274.68	1301.33	1561.05
1	3/4"	19.000	19.000	0.00	0.00	0.00	203.85	0.00	0.00	0.00	41.55	0.00	14.07
2	3/8"	9.500	14.250	33.52	0.00	0.00	302.25	0.00	9.62	0.00	44.60	34.66	139.27
3	#4	4.750	7.125	27.46	11.18	0.83	175.97	4.96	11.07	1.26	72.66	223.01	313.87
4	#10	2.000	3.375	29.97	34.99	36.66	108.67	41.73	85.80	26.00	64.06	382.20	316.62
5	#20	0.850	1.425	52.82	70.16	117.90	65.18	159.60	267.21	394.47	197.65	299.05	213.03
6	#35	0.500	0.675	158.05	137.90	190.66	48.91	182.76	559.91	957.03	145.63	155.60	187.33
7	#65	0.231	0.366	668.32	224.79	528.68	56.70	123.43	260.64	599.99	488.48	153.53	197.70
8	#100	0.150	0.191	129.91	48.81	256.95	16.70	54.52	13.95	68.37	130.54	32.52	69.59
9	#150	0.100	0.125	78.33	152.18	341.16	16.00	70.73	10.33	33.02	62.03	14.86	70.29
10	#200	0.075	0.088	6.10	11.60	38.57	0.77	7.27	0.83	1.27	2.07	0.83	6.12
Receiver		-	0.075	39.69	72.17	167.54	8.17	61.56	11.81	6.70	10.67	4.98	21.90
Total(g)				1224.17	763.78	1678.95	1003.17	706.56	1231.17	2088.11	1259.94	1301.24	1549.79
% Passing Sieve No.200				3.24	9.45	9.98	0.81	8.71	0.96	0.32	0.85	0.38	1.41
F = % Coarser than sieve No. 200				96.76	90.55	90.02	99.19	91.29	99.04	99.68	99.15	99.62	98.59
C = % Coarser than sieve No. 4				4.98	1.46	0.05	67.99	0.70	1.68	0.06	12.60	19.80	30.15
CF = Coarse Fraction				0.05	0.02	0.00	0.69	0.01	0.02	0.00	0.13	0.20	0.31
Stream sediment categorization				Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand

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4.3 Cadmium distribution

The bed load samples from the wet season were chose and sieved with sieve No. 65, 100, 150 and 200 (0.231- mm, 0.150- mm, 0.100- mm and 0.075-mm mesh openings respectively) to compare the distribution of the cadmium concentration in each fraction. The results show that cadmium does not high accumulate in only smallest size of bed load but it also accumulate in sand size particle as well. At the upstream stations located above the zinc mines, there show unvarying amount of cadmium between each of the fraction. Meanwhile, at stations located at downstream, the cadmium concentrations tended to be highest in the < 0.231-mm fraction (0.15-0.231 mm). This may have been caused by ore dressing processes that affect the cadmium composition in sediment (Krissanakriangkrai, 2009)

Table 4-13 The Cd and Zn concentrations distribute in the bed load

Station	Grain size (mm)	Cd (mg/kg)	SD	Zn (mg/kg)	SD
1	0.150 <size ≤0.231	27.92	±5.43	1,897.81	±159.37
	0.100<size≤0.150	30.86	±4.34	1,831.29	±136.37
	0.075<size≤0.100	19.15	±4.41	1,080.97	±84.91
	≤0.075	16.64	±2.56	1,149.87	±19.36
2	0.150 <size ≤0.231	31.79	±5.75	2,802.91	±395.95
	0.100<size≤0.150	14.90	±1.27	1,132.42	±155.03
	0.075<size≤0.100	13.42	±2.71	876.30	±22.34
	≤0.075	17.10	±2.15	844.37	±63.78
3	0.150 <size ≤0.231	6.91	±1.59	181.77	±18.93
	0.100<size≤0.150	8.42	±1.73	130.22	±11.03
	0.075<size≤0.100	8.72	±2.97	110.44	±6.59
	≤0.075	7.68	±0.57	118.49	±9.64
4	0.150 <size ≤0.231	40.65	±7.64	3,970.23	±167.33
	0.100<size≤0.150	19.87	±1.97	2,104.58	±34.07
	0.075<size≤0.100	14.21	*	1,276.73	*
	≤0.075	4.77	±6.78	1,373.33	±78.75

Station	Grain size (mm)	Cd (mg/kg)	SD	Zn (mg/kg)	SD
5	0.150 <size ≤0.231	0.57	±0.23	63.59	±9.13
	0.100<size≤0.150	1.14	±0.15	63.04	±5.53
	0.075<size≤0.100	1.79	±0.05	90.09	±2.31
	≤0.075	14.98	±0.67	111.47	±5.03
6	0.150 <size ≤0.231	14.14	±3.04	1,572.97	±148.34
	0.100<size≤0.150	10.73	±2.12	1,040.17	±23.26
	0.075<size≤0.100	13.80	*	1,032.55	*
	≤0.075	15.97	±0.90	1,325.80	±10.41
7	0.150 <size ≤0.231	1.58	±0.23	24.23	±2.87
	0.100<size≤0.150	1.46	±0.08	25.15	±2.09
	0.075<size≤0.100	1.61	±0.28	37.94	±6.93
	≤0.075	1.58	±0.03	46.17	±1.62
8	0.150 <size ≤0.231	1.53	±0.13	22.15	±1.37
	0.100<size≤0.150	1.52	±0.04	24.79	±1.88
	0.075<size≤0.100	1.51	±0.06	34.34	±1.97
	≤0.075	1.68	±0.07	51.94	±0.99
9	0.150 <size ≤0.231	1.58	±0.23	28.90	±2.10
	0.100<size≤0.150	1.46	±0.08	31.06	±3.75
	0.075<size≤0.100	1.51	*	56.69	*
	≤0.075	1.46	±0.10	108.22	±2.33
10	0.150 <size ≤0.231	1.56	±0.09	61.48	±16.50
	0.100<size≤0.150	1.51	±0.07	38.96	±5.47
	0.075<size≤0.100	1.47	±0.01	48.91	±4.31
	≤0.075	1.59	±0.20	69.18	±5.69

Note : * One sample measurement

**Average Cd concentration calculated from weighted average.

4.4 Model sensitivity

4.4.1 Parameters affecting water discharge

- **The bed resistance**

The sensible of resistance number were calculated using Eq. (3.12). The results in table 4-14 show that effect of resistance number to water discharge is small to negligible

Table 4-14 Sensitivity of bed resistance

Parameter	Sensitivity index	Sensitivity
Resistance number	0.00	Small to negligible

- **The surface and the root zone**

The amount of water in the surface storage and the soil moisture in the root zone control the amount of water that enters the groundwater storage as recharge and the overland flow components. The sensitivity of each parameter is presented in Table 4-15, which indicates that the most sensible the surface and root zone parameter is overland flow runoff coefficient processes (CQOF), which peak runoff decreased and runoff volume increased when CQOF increase. Meanwhile, the other parameters have a few effects on water discharge.

Table 4-15 Sensitivity of surface and root zone processes

Parameter	Sensitivity index	Sensitivity
Maximum water content in surface storage	0.02	Small to negligible
Maximum water content in root zone storage	0.02	Small to negligible
Overland flow runoff coefficient	0.21	Medium

Parameter	Sensitivity index	Sensitivity
Time constant for interflow	0.00	Small to negligible
Time constants for routing overland flow	0.00	Small to negligible
Root zone threshold value for inter flow	0.00	Small to negligible

- **The ground water**

Since water discharge in Mae Tao Creek highly depends on amount of ground water in the system, groundwater parameters were analyzed. The sensitivity of groundwater components is presented in Table 4-16. The results show that parameters in ground water model have high sensible to water discharge compare with the others part especially for maximum ground water depth causing base flow. However, the root zone threshold value for ground water recharge, which is the relative value of the moisture content in the root zone, is not sensitive to water discharge of Mae Tao Creek.

Table 4-16 Sensitivity of ground water processes

Parameter	Sensitivity index	Sensitivity
Root zone threshold value for ground water recharge	0.00	Small to negligible
Time constant for routing base flow	0.48	High
Specific yield for the ground water storage	0.41	High
Maximum ground water depth causing base flow	0.91	High

4.4.2 Parameters affecting water velocity

- **The bed resistance**

Even water discharge does not sensitive with the resistance. The effect of the bed resistance number to water velocity is high as show in table 4-17.

Table 4-17 Sensitivity of bed resistance

Parameter	Sensitivity index	Sensitivity
Resistance number	0.37	High

- **The surface and the root zone**

The sensitivity of surface and the root zone parameter to water velocity are presented in Table 4-18, which show the similar pattern with the sensitivity of surface and the root zone parameter to water discharge. Moreover, the overland flow runoff coefficient processes (CQOF) is the most sensible parameter.

Table 4-18 Sensitivity of surface and root zone processes

Parameter	Sensitivity index	Sensitivity
Maximum water content in surface storage	0.01	Small to negligible
Maximum water content in root zone storage	0.01	Small to negligible
Overland flow runoff coefficient	0.05	Medium
Time constant for interflow	0.00	Small to negligible
Time constants for routing overland flow	0.00	Small to negligible
Root zone threshold value for inter flow	0.00	Small to negligible

- **The ground water**

The sensitivity of groundwater components is presented in Table 4-19. The results show that the maximum ground water depth causing base flow is high sensible parameter to both water discharge and water velocity of Mae Tao Creek. While, time constant for routing base flow and specific yield for the ground water storage are show medium sensible to water velocity.

Table 4-19 Sensitivity of ground water processes

Parameter	Sensitivity index	Sensitivity
Root zone threshold value for ground water recharge	0.00	Small to negligible
Time constant for routing base flow	0.19	Medium
Specific yield for the ground water storage	0.17	Medium
Maximum ground water depth causing base flow	0.38	High

Sensitivity analysis shows that hydrodynamics (both water discharge and water velocity) of Mae Tao Creek sensitive to the processes in ground water especially for the maximum ground water depth causing base flow (CWLBF0). Moreover, the bed resistance has high affect to waster velocity but no affect to water discharge. Therefore, the parameters in ground water were the most attentive to adjust the optimum calibration.

4.5 Model calibration

4.5.1 Hydrodynamic simulation

Model calibration

The reliability of the calibration between observed and simulated water depth was evaluated based on the correlation coefficient (CC), which equal to 1 indicates the best performance of the model. The CC obtained during this study was 0.87. The root mean square errors (RMSE) value tends to be zero (0) for perfect agreement between observed and simulated values. The RMSE value obtained was 0.06. However, the model was prone to slightly underestimated especially from May to June. These underestimations may have been caused by data unavailable of each part of the creek; these data unavailable include bed material composition, anthropogenic water used, hydraulic structures, and morphology in each segment. However, in the calibration, all parameters were set uniformly along the creek. Furthermore, at the beginning part of the calibration inaccuracy could be attributed to the model's limitation to account for the complex mechanisms that occur during the transition period between the wet and dry season. Comparison between the observed and simulated water depth at Station 4 is presented in Figure 4-3.

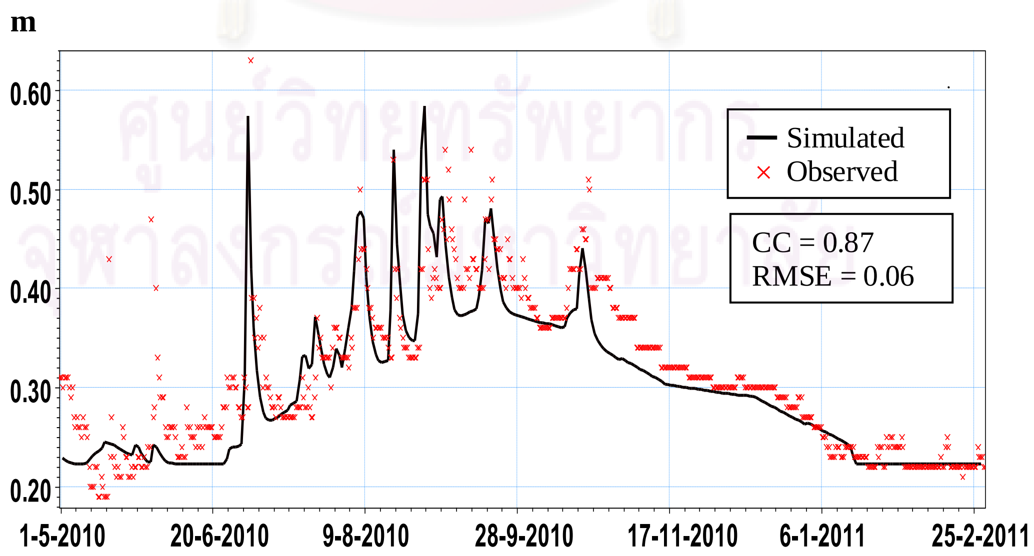

Figure 4-3 Observed and simulated water depths at Station 4(m)

Hydrodynamic results

The hydrodynamic results, obtained by running MIKE 11, were water depth and water discharge. Figures 4-4, 4-5 show discharge and water depths at each station, except Station 1 that used as downstream boundary condition. The hydrodynamic feature at each station was different due to the topography change. At Station 10 located in a high mountainous upstream part of Mae Tao Creek, there was very little water discharge. The discharge increased as the topography decreased along Mae Tao Creek, whereas the water discharge from Mae Tao Right (Station 9) and Mae Tao Left (Station 5) were small in quantity compared to the discharge from the main Mae Tao Creek. The moving discharge for each station displays similar pattern to each other. Factors that caused variability in discharge and water depth are precipitation and evaporation that directly influence the amount of water in the creek. Each station experience seven main peaks in discharge, First peak in July after shortly heavy storm, followed by the other peaks in August to October related to a combination of high precipitation.

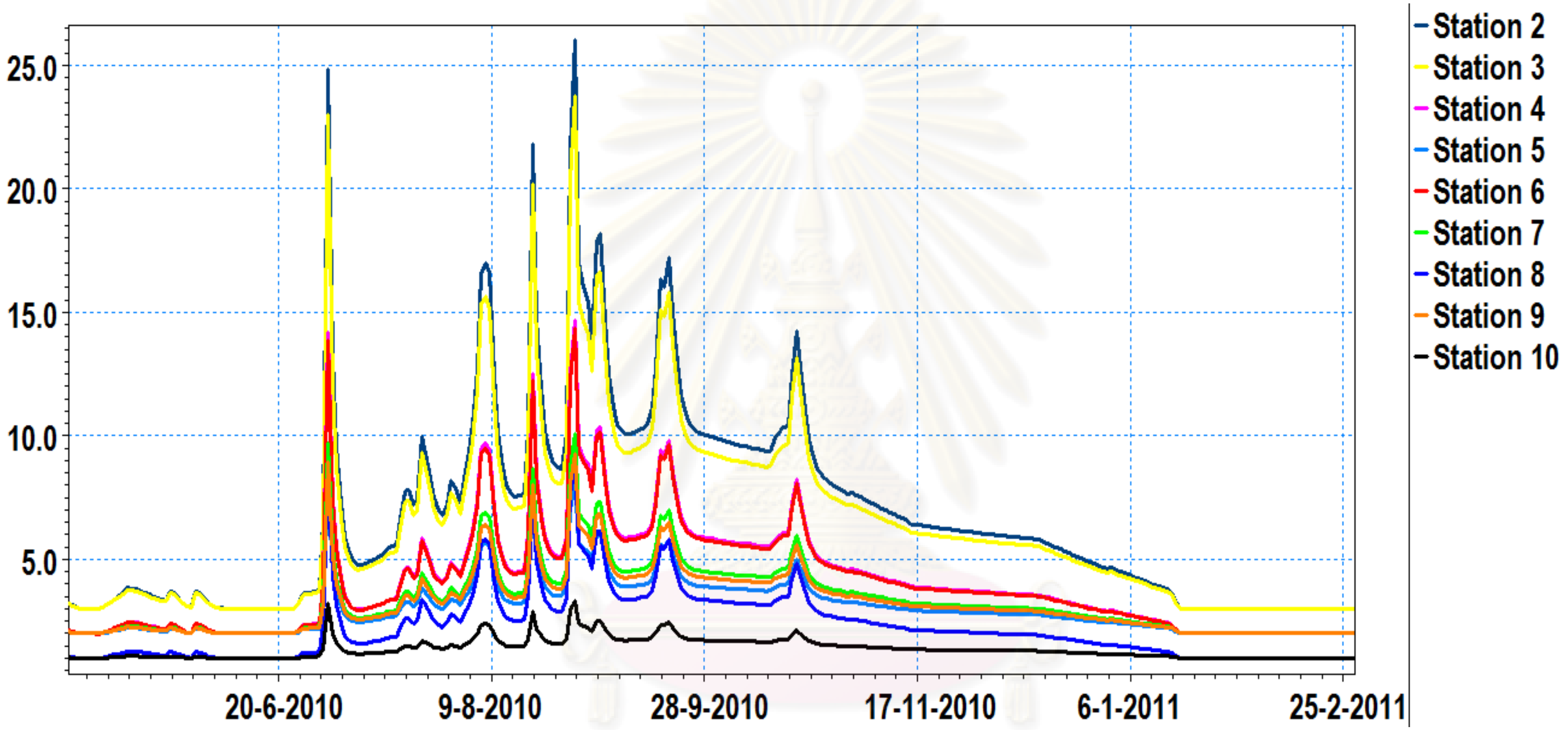

Figure 4-4 Simulated water discharge (m^3/s)

77

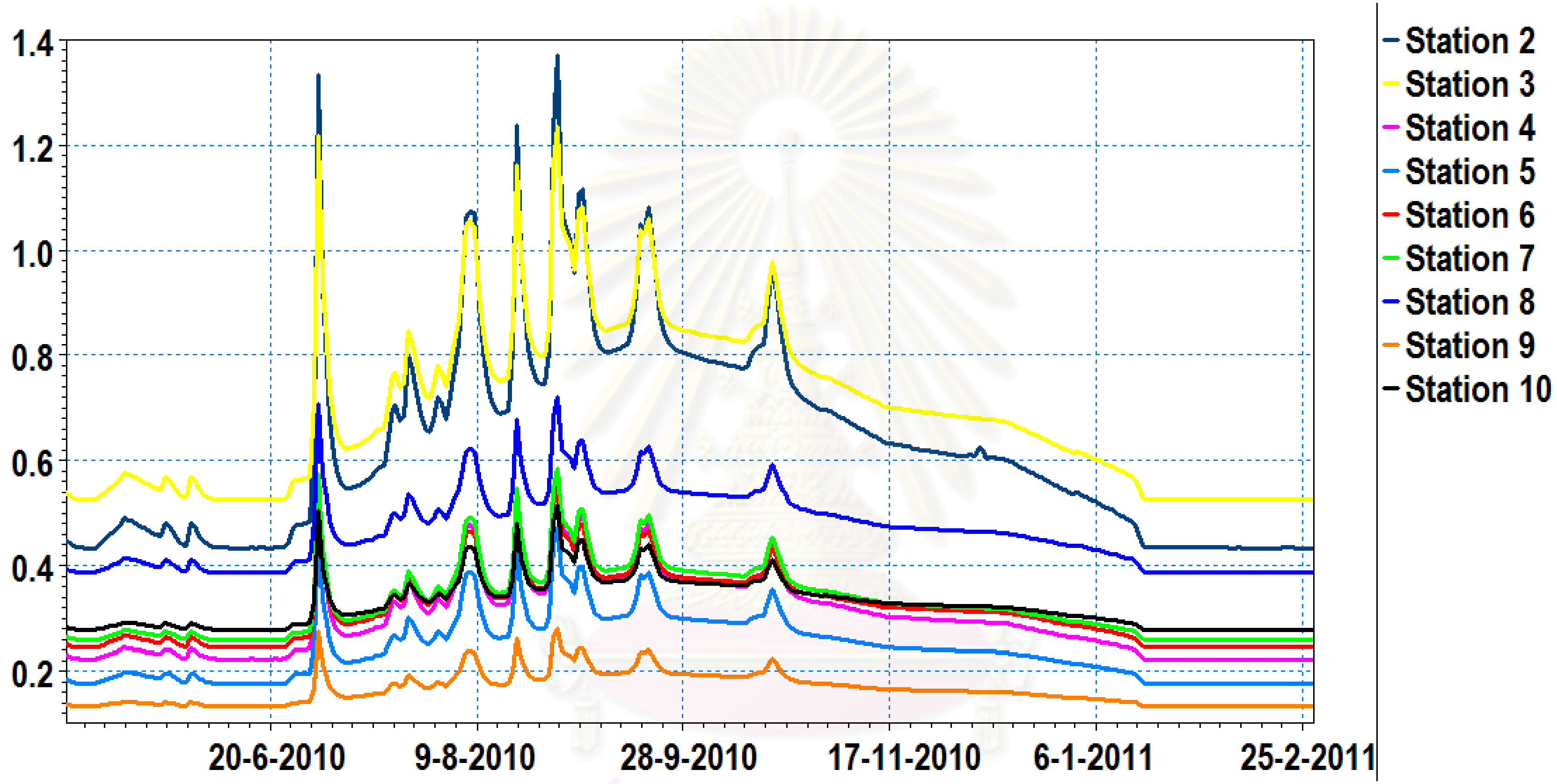

Figure 4-5 Simulated water depth (m)

78

4.3.2 Sediment transport simulation

The sediment transport module was added on once the hydrodynamic model was calibrated. Sediment transports in Mae Tao Creek were evaluated in two seasons: the wet and dry seasons. Total sediment transport was split up into bed load and suspended sediment.

From May 2010 to February 2011, 179.01×10^6 m^3 of water transported 760.17 m^3 of the total sediment down to downstream of Mae Tao Creek. In storm events from May to October 2010, 596.17 m^3 of the sediment was transported by 129.89×10^6 m^3 of water discharge. In the dry season from November 2010 to February 2011, a total of 164.00 m^3 of sediment was transported with a water discharge of 49.13×10^6 m^3. During the study period, 78.42% of total sediment transport occurred during the wet season, which was caused by high discharge and flow velocity that increased the movement of sediment. The total sediment load in the wet season was 3.6 times greater than the total load in the dry season. Moreover, 86.84% of the sediment transported was suspended sediment. This is in good agreement that bed load may comprise a small proportion (1-20%) of the total sediment in sand-bed channels (Simons and Senturk, 1977).

Sediment transport in the wet season

Total sediment transport in the wet season was simulated from May to October. Figure 4-6 shows the rate of the bed load transport at downstream, which was closely related to the water discharge. The highest rate of bed load transport was occurred in August (27th to 28th), during which time it from 3.25×10^{-5} to 4.83×10^{-5} m^3/s, while the discharge increased from 21.89 to 26.68 m^3/s. The volume of bed load transported downstream was simulated to be 84.09 m^3 in the 2010 wet season.

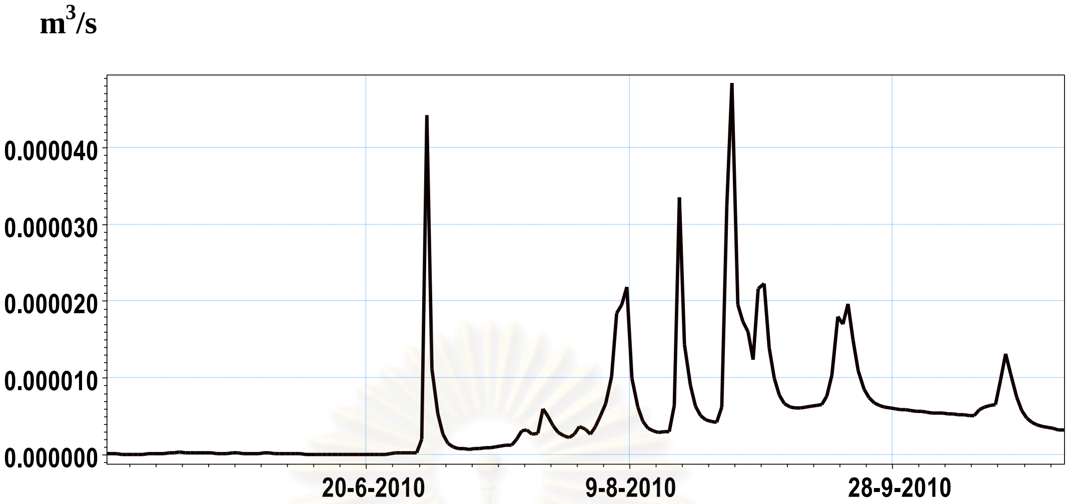

Figure 4-6 Bed load transport rate at downstream in wet season (m^3/s)

The rates of suspended sediment transport are shown in Figure 4-7. The highest suspended sediment rate occurred in tandem with the highest bed load amount, increased from $1.62{\times}10^{-4}$ to $2.35{\times}10^{-4}$ m^3/s. During the 2010 wet season, the accumulation of suspended sediment transported at downstream was simulated to be 512.08 m^3. Therefore, the total sediment transported (bed load and suspended sediment) downstream in the wet season was 596.17 m^3, as displayed in Figure 4-8.

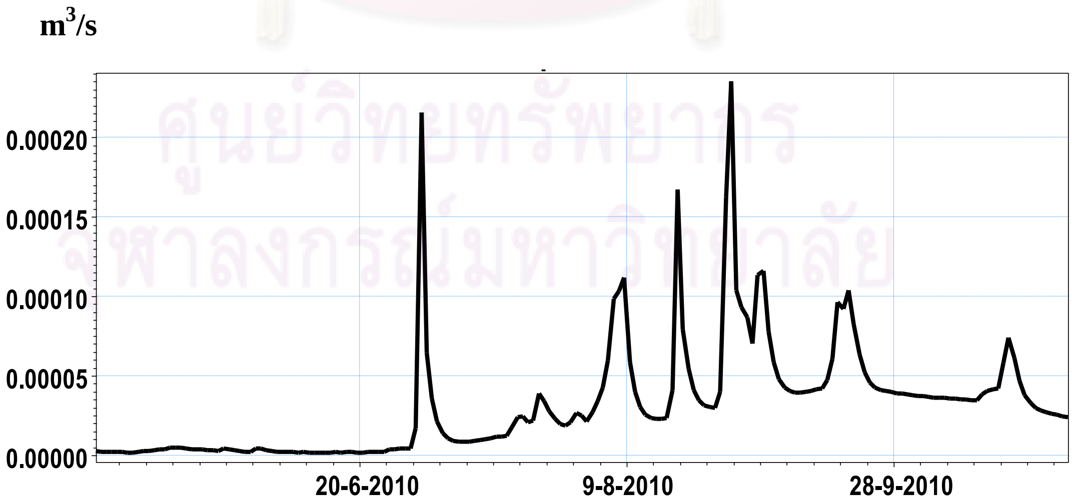

Figure 4-7 Suspended sediment transport rate at downstream in the wet season (m^3)

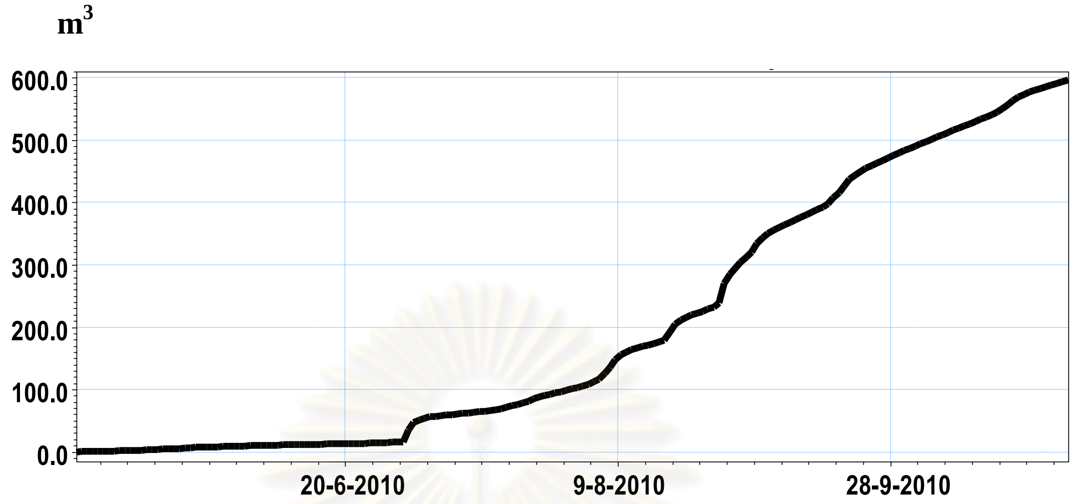

Figure 4-8 Accumulated sediment transport downstream in the wet season (m^3)

Sediment transport in the dry season

Total sediment transport in the dry season was simulated from November 2010 to February 2011. Figure 4-9 shows the bed load transport rate downstream. The volume of bed load transported downstream was simuated to be 15.97 m^3 in the 2010 -2011 dry season.

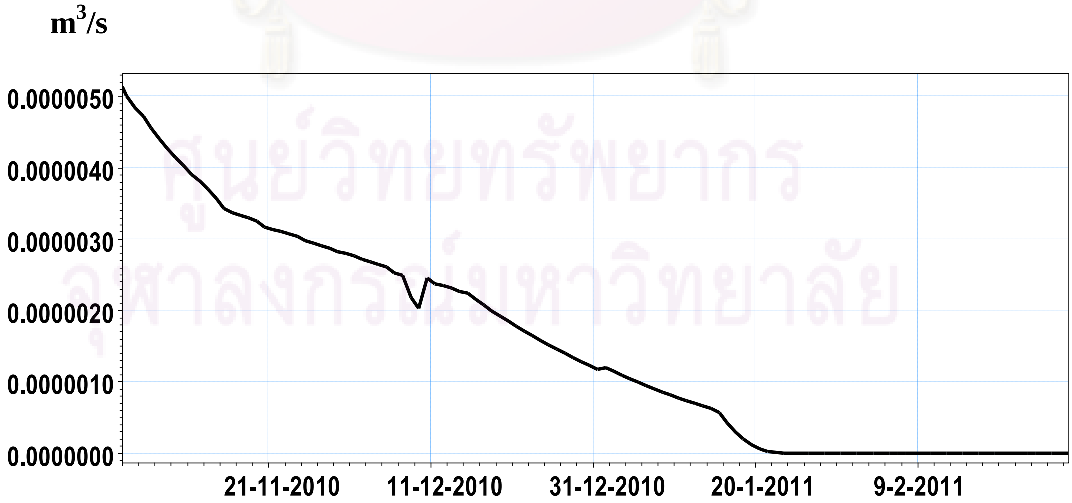

Figure 4-9 Bed load transport rate downstream in the dry season and wet season(m^3/s)

The rates of suspended sediment are shown in Figure 4-10. The transport of suspended sediment downstream during the 2010 - 2011 dry season was simulated to be 148.03 m^3. Therefore, the total sediment transported (bed load and suspended sediment) at downstream in the dry season was 164.00 m^3, as displayed in Figure 4-11.

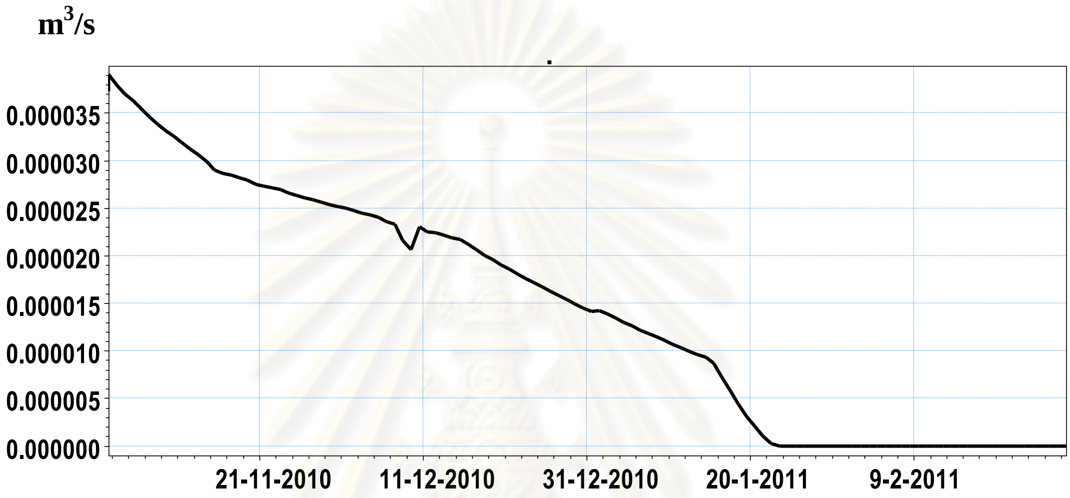

Figure 4-10 Suspended sediment transport rate downstream in the dry season (m^3)

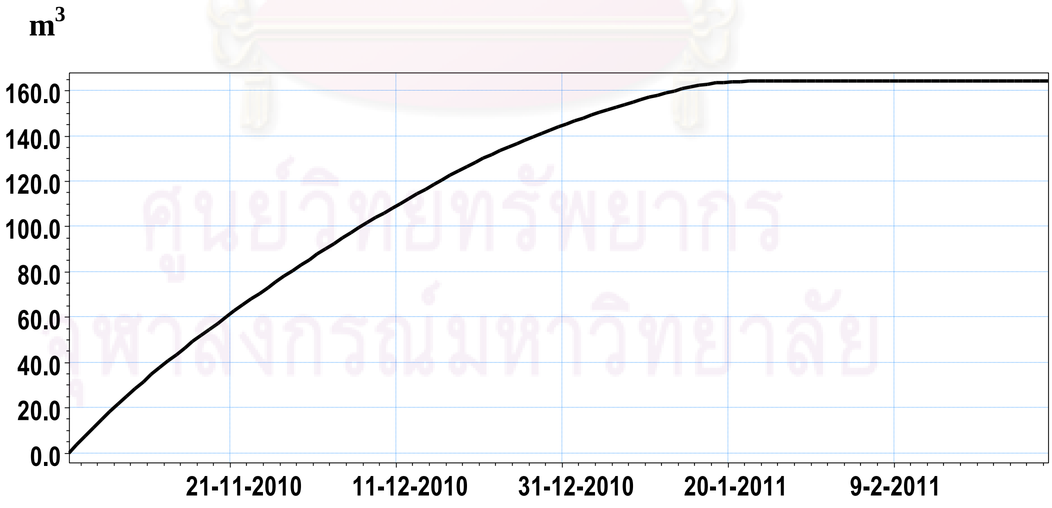

Figure 4-11 Accumulated transport downstream in the season (m^3)

The rate of sediment transport is primarily controlled by stream discharge (Kavin *et al*, 2008). Variations in sediment transport can generally be interpreted that the sediment transport rates naturally peaked as water discharges peaked, as shown in Figure 4-12. The sediment transport rates were high in July and at their highest in August. Thereafter, the rate of sediment transport gradually decreased until February. The low seasonal discharge of the dry months generally leads to sediment accumulation in the catchment. The lack of the transport capacity of the channel flow effects decreases in sediment transport.

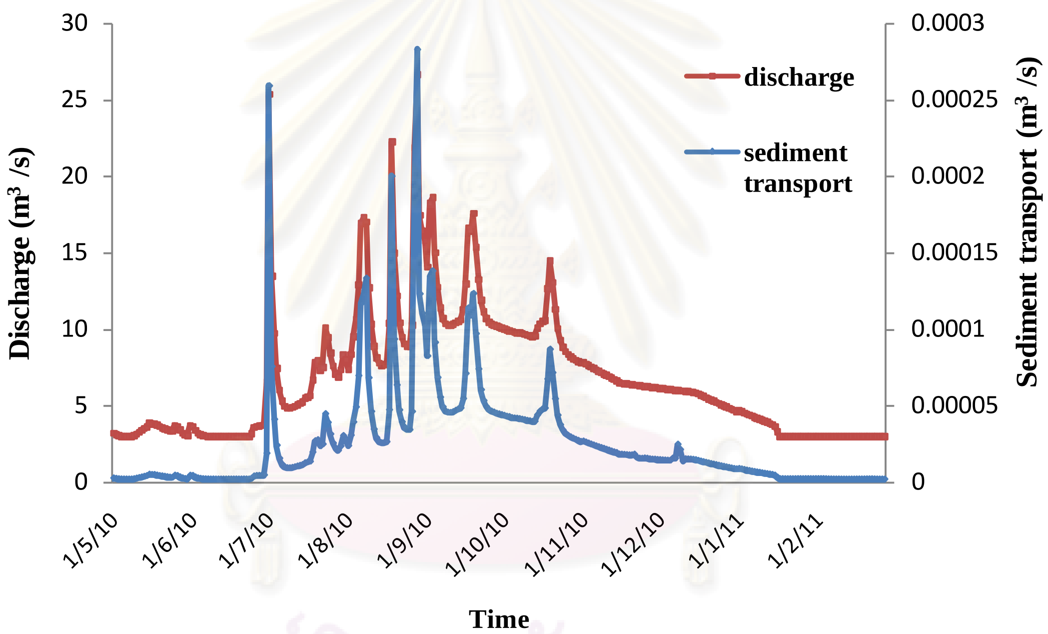

Figure 4-12 Total sediment transport downstream (m^3/s) and water discharge downstream (m^3/s)

4.6 Uncertainty analysis

Suspended sediment concentration was the important data for calculate calculation factor in sediment transport module, yet it was measured one time in each season. Therefore, calculation factor in sediment transport module was considered to have high uncertainty.

Calculation factor is a factor in sediment transport module, which can be applied to the calculated transport rates as correction factors. Calculation factor are simple multiplication factors used to either up- or downscale the calculated sediment transport. Calculation factor that used in the simulation was calculate from the ratio of suspended sediment concentration that measured the field per suspended sediment concentration simulated from the model, which used calculation factor equal to 1.

Suspended sediment concentration that measured at the field was a concentration at the half water depth. While the concentration profile of suspended sediment is fluctuate with water depth as show in Figure 4-13. Therefore, the total concentration can be calculate from Eq. (4.1).

$$\frac{c}{c_a} = \left[\frac{a}{d-a}\right]^z \left[\int_a^{0.5d} \left[\frac{d-z}{z}\right]^z ln\left(\frac{z}{z_0}\right) + \int_{0.5d}^{d} [e]^{-4z\left(\frac{z}{d}-0.5\right)} ln\frac{z}{z_0}\, dz\right] \tag{4.1}$$

where

c	=	suspended sediment concentration
c_a	=	reference concentration
a	=	reference level
d	=	depth (m)
z	=	vertical coordinate

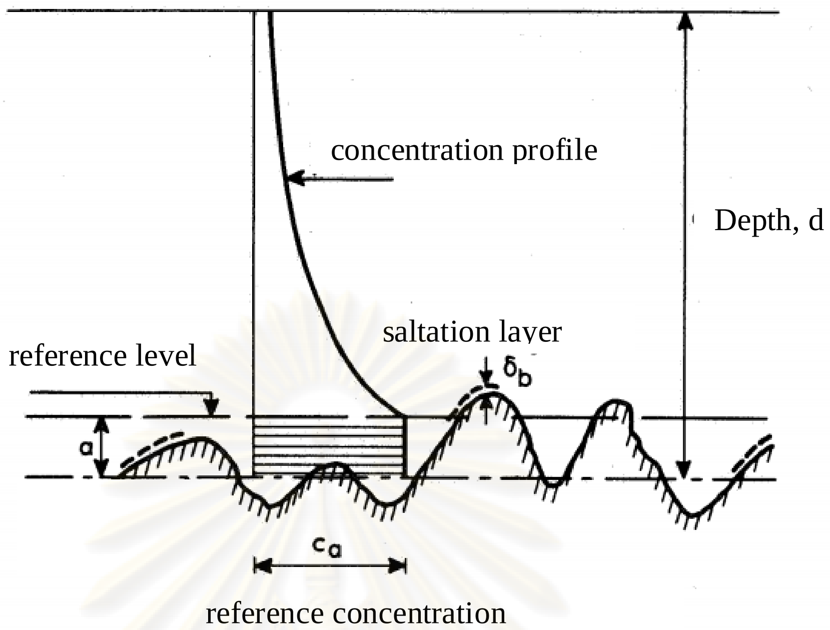

Figure 4-13 Sketch of concentration profile

Based on the basis of the analysis of parameter uncertainty, the method of sensitivity analysis can be used to identified the input parameter that have the greatest effect on the model output (Radwan and Willems, 2007). Highest and lowest suspended sediment concentration (see Appendix C) was used to calculate the calculation factor. The uncertainty analysis were calculated using Eq. (3.12) and used x_1 equal to 0.036, x_2 equal to 0.44, which is minimum and maximum calculation factor in sediment transport respectively. The output y is accumulated sediment transport in August 2010 due to the highest precipitation occurred in this month.

To identify uncertainties due to model input, which is calculation factor in sediment transport module. The sensitivity of model input change to the model output response is studied. The results of the sensitivity analysis show that sediment transport has high sensitive, therefore uncertainty in suspended sediment may have high effect on the sediment transport output. The sediment transport has high uncertainty because range of directly measured suspended sediment concentration as showed in Table 4-20. Moreover, model input is more sensitive than model parameters in general (Radwan and Willems, 2007).

Table 4-20 Sensitivity of sediment transport

Parameter	Sensitivity index	Sensitivity
Calculation factor	0.56	High

The error in sediment transport simulation due to high uncertainty was used to calculate the minimum and maximum total sediment transport that can possible occur as showed in Table 4-21.

Table 4-21 Values of the boundary total sediment transport at downstream of the study area

Period	Sediment	Minimum total sediment transport (kg)	Simulate total sediment transport (kg)	Maximum total sediment transport (kg)
Wet season	Bed load	0.06×10^6	0.13×10^6	0.74×10^6
	Suspended sediment	0.37×10^6	0.82×10^6	4.51×10^6
	Total	0.43×10^6	0.95×10^6	5.25×10^6
Dry season	Bed load	0.01×10^6	0.02×10^6	0.14×10^6
	Suspended sediment	0.10×10^6	0.24×10^6	1.30×10^6
	Total	0.11×10^6	0.26×10^6	1.44×10^6

Due to high uncertainty of sediment transport results, the minimum and maximum of sediment transport from uncertainty analysis was used estimate the boundary of cadmium transport in both wet and dry seasons. The results showed that, in worst-case; cadmium migration could be as much as 114.80 kg, which is 5.5 times greater than the simulation result. On the other hand, the minimum amount of cadmium migration could be transport out equal to 9.46 kg.

4.7 Cadmium transport estimation

The sediment transport rate (m^3/d) and the cadmium concentration in stream sediment (mg/kg) were used to evaluate the cadmium transport rate via sediment (mg/d) as displayed in Eq. (3.62).

At the downstream sampling site of Mae Tao Creek, the total amount of sediment transported from May 2010 to February 2011 was equal to 1.21×10^6 kg. In the wet season and dry season, the amount of accumulated sediment was equal to 0.95×10^6 kg and 0.26×10^6 kg, respectively. The later value was computed with the accumulated sediment values transported in the wet season and dry season of 596.17 m^3 and 164.00 m^3, respectively. Thus, the cadmium transport amount in Mae Tao Creek from May 2010 to February 2011 could be estimated at 20.74 kg from the cadmium transport values of 11.39 kg in the wet season and 9.35 kg in the dry season. Because the transport capacity of suspended sediment is higher than that of bed load, suspended sediment was the dominant process for cadmium transport in Mae Tao Creek in both the wet and dry seasons. The data in Table 4-22 describe the amounts of accumulated sediment and cadmium that were transported downstream.

Table 4-22 Values of the accumulated sediment and cadmium transport at downstream of the study area

Period	Sediment	Simulated total sediment transport (kg)	Measured Cd concentration (mg/kg)	Cd transport (kg)
Wet season	**Bed load**	0.13×10^6	18.29	2.37
	Suspended sediment	0.82×10^6	11.00	9.02
	Total	0.95×10^6		11.39
Dry season	**Bed load**	0.02×10^6	32.44	0.65
	Suspended sediment	0.24×10^6	36.25	8.70
	Total	0.26×10^6		9.35

Due to high uncertainty of sediment transport results, the minimum and maximum of sediment transport from uncertainty analysis was used estimate the boundary of cadmium transport in both wet and dry seasons. The results showed that in worst-case cadmium could be transport out equal to 114.80 kg, which is 5.5 times greater than the simulation. While in best case, cadmium could be transport out equal to 9.46 kg.

Table 4-23 Values of the boundary cadmium transport at downstream of the study area

Period	Sediment	Minimum Cd transport (kg)	Simulate Cd transport (kg)	Maximum Cd transport (kg)
Wet season	**Bed load**	1.12	2.37	13.53
	Suspended sediment	4.10	9.02	49.61
	Total	5.22	11.39	63.14
Dry season	**Bed load**	0.37	0.65	4.54
	Suspended sediment	3.87	8.70	47.12
	Total	4.24	9.35	51.66
Total		**9.46**	**20.74**	**114.80**

CHAPTER V
CONCLUSIONS

5.1 Conclusion

The cadmium contaminated sediment transport via bed load and suspended sediment in Mae Tao Creek have been studied. The metrological data, topographic map which provided by government department and hydraulic conditions from field observations were applied together as inputs of the MIKE 11 model for simulate hydrodynamics and sediment transport in Mae Tao Creek during wet season (May to October 2010) and dry season (November 2010 to February2011).

The processes in ground water were the most sensitive with water discharge. The sensitivity analysis showed that the parameters of ground water plated a significant role in the amount of water discharge, except for the root zone threshold value for ground water recharge that sensitivity was small to negligible.

The hydrodynamics of the creek was calibrated with the water depth measured from May 2010 to February 2011. The performance of the model in term of hydrodynamic has been assessed using the correlation coefficient (CC) and the root mean square errors (RMSE), which obtained values 0.87 and 0.06 for CC and RMSE respectively. The results show that the discharge increased with the topography decreased along Mae Tao Creek. Moreover, water depth and water discharge in wet season were much greater than they were in dry season.

The sediment in the Mae Tao Creek, classified by the grain size distribution method following the USCS, mostly belonged to sand size particles. Thus, the non-cohesive sediment transport module in MIKE 11 was applied to estimate the sediment transport. In the calculation, the sediment transports are separated into bed load and suspended sediment. The simulated results also manifested the difference between the wet and dry seasons. The total sediment transport passed the downstream during May 2010 to February 2011 was equal to 760.17 m^3, whereas 78.42% of sediment transport occurs in the wet season. Moreover, 86.84% of sediment that transport through downstream of Mae Tao Creek was suspended sediment. It was noted that sediment transport variability is related to changes in discharge. Factor that caused sediment transport variable is variability in precipitation. High amount of rainfall directly increase the amount of discharge and velocity of the creek, this events affect the sediment that is likely to become available for transport. However, the result of sediment transport obtained from the simulation has uncertainty in high level due to the variable of directly measured data.

The evident of cadmium contamination was obviously shown by the measured cadmium concentrations in bed load and suspended sediment in both the wet and dry seasons. The distribution of cadmium concentrations in bed load and suspended sediment were presented in the same pattern. Cadmium concentrations in both bed load and suspended sediment in the Mae Tao Creek change seasonally, giving higher concentration in dry season. Elevated concentrations of cadmium in the dry season may be reinforced by sediment that entrances into the creek were dominated by runoff from highly contaminated area along the creek. Meanwhile, sediment samples in the wet season was characterized by a high input of alluvium from the larger area than dry season, therefore it contains lower cadmium concentration than dry season. At downstream (station2), characterized as the most significant station that responds for cadmium distributed out from the area, bed load contained cadmium concentration equal to 18.29 mg/kg and 32.44 mg/kg for wet and dry seasons respectively. Meanwhile, suspended sediment contained cadmium concentration equal to 11.00 mg/kg and 32.65 mg/kg for wet and dry season respectively.

Even though cadmium concentration in dry season was higher than wet season, but the spread of cadmium contaminated due to stream sediment transport in Mae Tao Creek mainly occurred in storm event. This is because the high transport capacity of sediment was greater in wet season. From May 2010 to February 2011, approximately 20.74 kg of cadmium transport out of Mae Tao Creek (11.39 kg in wet season and 9.35 kg in dry season). Regarding to the transport capacity, the suspended sediment transport is a dominant process of cadmium transport in the Mae Tao Creek.

5.2 Recommendations

Because this research was focused on cadmium transport via bad load and suspended sediment, cadmium concentration was an important factor to estimate the transport. Therefore, more of the samples should be collected in each season for scrupulous estimation. Moreover, the cadmium contaminated area could represented by the cadmium concentration at each position along Mae Tao Creek. Water supply from downstream part of the creek for agricultural irrigation may enhance cadmium contamination in agricultural area due to suspended sediment.

Overall, the MIKE 11 model provided reasonable solutions for channel flow; however, the over prediction may be occurred due to data limitations. For instance, the model did not consider hydraulic structures, which could affect hydrodynamics of the creek. Nevertheless, this research was the approximately transport of cadmium in the study area. To improve the model, more effort should be focused on collecting accurate data of existing weirs along, sediment transport, which separately for bed load and suspended sediment to be used in sediment transport calibration. Recommend future study, extend present model to used ECOLab model, which can describe heavy metal transport with sediment and river flow.

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APPENDICES

APPENDIX A

Cross section profile

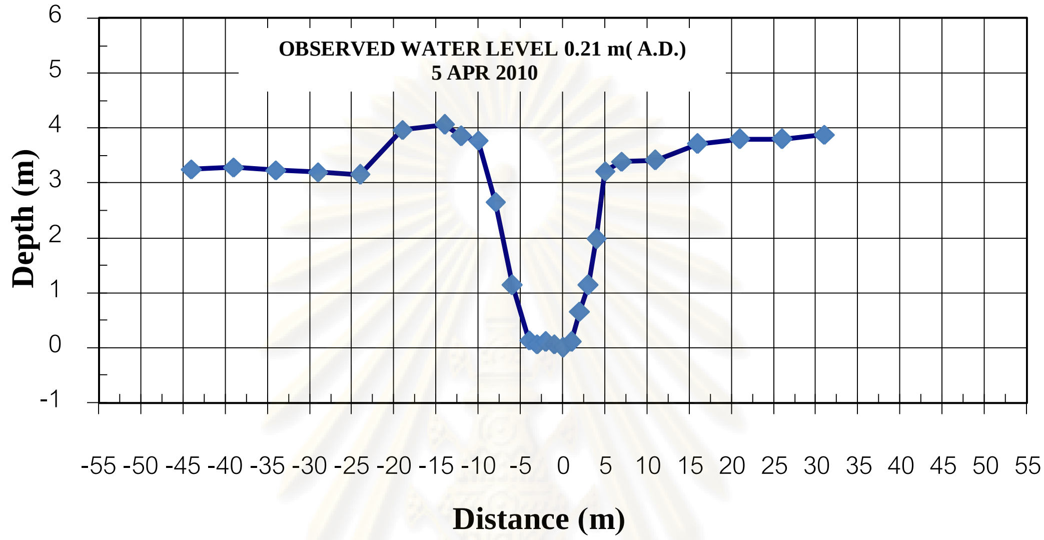

Figure A-1 Cross section profile of Station 1

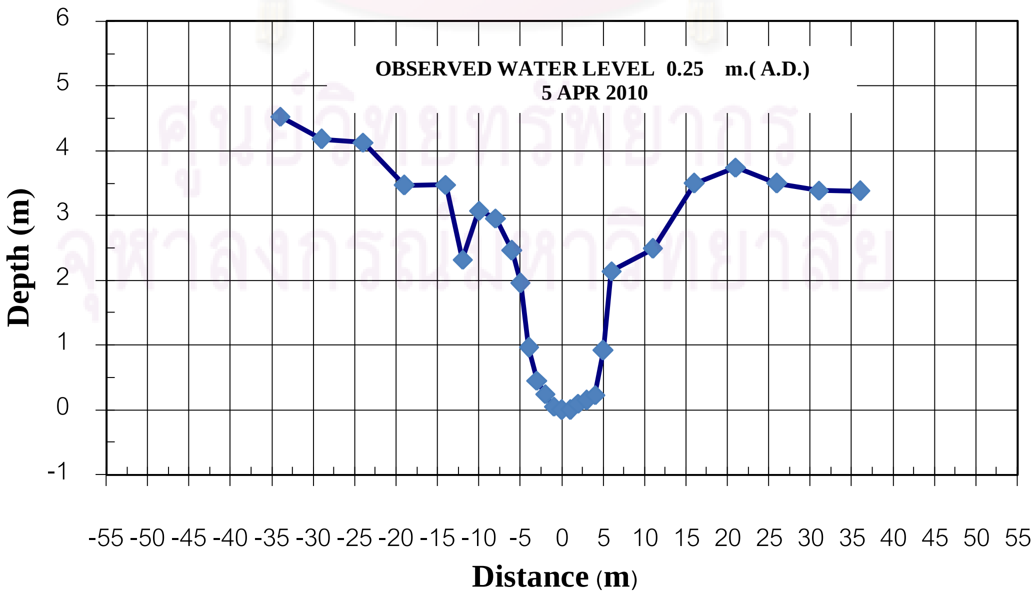

Figure A-2 Cross section profile of Station 2

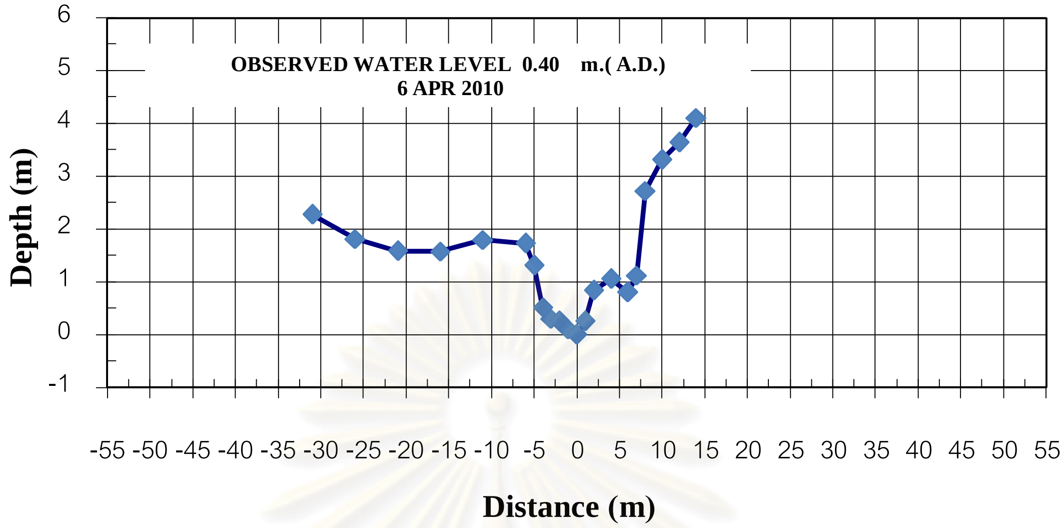

Figure A-3 Cross section profile of Station 3

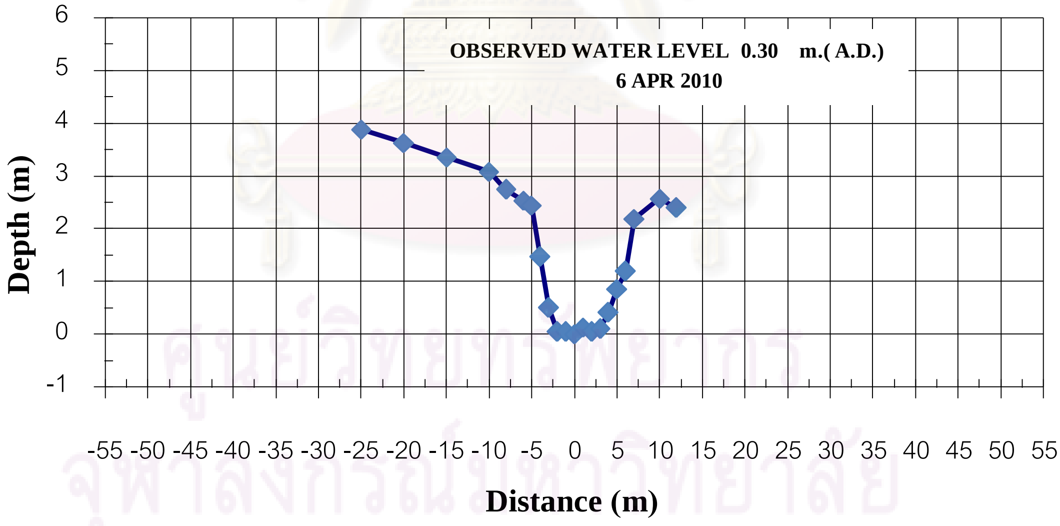

Figure A-4 Cross section profile of Station 4

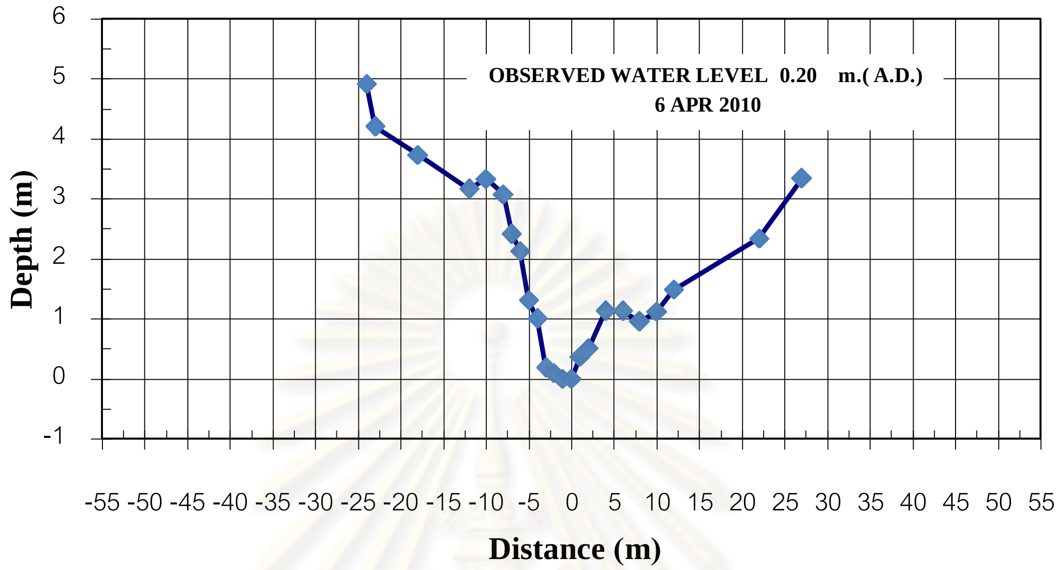

Figure A-5 Cross section profile of Station 5

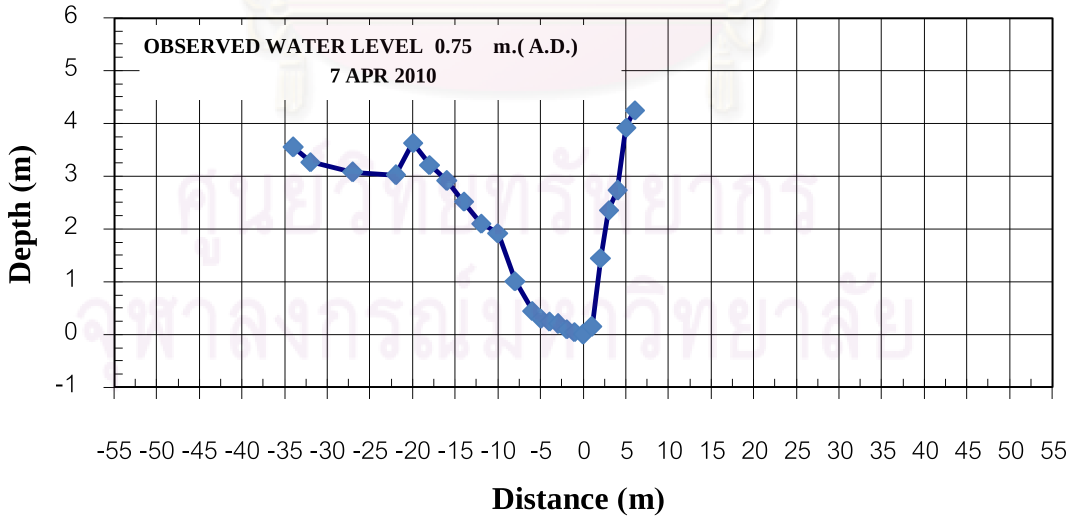

Figure A-6 Cross section profile of Station 6

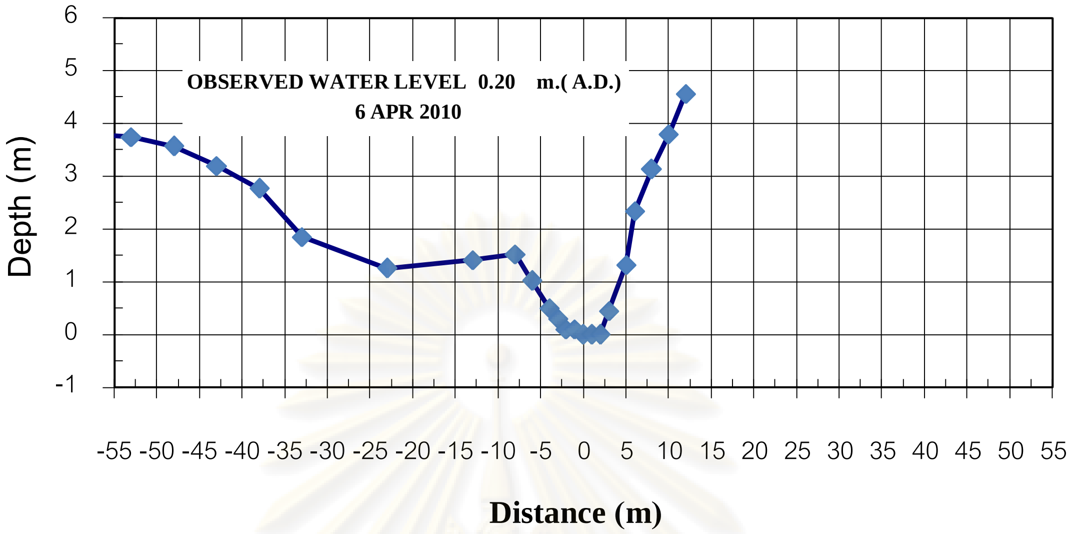

Figure A-7 Cross section profile of Station 7

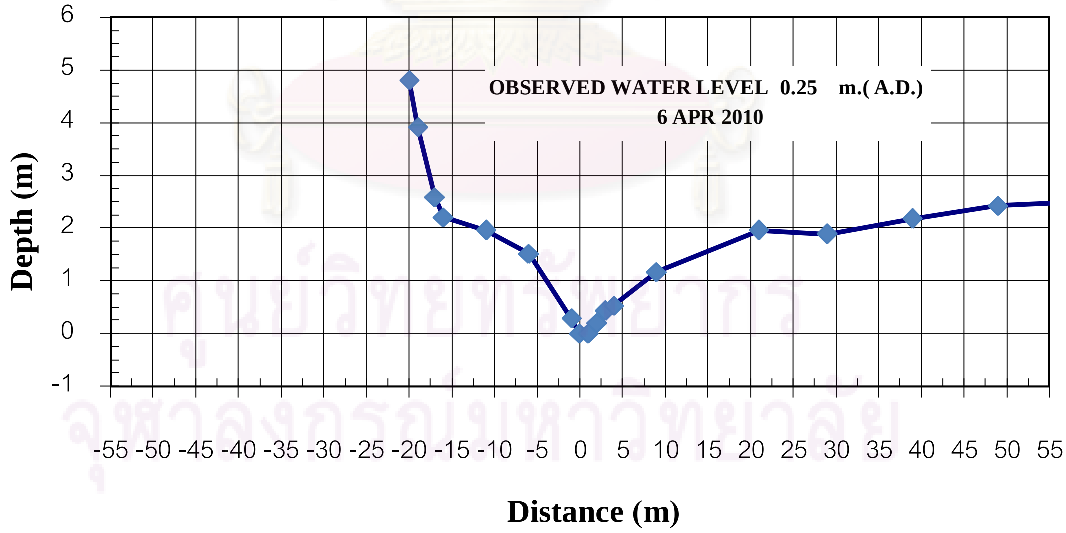

Figure A-8 Cross section profile of Station 8

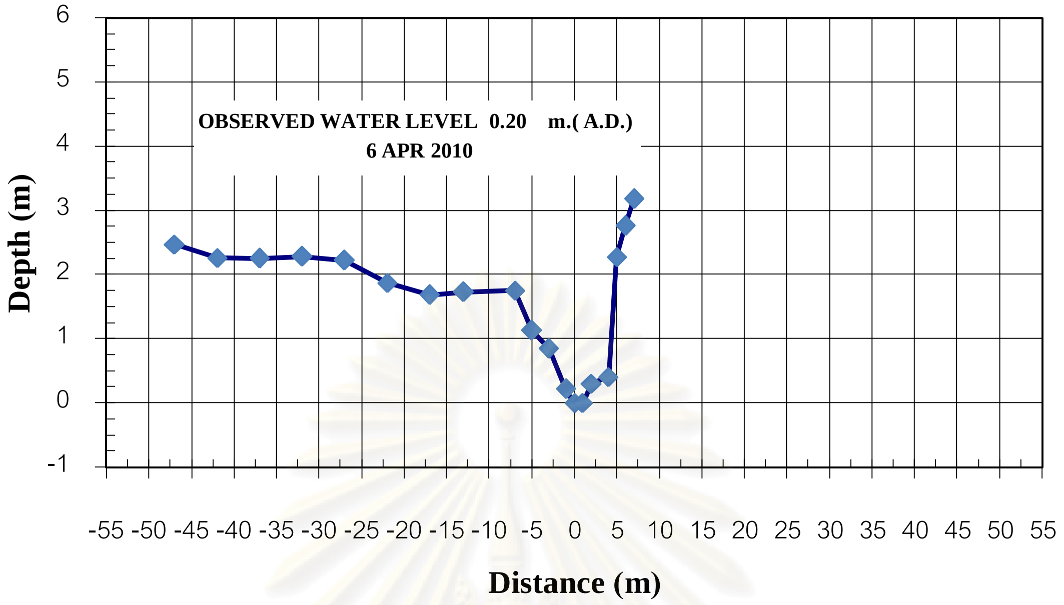

Figure A-9 Cross section profile of Station 9

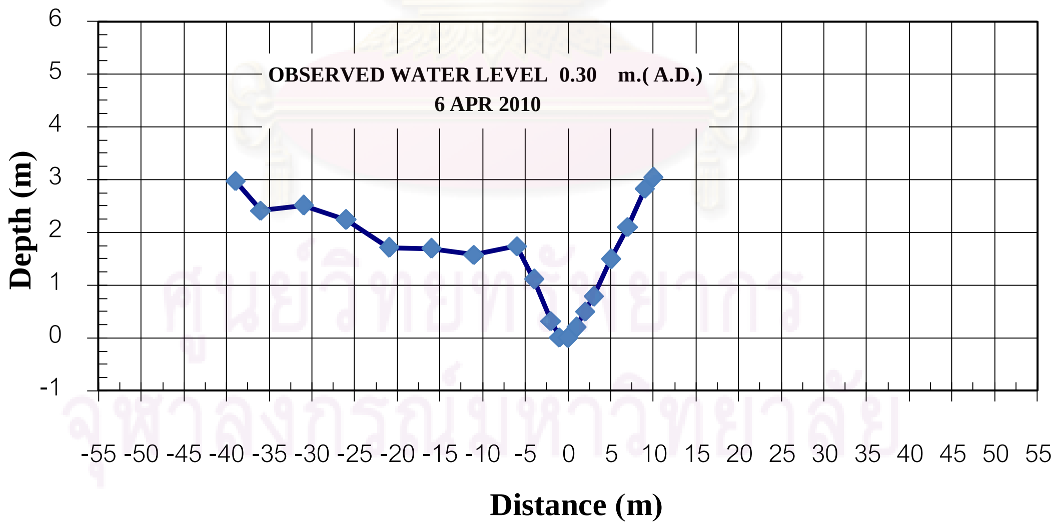

Figure A-10 Cross section profile of Station 10

APPENDIX B

The topographic map of study area

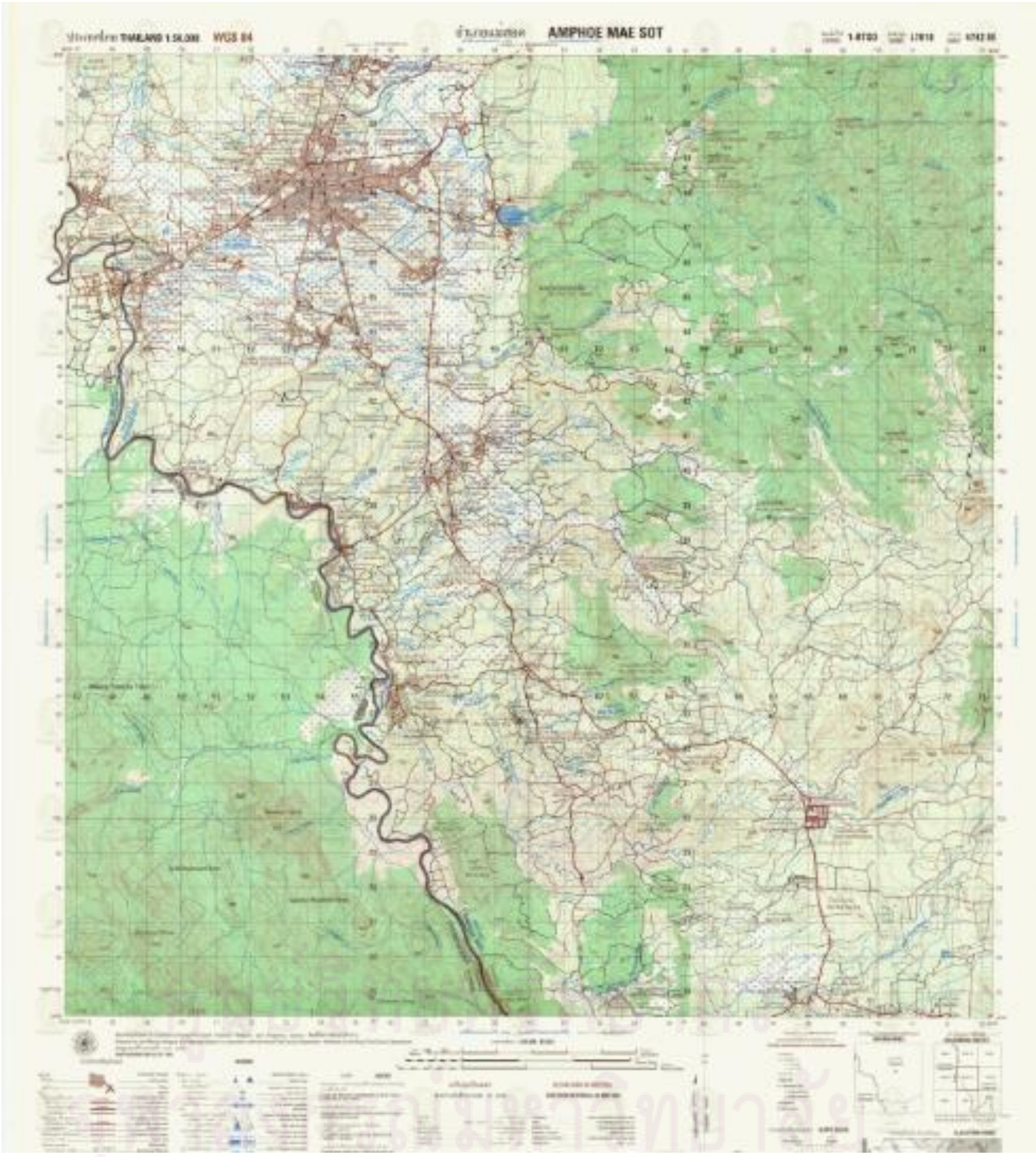

Figure B-1 The topographic map 1:50,000 scale, sheet 4742III, seriesL7018, edition 1-RTS

APPENDIX C

Weight of suspended sediment

Table C-1 The dry weight of suspended sediment

Dry season (g/2L)	**Wet season (g/2L)**
0.012	0.024
0.007	0.019
0.005	0.022
0.019	0.013
0.009	0.037
0.003	0.013
0.021	0.014
0.020	0.009
0.007	0.007

APPENDIX D

Rainfall rate and evaporation rate in year 2010 - February 2011

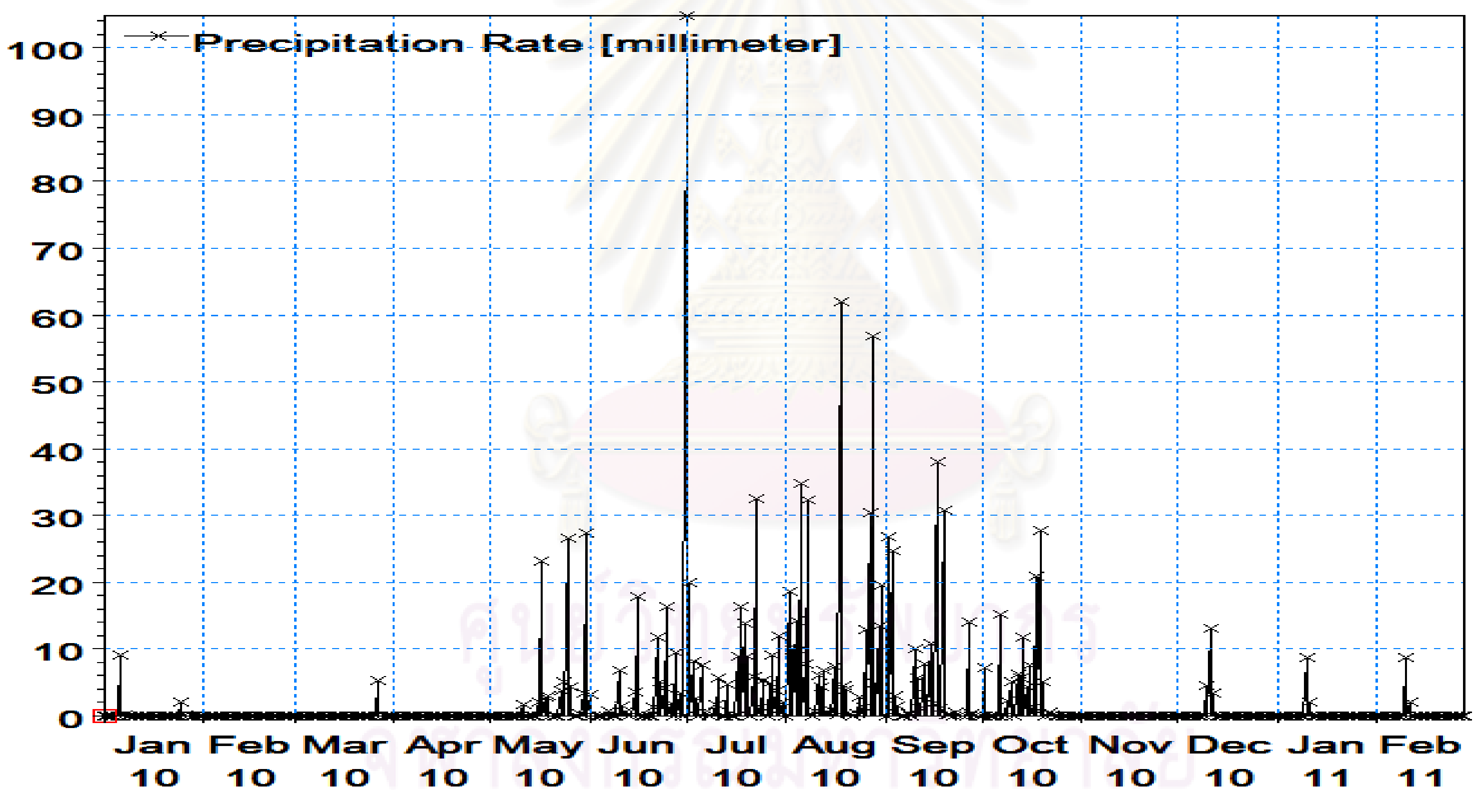

Figure D-1 Rainfall rate during simulation time (mm/d) (TMD)

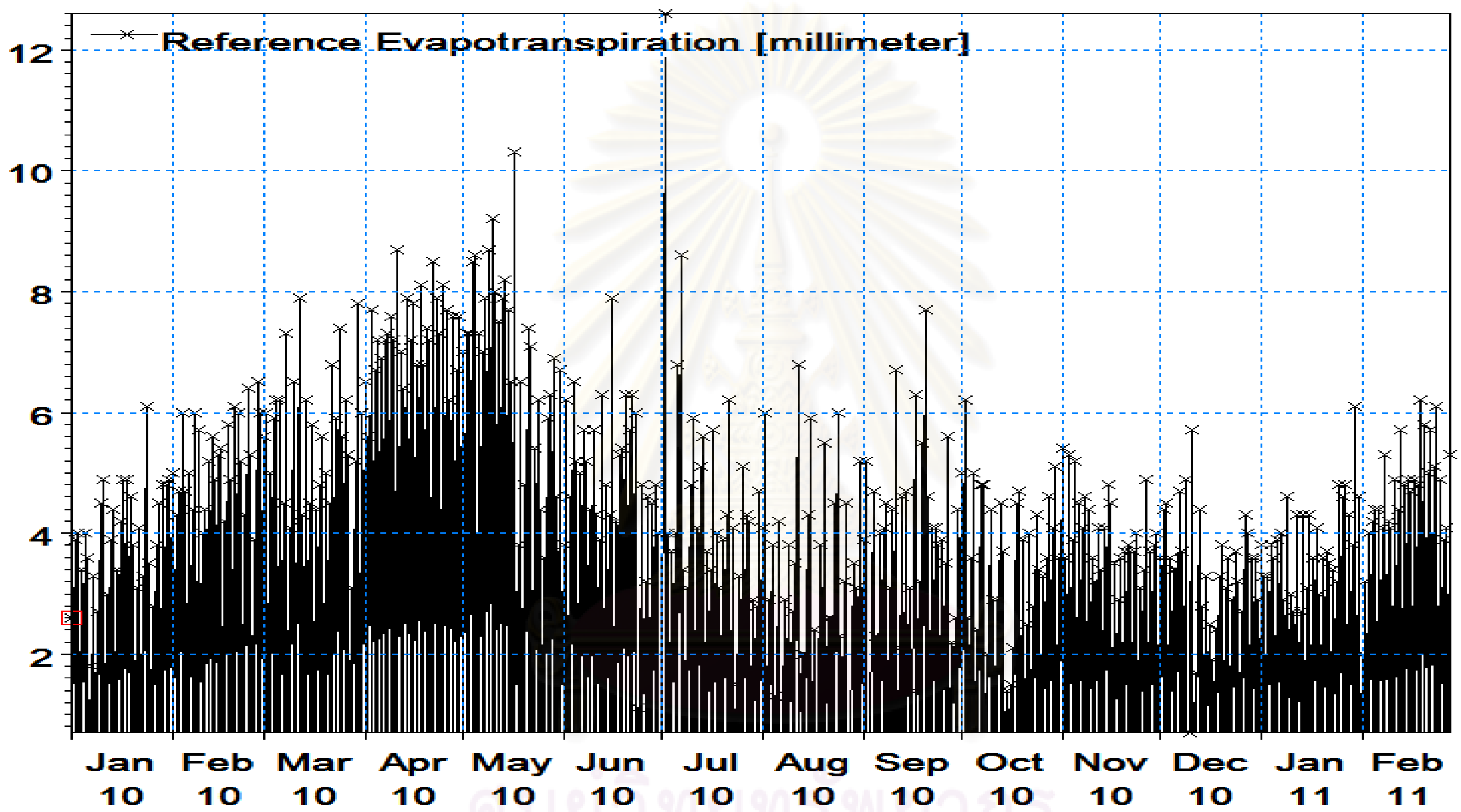

Figure D-2 Evaporation rate during simulation time (mm/d) (TMD)

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