EFFECTS OF AGRICULTURAL LAND USE ON THE TRANSPORT OF CADMIUM IN MAE TAO CREEK, THAILAND

Miss Thananporn Thamjedsada

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Science Program in Environmental Management
(Interdisciplinary Program)
Graduate School
Chulalongkorn University
Academic Year 2011

ผลกระทบของการใช้ประโยชน์ที่ดินทางการเกษตรต่อการเคลื่อนที่ของแคดเมียมในห้วยแม่ตาว ประเทศไทย

นางสาวธนัญพร ธรรมเจษฎา

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
สาขาวิชาการจัดการสิ่งแวดล้อม (สหสาขาวิชา)
บัณฑิตวิทยาลัย จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2554

Thesis Title	EFFECTS OF AGRICULTURAL LAND USE ON THE TRANSPORT OF CADMIUM IN MAE TAO CREEK, THAILAND
By	Miss Thananporn Thamjedsada
Field of Study	Environmental Management
Thesis Advisor	Pichet Chaiwiwatworakul, Ph.D.

Accepted by the Graduate School, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

....Dean of the Graduate School
(Associate Professor Amorn Petsom, Ph.D.)

THESIS COMMITTEE

....Chairman
(Assistant Professor Chantra Tongcumpou, Ph.D.)

....Thesis Advisor
(Pichet Chaiwiwatworakul, Ph.D.)

....Examiner
(Associate Professor Jin Anotai, Ph.D.)

....Examiner
(Assistant Professor Pisut Painmanakul, Ph.D.)

....External Examiner
(Somchai Chonwattana, Ph.D.)

ธนัญพร ธรรมเจษฎา : ผลกระทบของการใช้ประโยชน์ที่ดินทางการเกษตรต่อการเคลื่อนที่ของแคดเมียมในห้วยแม่ตาว ประเทศไทย. (EFFECTS OF AGRICULTURAL LAND USE ON THE TRANSPORT OF CADMIUM IN MAE TAO CREEK, THAILAND) อ.ที่ปรึกษาวิทยานิพนธ์หลัก : อ.ดร. พิเชฐ ชัยวิวัฒน์วรกุล, 132 หน้า

ลุ่มน้ำแม่ตาว เป็นบริเวณที่พบการปนเปื้อนของแคดเมียม เช่น ดินในแปลงนาที่ใช้น้ำจากลำห้วยแม่ตาว ดินตะกอนในห้วยแม่ตาว และข้าว จากปัญหาดังกล่าว ทำให้รัฐบาลดำเนินแก้ไขปัญหา โดยการรับซื้อและเผาทำลายข้าวเปลือกที่ปนเปื้อน การส่งเสริมการปลูกอ้อยเพื่อผลิตเอทานอล การสนับสนุนแหล่งน้ำเพื่อการเกษตรกรรม งานวิจัยนี้จึงมุ่งเน้นศึกษาผลกระทบของการใช้ประโยชน์ที่ดินทางการเกษตรและการก่อสร้างฝายในลำห้วยแม่ตาวต่อการเคลื่อนที่ของแคดเมียมในห้วยแม่ตาว

แคดเมียมในตะกอนแขวนลอยและตะกอนท้องน้ำ และขนาดของตะกอนท้องน้ำถูกสำรวจตลอดห้วยแม่ตาว ทั้งในฤดูฝนและฤดูแล้ง แบบจำลอง MIKE SHE ควบคู่กับ MIKE 11 ถูกนำมาใช้คำนวณระดับน้ำและอัตราการไหลในลำน้ำ โดยนำระดับน้ำที่บันทึกรายวันในห้วยแม่ตาวมาใช้ในการปรับเทียบแบบจำลอง หลังจากนั้นการเคลื่อนที่ของตะกอนจึงถูกคำนวณต่อยอดจากแบบจำลองชลศาสตร์ สุดท้ายจึงนำผลคำนวณการเคลื่อนที่ของตะกอนจากการจำลองและปริมาณแคดเมียมที่ตรวจวัดมาคำนวณการเคลื่อนที่ของแคดเมียมไปพร้อมกับตะกอนในห้วยแม่ตาว ผลการศึกษาพบว่า ตะกอนที่บริเวณท้ายน้ำส่วนใหญ่เคลื่อนที่มาในฤดูฝน โดยมีตะกอนแขวนลอยเป็นกระบวนการสำคัญ ปริมาณแคดเมียมที่เคลื่อนที่ผ่านไปทางบริเวณท้ายน้ำของลำห้วยในช่วงเดือนพฤษภาคม 2554 ถึงกุมภาพันธ์ 2555 มีค่าเท่ากับ 16.33 กิโลกรัม โดยเกิดขึ้นในฤดูฝนเป็นจำนวน 16.20 กิโลกรัม และในฤดูแล้งเป็นจำนวน 0.13 กิโลกรัม

จากการศึกษาการทดแทนการปลูกข้าวด้วยการปลูกอ้อยในการใช้ประโยชน์ที่ดินทางการเกษตร พบว่าตะกอนสะสมทั้งตะกอนแขวนลอยและตะกอนท้องน้ำมีปริมาณลดลง อย่างไรก็ตามเนื่องจากพื้นที่การเกษตรที่เปลี่ยนมาเป็นปลูกอ้อยมีจำนวนน้อยเมื่อเทียบกับพื้นที่เกษตรทั้งหมด จึงทำให้มีผลต่อการเคลื่อนที่ของแคดเมียมในปริมาณน้อยเช่นกัน และการศึกษาผลของการก่อสร้างฝายในลำห้วยแม่ตาวต่อการเคลื่อนที่ของแคดเมียมในห้วยแม่ตาว พบว่า การติดตั้งฝายบริเวณท้ายน้ำ ระหว่างสถานี MT 02 และสถานี MT 03 ส่งผลให้การเคลื่อนที่ของแคดเมียมที่ผ่านฝายมีปริมาณลดลง โดยที่ตำแหน่งที่ติดตั้งฝายเดิมมีการเคลื่อนที่ของแคดเมียมผ่านไปเท่ากับ 18.06 กิโลกรัม ลดลงเหลือ 12.86 กิโลกรัม จากอิทธิพลของฝายในช่วงการศึกษาจากเดือนพฤษภาคม 2554 ถึงกุมภาพันธ์ 2555

สาขาวิชา การจัดการสิ่งแวดล้อม ลายมือชื่อนิสิต ....

ปีการศึกษา 2554 ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก ....

5387528120 : MAJOR ENVIRONMENTAL MANAGEMENT
KEYWORDS : CADMIUM/ SUSPENDED SEDIMENT/ BED LOAD/ MAE TAO CREEK/ AGRICULTURAL LAND USE/ HYDRAULIC STRUCTRE/ SEDIMENT TRANSPORT/ MIKE SHE/ MIKE 11

THANANPORN THAMJEDSADA : EFFECTS OF AGRICULTURAL LAND USE ON THE TRANSPORT OF CADMIUM IN MAE TAO CREEK, THAILAND. ADVISOR : PICHET CHAIWIWATWORAKUL, Ph.D., 132 pp.

At the Mae Tao subcatchment high cadmium concentrations in environmental samples have been found i.e. soil in paddy fields absorbing water from the Mae Tao Creek, sediment in the Mae Tao Creek and rice. So, the government has established an implementation plan to solve the problems of cadmium contamination such as collecting and purchasing the contaminated rice and destroy it, establishment of the sugarcane plantation for ethanol production, construction of dams for development of water resources. This research concentrated on the effects of the change of agricultural land usage and the hydraulic structure on cadmium transport via suspended sediment and bed load in the Mae Tao Creek.

The cadmium concentrations of suspended sediment, bed load and grain size distribution of bed load along the Mae Tao Creek were gathered from field observations conducted from the dry and wet seasons. MIKE SHE coupled with MIKE 11 was applied to determine the time series of hydrodynamics (water depth and water discharge), which was calibrated with the measured water depth. Sediment transport was consequently computed by inputting the simulated hydrodynamics into the sediment transport module in MIKE 11. Eventually, the sediment transport data was simulated by the model and observed cadmium concentrations were used to obtain the cadmium transport in the Mae Tao Creek. From the results, cadmium contaminated via sediment transport in the Mae Tao Creek is mainly generated in the wet season, and was dominated by suspended sediment transport. From May 2011 to February 2012, the amount of cadmium transported out of the Mae Tao Creek was approximately 16.33 kg in the wet season with 16.20 kg and in the dry season with 0.13 kg.

As substitution of rice in current agricultural land use to sugarcane plantation leaded to a decrease of accumulated sediment both suspended sediment and bed load. However, the small change sediment slightly affected the cadmium; the land use change was a small area when compared to the whole study area. The assessment of hydraulic structure responses on cadmium transport in the Mae Tao Creek indicated that the cadmium transport through weir location for case without weir and with weir in the period May 2011 to February 2012 are 18.06 kg and 12.86 kg, respectively.

Field of Study : Environmental Management Student's Signature ....
Academic Year : 2011 .... Advisor's Signature ....

ACKNOWLEDGEMENTS

First and foremost, I would like to express deep sincere gratitude to my thesis advisor, Dr. Pichet Chaiwiwatworakul, for his valuable support and encouragement. His valuable help of knowledge and suggestions through thesis works have contributed to the success of this research.

Besides, I would like to express my sincere gratitude to the thesis committee, Assistant Professor Dr. Chantra Tongcumpou, Associate Professor Dr. Jin Anotai, Assistant Professor Dr. Pisut Painmanakul, and Dr. Somchai Chonwattana for their constructive recommendations and useful suggestions.

I would like to express my thankfulness to the Center of Excellence for Environmental and Hazardous Waste Management, Chulalongkorn University for fully support scholarship and funding for this research. Furthermore, the study was also earned the scholarship from CU. graduate school thesis grant.

I would like to special thank to the DHI Group for giving me the student license of the MIKE SHE and MIKE 11. Also, I would like to express my special appreciation to Dr. Somchai Chonwattana for his valuable help and suggestion on model simulation**.** My appreciation is also extended to the professor and staff at the EHWM for the knowledge and assistance. Moreover, I would like to express my acknowledgement to my friends for encouragement when I am experiencing a different situation.

Eventually, I do wish to express specially thank my beloved family for their financial support, moral support, valuable suggestions and confidence in me.

CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

1.1 Introduction

Cadmium is a heavy metal that has been concerned in terms of usage and toxicity of contaminants in the environment. Cadmium presents mainly as cadmium sulfide and associates with zinc, copper and lead ores. Cadmium is a main by-product of zinc treatment processes (National Toxicology Program, Department of Health and Human Services, 2011*)*. It can accumulate in plants is not toxic to them, but its toxic is affected to animals and humans eating the plants. Moreover, cadmium is very harmful to humans because of its longevity and accumulation. Long term exposure of cadmium via contaminated food can produce chronic known as Itai-Itai with a form of osteomalacia and proximal tubular renal dysfunction (Tohyama *et al*., 1982; Nogawa *et al*., 1983; Kido *et al*., 1988; Honda *et al*., 2010). Acute effects include pulmonary edema, headaches, nausea, vomiting, chills, weakness, and diarrhea (Nogawa and Kido, 1993).

Heavy metals are transported to natural water by trapping with sediments in the water system, and their accumulation is dominated by physical-chemical properties of the sediment. Beside acting as a pollutant accumulation and transporter, sediments are concerned about being a possible source of contamination because heavy metals can be released from the sediment bound back into the water system. The solubilities of heavy metal depend on water chemical properties such as pH, chelating agents, redox conditions and, salinity (Arnason and Fletcher, 2003; Jain, 2004; Chen *et al*., 2007; Yunus *et al*., 2011).

Thailand's largest zinc deposit is located in Mae Sot district, Tak province. Zinc mines are operated by several companies over the past 30 years (Tharathammathigorn, 2010). Some mining activities can cause cadmium contamination in the nearby surroundings, for example, drilling material transfer, disposal of mine tailings and drainage (Unhalekhaka and Kositanont, 2008). In the 1998-2003, the International Water Management Institute (IWMI) and Department of Agricultural (DOA) reported that the cadmium levels in paddy fields and rice were high at Ban Pateh and Ban Mae Tao Mai, Pratat Padaeng sub-district, Mae Tao district Tak province (Simmons *et al*., 2005). Then, the study was reported to the Ministry of Natural Resources and Environment for further action. In 2004, the ad hoc committee was established to investigate the problem of high cadmium contamination which consisting of representatives from the Ministry of Natural Resources and Environment, Ministry of Public Health, Ministry of Industry, Ministry of Agriculture and Cooperatives, Tak provincial officers and experts. According to several studies, all of results are similar to the results from the study of IWMI and DOA. They showed that Ban Pateh and Ban Mae Tao Mai, Pratat Padaeng sub-district covering 40 km^2 had low cadmium levels in surface water, groundwater and aquatic animals but had high cadmium levels in soil, sediment and rice. The stream sediment, which passed through the active zinc mine area, contained high cadmium concentrations ranging from 82 to 326 mg/kg. On the other hand, the stream sediment which located at the upstream contained a low cadmium concentration of 0.5 mg/kg. In agricultural area, 95% of rice was found to contaminate with cadmium which the levels exceeding the standard of Codex Committee on Food Additives and Contaminants; CCFAC, 1972 (maximum level for cadmium of 0.2 mg/kg in rice). The cadmium concentrations of soil samples collected from the agricultural area receiving water from the Mae Tao Creek were in the range of 61-207 mg/kg, which exceeded the soil standard of European Economic Community (3 mg/kg). According to the public health, the Ministry of Public Health reported that 220 from 1,000 local persons were detected by urine examinations, high cadmium concentrations in a range of 5 to 10 μg/g creatinine was found, which is a significant health risk. Consequently, the Royal Thai Government has solved the problems in the Mae Tao Creek since 2004 such as collecting and purchasing the contaminated rice to be destroyed, establishment of non food crops plantation such as a sugarcane for ethanol production, developing the water resources such as canals, reservoirs and irrigation by construction of check dams (PCD, 2011).

According to the previous studies as mentioned above, Mae Tao subcatchment was high potential for cadmium contamination in agricultural areas and productions. Moreover, the natural pH of the water in the study area is about 7.91-8.44 (Maneewong, 2005; Karoonmakphol and Chaiwiwatworakul, 2010; Tharathammathigorn, 2010) that means cadmium is not in a soluble form. Therefore, Mae Tao subcatchment was selected to demonstrate the cadmium contamination via suspended sediment and bed load, and its transport. This study focuses on the effects of the change of agricultural land use in study area on hydrological change to the sediment transport by simulating with MIKE SHE coupled with MIKE 11.

1.2 Objective of the study

- To demonstrate the effects of agricultural land use on hydrological change in term of the transport of cadmium contaminated sediment in the Mae Tao Creek, Thailand.

Sub-objectives:

- To demonstrate the effects of land use changing by applying Geographic Information System (GIS).
- To demonstrate the effects of hydraulic structures on the transport of cadmium in the Mae Tao Creek, Thailand.
- To estimate the accumulated cadmium transport via bed load and suspended sediment in the Mae Tao Creek, Thailand.

1.3 Hypothesis

- The changing of agricultural land use in study area could affect the transport of cadmium via bed load and suspended sediment.

1.4 Scope of study

- The effects of agricultural land use focused on the transport of cadmium via bed load and suspended sediment in the Mae Tao Creek, Thailand.
- The changing of agricultural land use focused on the crop type changing and the hydraulic structure operation.
- There are four scenarios which are set up in the model to examine the effects on sediment transport by focusing on the effect of agricultural land use and the effect of hydraulic structure operation:
    1. current agricultural land use: setup the land use as current crop type
    2. conversion of rice to sugarcane plantation

3. without hydraulic structure operation
4. with hydraulic structure operation: by opening the gate's weir

- Bed load and suspended sediment samples were collected and analyzed to determine the effects of both the wet and dry seasons.
- The bed load and suspended sediment were collected by compositing and analyzed triplicate at the laboratory.
- The study focuses on total cadmium accumulated in bed load and suspended sediment.
- Topography, metrological data, properties of the saturated zone and unsaturated zone data for model were reviewed from the government sectors.
- MIKE SHE and MIKE 11 model are used to simulate the hydrodynamic system and sediment transport.
- Station MT 01 was used as downstream boundary condition.
- The water level at station MT 04 was record daily to verify model.

1.5 Expected outcome

- The accumulated cadmium transfer values due to sediment transport are quantified with scenarios of agricultural land use change and hydraulic structure.

CHAPTER II

LITERATURE REVIEWS

2.1 Studied area

2.1.1 Location

The studied area is located in Mae Sot district, Tak province, Thailand approximately from 1836000N to 1848000N and 457000E and 472000E. Mae Sot consists of 10 sub-districts, namely, Mae Sot, Mae Ku, Phawo, Mae Tao, Mae Kasa, Tha Sai Luat, Mahawan, Dan Mae La Mao, and Pratat Padaeng. There are two zinc mines in the area which are operated by Padaeng Industry Public Company Limited and Tak Mining Company Limited (Karoonmakphol, 2009).

2.1.2 Hydrology and Climates

Mae Sot district consists of seven subcatchments, namely, Luang Creek, Pong Creek, Mae Tao Creek, Mae Ku Creek, Mae Ku Luang Creek, Phak La Creek and Mae Paen Creek. Mae Tao Creek originates from Doi Mae Tao and Doi Re Pha Do. Major branches are Mae Tao Right, Mae Tao Left, Pa Pu Creek and Pong Creek. The Mae Tao Creek is a stream with continued flow throughout the year; however: it has little amount of water and is shallow in some sections during the dry season. The waterways formed a dentritic pattern. The flow direction is from the east to west passing zinc deposits area to Moei River. The distance of the Mae Tao Creek, riverhead to Moei River, is about 33 kilometers. The grain size particle in water is classified as gravelly sand. The stream has a height bank about 1.5 to 2.0 meters, and an average width about 3.0 to 4.0 meters. The depth of Mae Tao Creek is about 0.15 to 0.20 meters in the dry season, and 1.0 to 1.2 meters in the wet season. Average amount of water is 16.3 million cubic meters per year. The lowest average minimum flow is about 7,499 cubic meters in December while the average maximum flow is about 5.6 million cubic meters in August (Mahidol University, 2009).

The studied area is in the western part of Tak province. This area has a high rainfalls potential because of the monsoon. Tak's climates consist of 3 seasons: summer (February to mid-May), rainy (mid-May to October), and winter (October to February) (PCD, 2011).

2.1.3 Land utilization

According to the Department of Primary Industries and Mines, under the Ministry of Industry, the land use of Mae Sot can be classified into five major categories (DPIM, 2006).

1) Forest area: is in the eastern part of the study area. The area is in the national forest area. Mae Sot Forest is covered with mixed deciduous forest and underlain by sandy loams or lateritic soil with low fertility, which results in dwarfed trees. Several areas are trespassed that results in forest degradation, so there are a reforestation such as teak planting.

2) Agricultural area: is in the western part and is the largest type of land use in the area. Main agriculture is growing rice which applied water from rainfall and the Mae Tao Creek. The other economic plant, such as soybeans and corn, are grown to replace the rice during dry season.

3) Urban area: Community of Karen by locating at the area by consisting of Ban Mae Tao Mai (western part), Ban Thum Suea (north part), Ban Nong Khiao (southeast part), Ban Pateh (northwest part), and a few of Ban Mae Ku Nuea (southwest part).

4) Public area: Roads, creeks and reservoirs. The roads are not only highways, but also the roads which are divided to get to other village such as concrete roads, laterite roads and local ground road.

5) Mining area: 10 concession blocks to be granted the zinc mining by including mining area, ore processing area and discharge area.

Table 2-1 Land use around zinc mines area

Land use	Area (m^2)				
	Zone A	Zone B	Zone C	Zone D	Total
	within 0-5 kilometers downstream mining	within 5-10 kilometers downstream mining	greater than 10 kilometers downstream mining	upstream and within mining	
Forest	2,907,743	749,060	3,320,631	13,516,819	20,494,253
Agriculture	18,763,074	21,004,936	8,689,164	7,369,610	55,826,784
Community	2,288,958	2,874,886	1,269,381	46,141	6,479,366
Public land	336,100	300,298	982,095	145,492	1,763,985
Mine	-	-	-	3,921,938	3,921,938
Industry	704,126	70,820	738,729	-	1,513,675
Total area	25,000,000	25,000,000	15,000,000	25,000,000	90,000,000

2.1.4 Mining

Around 1947, the Department of Mineral Resources found the source of zinc ore at Doi Padaeng, Mae Tao Sub-district, Mae Sot district, Tak province. In 1969-1975, Thai Zinc Company Limited surveyed and was granted the zinc mining by obtaining about 150,000 tons of ore, and closed at a later time. The mine was left for 6 years and was taken over by Padaeng Industry Public Company Limited in 1981. In 1985, Tak Mining Company Limited was granted the concession for mining in a relative area. The 2 zinc mines have been granted the concession for mining until now (Nunman, 2006; PCD, 2012).

Padaeng Industry Public Company Limited has been received 6 concession blocks from the Department of Mineral Resources since 1982. Four of these were expired and the other 2 concession blocks are still in operation, which will be expired in 2017 and 2023. Tak mining Company Limited has been granted 5 concession blocks in operations both surface and underground mining. From 5 concession blocks, 2 were expired but have been continually renewed. One concession block will be expired in 2012 and the other 2 concession blocks will be expired in 2021. Although Tak Mining Company Limited has stopped mining activities since 2003, the company has operated to take out zinc ore from the rock gaps and sell it to Padaeng Industry Public Company Limited (DPIM, 2006).

For the environment impact assessment, Padaeng Industry Public Company Limited conducts and submits report to the office of Natural Resources and Environmental Policy and Planning (ONEP) and other agencies every 6 months. Tak Mining Company Limited chose to stop mining activities hence dose not conduct the environmental impact assessment report. However, environmental management of Tak Mining Company Limited was not sufficient during the non-production period that might affect the environment. According to the study, three major causes of contamination could be identified as: (1) rainfall flowing through mining area, (2) settling ponds near the creek, and (3) flooding of erosive mine drift (PCD, 2011).

2.2 Cadmium

Cadmium naturally presents in the environment as it occur together with zinc ores and less occuring together with lead and copper ores. The cadmium using was firstly in paint pigment, dental amalgams, and substitute for tin after discovering in 1817. However, almost all using has been occurred in nickel-cadmium batteries, pigments, alloy electroplating and coating, and stabilizers in plastics (IARC, 1993; Llewellyn, 1994; Plachy, 2001; National Toxicology Program, Department of Health and Human Services, 2011).

Cadmium exists in nature in various inorganic forms. In air, cadmium vapor is instantly oxidized to be cadmium oxide. Cadmium vapor is produced to be another compound such as cadmium carbonate, cadmium hydroxide, cadmium sulfite, cadmium sulfate and cadmium chloride when reacts to carbon dioxide, water vapor, sulfur dioxide, sulfur trioxide and hydrogen chloride, respectively. Moreover, the transform compounds can be accumulate and discharge to the environment. In water, cadmium consists of two forms that are water-soluble form (Cd^{2+}) and water-insoluble form (cadmium sulfide, cadmium carbonate, cadmium oxide). However, cadmium in insoluble form can be changed to a soluble form when water quality in nature changes such as water pH (IPCS, 1992; World Bank Group, 1998).

2.2.1 Sources of cadmium contamination in the environment

Cadmium contamination in environment is occurred from 2 sources that are natural sources and anthropogenic sources (ICdA, 2011).

1) Natural sources: the major natural source of cadmium emission to the atmosphere is volcanic occurrence which during episodic eruptions and continuous low-level activity. The amount of natural cadmium accumulation is different in each area depending on the types of rocks which the rocks originate from (IPCS, 1992).

2) Anthropogenic sources: human activities are the greater source of cadmium contamination than natural sources. Anthropogenic sources consist of many activities such as industry activity, fossil fuel combustion, fertilizer application, sewage sludge, municipal incineration, landfill, traffic and transport. Cadmium from industry activities can be divided into 3 parts that are primary production, secondary production and recycling production (OSPAR Commission, 2002)

- Primary production: metallurgic process such as non-ferrous industry (mining, smelting and refining of zinc, lead and copper ores), meting and pouring of cadmium element, and iron and steel industry.
- Secondary production: manufacture and disposal of cadmium containing products such as nickel-cadmium battery, solar cell, alloy and electronic compound, pigment and coloring agent, stabilizer, coating.
- Recycling production: cadmium recycling plants

2.2.2 Cadmium contamination and distribution in the environment

As mention above, human activities are major source of cadmium contaminations in the environment; especially emission from manufacturing of industry, mining wastewater, disposal of cadmium containing wastes. These human activities can cause cadmium distribution into the environment by soil to water, water to atmosphere, atmosphere to soil, soil to atmosphere and etc. Using of wastes or contaminated byproducts can directly and widely increase the impacts. A cycle of cadmium distribution is shown in Figure 2-1 (Llewellyn, 1994).

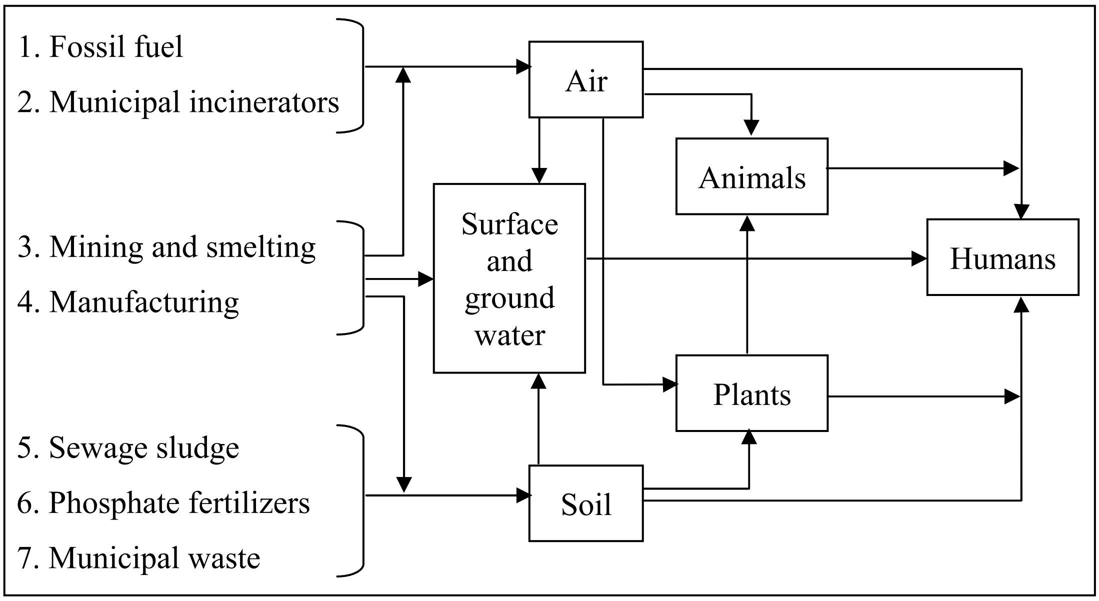


Figure 2-1 Human exposure to cadmium (Llewellyn, 1994)

2.2.3 Cadmium and regulation

Cadmium exists everywhere in nature such as air, water, soil, and foodstuff. The standards of cadmium concentration in nature are issued by various organizations as shown in Table 2-2. Cadmium concentrations in air, water and soil are under the Hazardous Substances Acts of B.E. 2535 (1992). Moreover, European Economic Community (EEC) established the soil quality standard. Maximum levels for cadmium in water are complied with in the surface water quality standard and groundwater quality standard according to the Notification of the National Environmental Board No. 8, B.E. 2537 (1994) and the Notification of the National Environmental Board No. 20, B.E. 2543 (2000), respectively (PCD, 2009). Cadmium level standards in aquatic animals are issued by various countries and organizations. Cadmium concentration in food is compared with the Codex Committee on Food Additives and Contaminants (CCFAC, 2002) and the joint FAO/WHO Expert Committee on Food Additives (JECFA, 2003).

Table 2-2 Standard of cadmium concentration in the environment

Substances	Cadmium Concentration Permission	References
Air Quality Standards		
- Air emission	1 mg/m^3	PCD, 1998
- Dust in working area	0.2 mg/m^3	
- Dust in working area (maximum level)	0.6 mg/m^3	
- Fume in working area	0.1 mg/m^3	
- Fume in working area (maximum level)	3 mg/m^3	
- Emission from infected waste incinerator	0.05 mg/m^3	PCD, 2009
Water Quality Standards		
- Surface water: Hardness ≤ 100 mg/L of $CaCo_3$	0.005 mg/L	PCD, 2009
: Hardness > 100 mg/L of $CaCo_3$	0.05 mg/L	
- Groundwater	0.003 mg/L	
- Groundwater for drinking purposes	0-10 mg/m^3	
- Drinking water	0-10 mg/m^3	
- Bottled drinking water	5 mg/m^3	
- Water for aquatic living	1 mg/m^3	
- Industrial effluent	0.03 mg/m^3	
- Discharged water into irrigation system	30 mg/m^3	
- Discharged water into deep wells	100 mg/m^3	
- Zinc smelter effluent	100 mg/m^3	PCD, 1998
Soil Quality Standards		
- Soil for habitat and agriculture	37 mg/kg	PCD, 2009
- Soil for other purposes	810 mg/kg	
- Sludge amended soil for agriculture	1.0-3.0 mg/kg	EEC, 1986
- Agricultural soil	3.0 mg/kg	NEPC, 1999

Table 2-2 Standard of cadmium concentration in the environment (continued)

Substances	**Cadmium Concentration Permission**	**References**
- Agricultural soil	1.4 mg/kg	Canadian Council of Ministers of the Environment, 2006
- Agricultural soil (Vietnam standard)	2.0 mg/kg	Simmons *et al*., 2008
Food Quality Standards		
- Rice grain	0.2 mg/kg	CCFAC, 2002
- Milled Rice (Codex & Japanese)	0.4 mg/kg	JECFA, 2005
Aquatic animal Quality Standards		
- Fish and fishery: CAC, WHO/FAO	1.00 mg/kg	PCD, 2011
: TPHR, Australia	5.50 mg/kg	
: NHMRC, Australia	2.00 mg/kg	
: FDA, USA	2.00 mg/kg	
: EU	0.10-1.00 mg/kg	
: Japan	1.00 mg/kg	
: India	3.00 mg/kg	
- Sea fish (Czech Republic)	0.20 mg/kg	
- Fresh water fish (Czech Republic)	0.10 mg/kg	
- Molluscs (Czech Republic)	1.00 mg/kg	
- Crustaceans and gastropods (Czech Republic)	0.50 mg/kg	
Health Perspective		
- Provisional Tolerable Weekly Intake (PTWI)	7 µg/kg body weight/week	JECFA, 2003

2.2.4 Cadmium contamination in Mae Sot district

The preliminary assessment of cadmium contamination previous research conducted by many researchers consists of surface water quality, groundwater quality, soil quality, sediment quality and rice quality as shown in Tables 2-3, 2-4, 2-5, 2-6 and 2-7, respectively.

Table 2-3 Summary of cadmium contaminated surface water from literature review

Researcher and study year	**Study area/ Sample**	**Result of cadmium contamination**
Padaeng Industry Public Company Limited, 1992-2002 and 2008-2009 (Padaeng Industry Public Company Limited, 2009)	During 1992-2002: Mae Tao Creek: 5 stations located before entering zinc mine area to Mae Tao Mai During 2008-2009: - Mae Tao Creek: 11 stations, Mae Ku Creek: 4 stations - Both dry and wet season	Most surveyed stations in the Mae Tao Creek showed that cadmium levels in surface water were lower than 0.003 to 0.005 mg/L. However, cadmium at discharge point of zinc mine was in the range of 0.05-0.10 mg/L that was higher than the surface water quality standard. Mae Tao Creek: The water pH values were slightly alkali that ranged from 6.94-8.37 in dry season and 7.33- 8.56 in wet season. The total cadmium concentrations in surface water were between lower than 0.0001-0.0029 mg/L in dry season, and lower than 0.0001- 0.0278 mg/L in wet season. Mae Ku Creek: Water pH values tended to be slightly alkali liked in the Mae Tao Creek that were between 7.33-8.50 in dry season and 6.61-8.40 in wet season. Total cadmium values ranged from lower than 0.0001-0.0006 mg/L in dry season and lower than 0.0001-0.0046 mg/L in wet season. The results showed that all stations in the Mae Tao Creek and the Mae Ku Creek contained lower cadmium levels than the surface water quality standard.

Table 2-3 Summary of cadmium contaminated surface water from literature review (continued)

Institute/Researcher and study year	Study area/ Sample	Result of cadmium contamination
DPIM, 2003-2004 (DPIM, 2006)	- Natural Creek - Water samples from zinc mine project and water supply	From the water quality results, water pH values in surface water ranged from 5 to 9. Cadmium concentration complied with Surface Water Quality Standard for Type III surface water resource (< 0.05 mg/L).
Department of Water Resources, 2004 (PCD, 2011)	- Mae Tao Creek: downstream of Ban Mae Tao Mai for 10 km. (20 samples)	The amount of cadmium contamination was in the range of lower than 1-2.81 µg/L, which was less than the surface water quality standard.
Mahidol University, 2004 (Mahidol University, 2006)	- Mae Tao Creek: 8 stations, Mae Ku Creek: 2 stations, Mae Sot Creek: 1 control station - Both dry (April 2004) and wet season (September 2004)	Water pH ranged from 6.9-8.6 at the Mae Tao Creek and the Mae Ku Creek, and 7.0-7.2 at the Mae Sot Creek. At the Mae Tao Creek and the Mae Ku Creek, cadmium concentrations ranged from 0.004-0.006 mg/L in dry season, and 0.0241-0.0318 mg/L in wet season. At the Mae Sot Creek, cadmium levels were 0.006 and 0.0241 in dry and wet season, respectively. Cadmium was less than the surface water quality standard in all stations. Control station was also detected because surrounding area is agriculture. Cadmium in surface water may be influenced by fertilizer using, which may distribute cadmium into agricultural area and leach into water. Moreover, the cadmium level was higher in wet season.

Table 2-3 Summary of cadmium contaminated surface water from literature review (continued)

Institute/Researcher and study year	Study area/ Sample	Result of cadmium contamination
Maneewong, 2005	- Mae Tao Creek, Mae Ku Creek, and Nong Khiao Creek (control station)	Surface water's pH varied in a range of 7-8.5. Cadmium values showed very low concentrations and complied with the surface water quality standard (less than 0.005 mg/L).
Krissanakriangkrai, 2006 (Krissanakriangkrai, 2007)	- Mae Tao Creek: 9 stations at upstream to downstream of mining area for 10 km. - Both dry and wet season	Average cadmium levels were 0.5 µg/L and 2.16 µg/L in dry and wet season, respectively. During the dry season, cadmium along the Mae Tao Creek was not significantly different for sampling stations at upstream and downstream of mining area. During the wet season the distribution of cadmium was significantly higher than the dry season. However, cadmium levels in all stations were less than the standard.
Primary Industries and Mines Office, Northern part, 2009	- Mae Tao Creek: 13 stations, Mae Ku Creek: 6 stations	The water pH values ranged from 7.3-8.2. The average cadmium concentration was lower than 0.005 mg/L, which presented in very low quantity and in range of surface water quality standard.
Pollution Control Department, 2010 (PCD, 2011)	- Upstream to downstream of Mae Tao Creek and Mae Ku Creek with 20 water samples	The surface water samples were collected during Aug. 2010. The cadmium concentrations in all sampling stations were < 0.0001 mg/L, which complied with the surface water quality standard.

Table 2-4 Summary of cadmium contaminated groundwater from literature review

Institute/Researcher and study year	Study area/ Sample	Result of cadmium contamination
Padaeng Industry Public Company Limited, 1992-2002 and 2008-2009 (Padaeng Industry Public Company Limited, 2009)	During 1999: shallow wells: 3 stations During 2008-2009 (dry and wet season): shallow and deep wells - Around mining area (village area): Ban Mae Tao Mai, Ban Thum Suea, Ban Pateh - At mining area: before and after tailing storage basin, discharge of tailing storage basin	During 1999, pH values ranged from 7.2 to 7.6, and the total cadmium values ranged from lower than 0.001 to 0.001 mg/L. During 2008-2009, the total cadmium values from shallow and deep wells around mining area were lower than 0.001 to 0.002 mg/L. At mining area, the water pH values were between 6.74-7.67 in dry season and 6.87-7.78 in wet season. The cadmium concentrations were between lower than 0.0001-0.0034 mg/L in dry season and lower than 0.0001-0.0310 mg/L in wet season. Cadmium in wet season was not only higher concentration than in dry season but also higher than groundwater quality standard for drinking.
Department of Groundwater Resources, 2004 (PCD, 2011)	- Ban Pateh, Ban Mae Tao Mai, Ban Mae Ku Noi, Ban Mae Ku Nuea, Ban Mae Ku Tai - Shallow well for consumption using (10 samples), and public groundwater wells (4 samples)	All of groundwater samples had cadmium less than 1.00 µg/L, This study monitored groundwater level in the study area that can indicate the flow direction in floodplain deposits aquifer (Qfd) by flowing from Ban Pateh, which is foothills area and sloping through the Mae Tao Creek and Ban Mae Tao Mai, and finally flowing into Ban Mae Ku Noi, Ban Mae Ku Nuea and Ban Mae Ku Tai, respectively.

Table 2-4 Summary of cadmium contaminated groundwater from literature review (continued)

Institute/Researcher and study year	Study area/ Sample	Result of cadmium contamination
Mahidol University, 2004 (Mahidol University, 2006)	- Groundwater wells at Ban Mae Ku Nuea and Ban Pateh, Shallow wells at Ban Thum Suea - Both dry season (April 2004), and wet season (September)	During dry season, the average cadmium concentrations ranged from 0.004-0.006 mg/L, which was higher than the appropriate groundwater standard for drinking (lower than 0.003 mg/L), but still lower than maximum permission of groundwater quality standard (less than 0.01 mg/L). During wet season, the average cadmium concentrations ranged from 0.02 to 0.0268 mg/L, which higher than the groundwater quality standard for drinking.
Pollution Control Department, 2010 (PCD, 2011)	- Mining area and downstream: 17 groundwater wells and shallow wells - Padaeng Industry Public Company Limited: 3 monitoring wells	The groundwater samples were collected during August 2010. The cadmium concentrations in all sampling stations were between 0.001-0.003 mg/L, which was lower than the groundwater quality standard. Moreover, cadmium concentrations in groundwater from shallow wells were not different when comparing between before and after stirring water in the well.

Table 2-5 Summary of cadmium contaminated soil from literature review

Institute/Researcher and study year	Study area/ Sample	Result of cadmium contamination
IWMI-DOA, 1998-2000 and 2001-2003 (Simmons *et al*., 2005)	- During 1998-2003: paddy field area near Ban Pateh (154 plots) - During 2001-2003: paddy field near Mae Tao Creek (434 plots)	Total cadmium concentrations in soil were higher than EU standard (level of cadmium contamination lower than 3 mg/kg) for 94 times and 72 times during 1998-2002 and 2001-2003, respectively.
Somboon, 1999	- Upstream and downstream areas located in the same watershed with zinc mine, and nearby area outside the watershed boundary	Total cadmium was 50.84 mg/kg, which was higher than that in upstream area (0.93 mg/kg) and in nearby area (1.09 mg/kg). Furthermore, average cadmium was higher than the soil quality standard in downstream while the other two study areas were lower. There was statistical evidence that the distribution of cadmium concentrations in the downstream area was significant higher than the other two areas at statistically significantly level of 0.05. The average cadmium concentrations at 3 study area differed from the soil quality standard at the statistically significantly level of 0.05.
Simmons, 2000-2002 (Simmons *et al*., 2003)	Rice fields receiving water from zinc mining area	Cadmium concentrations in soil samples varied between 2.91-284 mg/kg.

Table 2-5 Summary of cadmium contaminated soil from literature review (continued)

Institute/Researcher and study year	**Study area/ Sample**	**Result of cadmium contamination**
Simmons, 2001-2002 (Simmons *et al*., 2005)	- Pratat Padaeng sub-districts	Soil samples contained cadmium concentrations between 0.5-284 mg/kg.
Simmons, 2001-2003 (Simmons *et al*., 2008)	- Pratat Padaeng and Mae Tao Mai sub-districts - During 2001-2002: 308 soil samples at 0-20 cm. depth levels During 2003: 20 fields	During 2001-2002, cadmium levels in soil samples were in the range of 0.59-217 mg/kg with the average of 26.2 mg/kg. 89% of total soil samples led cadmium concentration exceeded the standard (3.0 mg/kg). In comparison with the Thai Investigation Level of cadmium, 0.15 mg/kg (Zarcinas, 2004), total soil exceeded this standard. During 2003, cadmium concentrations in 20 soil samples varied between 2.38-168 mg/kg with the average of 36.7 mg/kg. Only 2 samples complied with the soil quality standard of EU.
Department of Primary Industries and Mines, 2003-2004 (DPIM, 2006)	- Pratat Padaeng, Mae Tao and Mae Ku sub-district - soil at every depth levels of 20 cm. for 1-2 m.	Upstream of the Mae Tao Creek and Mae Ku were designated 13 stations located before zinc mines with 57 samples. Soil contained cadmium lower than 1-9 mg/kg at depth level of 1 m. Mine area was designated 24 stations, a high terrain and colluvium on western region with 119 samples. Cadmium was <1-430 mg/kg.

Table 2-5 Summary of cadmium contaminated soil from literature review (continued)

Institute/Researcher and study year	Study area/ Sample	Result of cadmium contamination
		Alluvial plain area was designated 16 stations with 83 samples. The samples were collected at agricultural area on the western region of study area. They contained cadmium between <1-101 mg/kg. Furthermore, the cadmium contamination depended on distance from the zinc deposit area; for example: they will comply with the standard with 4 kilometers from the zinc deposit area.
Mahidol University, 2004 (Mahidol University, 2006)	- Soil samples at depth level of 0-30 cm (10 stations): 8 stations at impact area and 2 stations at near zinc deposit area.	The soil pH values ranged from 6.2 to 8.0. The most surveyed station contained cadmium concentrations between no detection (ND)-136.13 mg/kg, except both in dry and wet season that the amount of cadmium contamination at downstream of discharge point's Padaeng Industry Public Company Limited was higher than 37.0 mg/kg.
Department of Mineral Resources, 2004-2005 (PCD, 2011)	Mae Tao Creek and Mae Ku Creek: 184 stations	Shallow soil samples contained cadmium concentrations between 0.3-192.3 mg/kg while the soil samples around road contained high cadmium concentrations between 159-1,027 mg/kg.

Table 2-5 Summary of cadmium contaminated soil from literature review (continued)

Institute/Researcher and study year	Study area/ Sample	Result of cadmium contamination
IWMI-LDD, 2004-2005 (Simmons *et al*., 2005)	Pratat Padaeng and Mae Tao Mai sub-district: 660 soil samples	The total cadmium concentrations in soil were between 0.1-284 mg/kg, and over 85% was higher than EU standard.
Chanpo, 2005	Mae Ku Creek	Total cadmium ranged from 0.42 - 101.69 mg/kg, with an average of 493 mg/kg. Cadmium, which plant can absorb, ranged from 0.03 - 63.78 mg/kg with an average of 2.48 mg/kg. 75% of samples led cadmium lower than 3 mg/kg, only 2 samples were >80 mg/kg.
Chanthachot. *et al*., 2005	Mae Tao Creek: 12 stations	Soil samples contained cadmium concentrations between 4-92 µg/kg, which higher than EU standard.
Sriprachot, 2006	- shallow soil: every 200 m. for 1 km^2 at Ban Pateh - deep soil: at lowland/highland of Mae Tao Creek (right/left side) - control soil: at paddy field for 7 km. from northern of Ban Pateh	Soil contained cadmium levels between 23-27 mg/kg. The results of soil analysis showed that soil, which received water from the Mae Tao Creek contained cadmium higher concentration than other samples in same study area. The cadmium contaminated was low at more depth levels of soil and highest at depth levels of 0-20 centimeters by immediately decreasing at depth levels of 20-40 cm.

Table 2-5 Summary of cadmium contaminated soil from literature review (continued)

Institute/Researcher and study year	Study area/ Sample	Result of cadmium contamination
Phaenark. *et al*., 2006-2007 (Phaenark. *et al*., 2009)	- Padaeng Industry Public Company Limited and Ban Pateh - tailing pond area, open pit area, stockpile area, forest area, and cadmium contaminated rice field.	Soil pH values were between 7.1-7.6. Total cadmium concentrations were in the range of 64-1,458 mg/kg. The total cadmium concentrations at each station were 596 in mg/kg in tailing pond area, 543 in mg/kg open pit area, 894 mg/kg in stockpile area, 1,458 mg/kg in forest area, and 64 mg/kg in cadmium contaminated rice field.
Akkajit, 2007 (Akkajit and Tongcumpou, 2010)	- Downstream of Padaeng Industry Public Company Limited - 81 soil samples at 0-30 cm depth level	Soil contained cadmium concentration in the range of 0.73-172.7 mg/kg, with the average cadmium concentration of 15.14 mg/kg. In comparison with the soil quality standard for sludge-amended soil of European Union (level of cadmium contamination lower than 3.0 mg/kg), 50% of 81 soil samples complied with the standard.
Unhalekhaka and Kositanont, 2008	- Mae Tao Creek Ngae Sai, Mae Tao Creek, Mae Ku Creek and Nong Khiao Creek - 8 soil sample: at 0-10 depth level were taken with 55 mm. diameter	Soil pH values were between 6.3-6.8. The total cadmium concentrations in soil ranged from 8.45 mg/kg (upstream) to 22.50 mg/kg (downstream) at the Mae Tao Creek, and 3.50 mg/kg at the Mae Tao Creek Ngae Sai. The lowest cadmium concentration found at the Nong Khiao Creek with 1.10 mg/kg while the highest cadmium concentration found at the Mae Ku Creek with 34.95 mg/kg.

Table 2-5 Summary of cadmium contaminated soil from literature review (continued)

Institute/Researcher and study year	**Study area/ Sample**	**Result of cadmium contamination**
Pollution Control Department, 2010 (PCD, 2011)	- Soil in agricultural area that received water from Mae Tao Creek and Mae Ku Creek - 16,500 samples at depth levels of 0-30 cm., and 481 samples at depth level of 30-60, 60-120, 120-180 cm.	Average cadmium levels in soil at 0-30 cm. were lower than 0.5-338 mg/kg. While 25 samples were collected from agricultural area, where was not received water from the Mae Tao Creek and the Mae Ku Creek, they contained cadmium concentrations between 0.5-3.96 mg/kg. 86.4% of soil samples were lower than soil quality standard. 88% of 161 soil samples at 30-60 cm. contained cadmium levels less than 0.05 mg/kg with an average of 0.8 mg/kg, but 5.0% of 161 soil samples had higher level than the soil quality standard. The highest cadmium concentrations in soil found at Ban Mae Ku Nuea and the Mae Ku Creek for 32 mg/kg and 21 mg/kg, respectively. 93% of 161 soil samples at 60-120 cm. depth level contained cadmium concentrations lower than 0.05 mg/kg. Only 1 soil samples at the Mae Ku Creek contained cadmium concentration higher than the soil quality standard with 29.48 mg/kg. 158 of 159 soil at 120-180 cm. contained cadmium lower than 0.05 mg/kg while the other one contained cadmium with 1.94 mg/kg.

Table 2-6 Summary of cadmium contaminated sediment from literature review

Institute/Researcher and study year	Study area/ Sample	Result of cadmium contamination
Padaeng Industry Public Company Limited, 1992-2002 and 2008-2009 (Padaeng Industry Public Company Limited, 2009)	During 1999: - sediment samples from tailing storage basin and downstream of water discharge point During 2008-2009: - Mae Tao Creek and Mae Ku Creek (15 stations) - Both dry (2 times/year) and wet season (6 times/year)	During 1997, upstream and downstream of discharge point and upstream of Ban Pateh village contained cadmium levels of 13, 50, 6 mg/kg in dry season, and 6, 7, 5 mg/kg in wet season. During 1998, cadmium levels at same study areas were 40, 150, 223 mg/kg in dry season, and 289, 1350, 150 mg/kg in wet season. During 1999, cadmium level became 0.01 mg/kg at tailing storage basin and came down at downstream of discharge as 0.001 mg/kg. During 2008-2009, cadmium levels at the Mae Tao Creek were lower than 1-218 mg/kg in dry season and lower than 1-66 mg/kg in wet season. Cadmium levels at the Mae Ku Creek were lower than 1-34 mg/kg in dry season and lower than 1-182 mg/kg in wet season.
Department of Primary Industries and Mines, 2003-2004 (DPIM, 2006)	- Mae Tao Creek and Mae Ku Creek: 43 samples - During March and May 2003, April and August 2003	Cadmium levels tended to be high at downstream of mine area, but they were decreased by distance. High cadmium levels were found in the Mae Ku Creek with 101-114 mg/kg, even if it did not receive discharge directly from the zinc mine. Sediment in tailing storage basin had cadmium levels of 195-1,260 mg/kg.

Table 2-6 Summary of cadmium contaminated sediment from literature review (continued)

Institute/Researcher and study year	Study area/ Sample	Result of cadmium contamination
Mahidol University, 2004 (Mahidol University, 2006)	- Mae Tao Creek: 8 stations, Mae Ku Creek: 2 stations, Mae Sot Creek: control station - Both dry season (April 2004) and wet season (September 2004)	At the Mae Tao Creek, cadmium levels were between ND - 49.0 mg/kg in dry season and ND - 80.79 mg/kg in wet season. At the Mae Ku Creek, the cadmium levels were between 4.0 to 34.0 mg/kg and 16.15 to 22.25 mg/kg in dry and wet season. At Mae Sot Creek, it was not contaminated both dry and wet season.
Pollution Control Department, 2004-2009 (PCD, 2011)	- Mae Tao Creek and Mae Ku Creek: from upstream of creek before entering zinc mine to downstream of zinc mine - 30 stations with 285 samples	Cadmium levels at the Mae Tao Creek were very low before entering zinc mining area, but they were high within and downstream of zinc mining area. However, the cadmium concentration was decreased by distance from downstream of the mining activity boundary. At the Mae Ku Creek, cadmium distributed at upstream and downstream of zinc mining, but it has tended to decreased since 2004-2009.
Maneewong, 2005	- Mae Tao Creek, Mae Ku Creek, Nong Khiao Creek (control area) - Suspended sediment and bed load	Average cadmium levels in suspended sediment were 18.27, 7.75 and 6.32 mg/kg at the Mae Tao Creek, the Mae Ku Creek, and the Nong Khiao Creek, respectively. The average cadmium levels in bed load were 37.11, 7.99 and 5.67 mg/kg at the Mae Tao Creek, the Mae Ku Creek, and the Nong Khiao Creek, respectively.

Table 2-6 Summary of cadmium contaminated sediment from literature review (continued)

Institute/Researcher and study year	Study area/ Sample	Result of cadmium contamination
Krissanakriangkrai, 2006 (Krissanakriangkrai, 2007)	Mae Tao Creek: 22 stations located at upstream to downstream of zinc mine for 10 km.	Cadmium concentration along the Mae Tao Creek was significantly lower for upstream of mining area (with average of 2.2 mg/kg) than for downstream of mining area (with average of 20.2 mg/kg) both dry and wet season.
Office of Primary Industries and Mines , Khet 3 Northern part, 2009	Mae Tao Creek: 13 stations, Mae Ku Creek: 6 stations	Cadmium contribution at the Mae Tao Creek was < 0.5 mg/kg before entering the mine, and was 2.9-75.8 mg/kg at discharge point and downstream of the mine. The cadmium concentration was highest at Ban Pateh and Ban Mae Tao Mai. The cadmium contamination levels at the Mae Ku Creek ranged from 8.0 to 17.2 mg/kg at Ban Mae Ku Nuea and Ban Palad while the other area was contaminated with concentration of 0.5 mg/kg.
Karoonmakphol and Chaiwiwatworakul, 2009 (Karoonmakphol and Chaiwiwatworakul, 2010)	Mae Tao Creek: 10 stations with bed load samples	From water quality results, water pH values in surface water were in the range of 8.16-8.46. The total cadmium concentrations in bed load were in the range of 1.120-33.93 mg/kg. It was observed that high levels of cadmium were found at downstream of zinc mining area, and highest level was found at downstream of the Mae Tao Creek.

Table 2-6 Summary of cadmium contaminated sediment from literature review (continued)

Institute/Researcher and study year	Study area/ Sample	Result of cadmium contamination
Tharathammathigorn, 2010	- Mae Tao Creek : 10 stations with suspended sediment and bed load samples - Both dry (April) and wet season (October)	Water pH values in surface water were in the range of 7.68-8.35 and 7.99-8.44 in dry and wet season, respectively. The total cadmium concentrations in suspended sediment were in the range of 4.40-62.02 mg/kg in dry season and 1.61-11.00 mg/kg in wet season. The total cadmium concentrations in bed load were in the range of 0.90-38.93 mg/kg in dry season and 1.50-25.14 mg/kg in wet season.
Pollution Control Department, 2010 (PCD, 2011)	- Mae Tao Creek, Mae Ku, Nong Nam Kaew, Huay Muang, drain block of Padaeng Industry Public Company Limited - 220 stations with 224 samples: 220 shallow sediment, 4 deep sediment at 30 cm depth level	The cadmium concentrations in sediment were between lower than 0.05-78 mg/kg, with the average of 5.71 mg/kg. At the Mae Tao Creek, cadmium concentration was lower than 1 mg/kg at before the mine, and was 13.9 mg/kg from tailing storage basin of Padaeng Industry Public Company Limited to Moei river. At the Mae Ku Creek, the cadmium concentration at east before the mining boundary at south was < 1 mg/kg while at south of mine contained high cadmium with 2.6-9.8 mg/kg. At small hill at east of Ban Mae Ku Nuea contained the cadmium level with 52.8 mg/kg and came down at downstream of the Mae Ku Creek as 0.7 mg/kg.

Table 2-7 Summary of cadmium contaminated rice from literature review

Institute/Researcher and study year	Study area/ Sample	Result of cadmium contamination
IWMI-DOA, 1998-2000 and 2001-2003 (Simmons *et al*., 2005)	- During 1998-2000: rice grain (154 plots) at Ban Pateh - During 2001-2003: rice grain (434 plots) near Mae Tao Creek	During 1998-2000, 95% of rice grain samples were found that the cadmium concentration ranged from 0.1 to 4.4 mg/kg. During 1998-2000, 80% of rice grain was found that the cadmium concentration exceeded Standard of Codex and Japanese (0.4 mg/kg).
Simmons, 2000-2002 (Simmons *et al*., 2003)	Rice fields receiving water from zinc mining area	Cadmium levels in rice grain samples varied between 0.02-5.00 mg/kg.
Simmons, 2001-2002 (Simmons *et al*., 2005)	- Pratat Padaeng sub-districts	Rice grains from 524 fields receiving water from the Mae Tao Creek contained cadmium between 0.05-7.7 mg/kg. Over 90% of samples led cadmium levels higher than the standard (0.2 mg/kg).
Simmons, 2001-2003 (Simmons *et al*., 2008)	- Pratat Padaeng and Mae Tao Mai sub-districts - During 2001-2002: 308 rice samples During 2003: 20 rice fields	In 2001-2002, cadmium levels in unpolished rice were 0.02-7.75 mg/kg with average of 1.15 mg/kg. 67% of samples led cadmium exceeded the Codex Alimentarius Commission standard (0.4 mg/kg). In 2003, the cadmium levels in unpolished rice were 2.31 mg/kg (0.04-16.2) in stem, 0.94 mg/kg (0.29-4.55) in leaf, and 1.05 mg/kg (0.29-5.83) in grain. 14 samples led cadmium exceeded the standard.

Table 2-7 Summary of cadmium contaminated rice from literature review (continued)

Institute/Researcher and study year	Study area/ Sample	Result of cadmium contamination
IWMI-LDD, 2004-2005 (Simmons *et al*., 2005)	Pratat Padaeng sub-district and Mae Tao sub-district: 532 rice samples	Cadmium levels in rice were < 0.01-7.78 mg/kg while 83% of rice samples exceeded the Codex Standard (0.2 mg/kg). So, 75%-100% of paddy fields which received water directly from the Mae Tao Creek tended to have higher cadmium level than the Codex Standard.
Development of Mae Tao Watershed, Tak Province Project, 2008-2010 (PCD, 2011)	Rice grain from: Mae Tao sub-district (6 villages), Pratat Padaeng sub-district (3 villages) and Mae Ku sub-district (3 villages)	During 2008-2009, 166 rice samples exceeded the Standard of Codex and Japanese (0.4 mg/kg).During 2009-2010, rice samples in the study paddy field, which only exceeded the standard, had still higher cadmium concentration than the standard for 105 rice samples.

Table 2-8 Summary of cadmium contaminated assessment from literature review

Sample	Cadmium concentration	Standard for Thailand
Water	0.0001-0.1 mg/L	≤ 0.05 mg/L (Thai Water quality Standard)
Soil	0.1-1,458 mg/kg	≤ 37 mg/kg (Thai Soil Quality Standard for Residential and Agricultural area)
Sediment	<1-1,350 mg/kg	≤ 3.5 mg/kg (Probable Effect Levels standard: Canada)
Rice	0.02-7.75 mg/kg	≤ 0.2 kg/kg (Codex Standard)

2.3 Impact on sediment transport

Sediment in water system can be interfered by natural activity and anthropogenic activity by resulting in change of sediment erosion, transport and precipitation (Taylor *et al*., 2008).

1) Natural activity

The results from natural activities both short term changes and long term changes especially in meteorological and hydrological conditions influence a disturbance in sediment transport. One of the most impacts of climatologically changes is rainfall. During the rainy season, increased rates of precipitation can cause an increased of surface runoff, which results in the rise of sediment transport through the river system. For example, in Mae Tao Creek, Mae Sot district, Tak province, Karoonmakphol, (2009) investigated the transport of cadmium contamination due to bed load sediment transport for the year 2009 both dry and wet seasons. The results revealed that the total sediment transport in the study area was equal to 24.52 m^3 by occurring in the wet season for 99.77% of total. The researcher concluded that the sediment transport during the wet season is a significant process and caused the spread of cadmium contamination through the river basin. Tharathammathigorn (2010) studied cadmium contaminated sediment transport during dry and wet season in the Mae Tao Creek. During wet season, the total sediment transport over 78.42% was estimated with resulting high levels of cadmium contaminated. High precipitation had a major impact on increasing of water discharge and velocity. This event caused the available transport of sediment. High-flow events, therefore, influenced the great impact on increased movement of cadmium contaminated.

2) Anthropogenic activity

Human activities created greater disturbance of fluxes and transport of sediment in the river basin. The disruption from anthropogenic changes focused on construction in river and land use changing.

- *River engineering*: the river engineering especially impoundments and reservoirs cause a interruption on the transport of sediment in the river system by trapping the inflow sediment both suspended sediment and bed load. Reservoirs are caused a decreasing on capacity and a degraded on storing water quality from sedimentation. Additionally, the impoundment for flood protection mainly reduces the magnitude of downstream flooding, which can cause the major sediment transport. During such events, decreased flooding can result in orders of magnitude decreases in coarse sediment, such as sand and gravel transfer through the basin (Taylor *et al.*, 2008). For example, Vorosmarty *et al.* (1997) reported that large impoundment disrupted over 40% of water discharge of the world's rivers, and trapped transport of contemporary sediment from land surface to ocean for more than 25%. The most impact of dam construction was perchance the result in the Aswan Dam on the River Nile that diminished suspended sediment from ca. 100 x 10^6 t/year to nearly equal zero.

- *Land use changing*: the effects of deforestation on land use can cause dramatic change on increasing soil erosion rates. Because of removing of the protective vegetation cover, soil is likely to become available expose to water especially enhancing by precipitation and overland flow. Morgan (1986) presented that the land use with natural vegetation had a lower rates of soil erosion than the clearance of natural vegetation. The clearance of natural vegetation not only builds soil erosion rates up, but it also influences the increasing in river sediment loads. Moreover, one of the most pronounced changes in land use is due to population growth that impacted the extension in agricultural area for food production. Such increasing in agricultural land use change and intensification, especially deforestation and transformation of grassland to arable land, are likely to be reflected a building up of soil erosion contributing to an increase in sediment yield.

2.4 Mathematic model

MIKE SHE and MIKE 11, which have been developed and extended by DHI Group, were chosen as a tool to simulate the results in this project.

2.4.1 MIKE SHE

MIKE SHE, a distributed and physically based model system, provides the simulation for the hydrological cycle. It includes overland flow (OL), evapotranspiration (ET), unsaturated flow (UZ), saturated flow (SZ) and river and lake (channel flow, OC), as illustrated in Figure 2-2. Related water quality modules composed of advection-dispersion, particle tracking, sorption and degradation, geochemistry, biodegradation, crop yield, and nitrogen consumption (DHI, 2010). Each process can be specified in various levels of spatial distribution and complexity corresponding to desired outputs, availability of input data, and user's preference (Butts *et al*., 2004). MIKE SHE has been used in a wide range of application for the analysis, planning and management of a broad range of water resources and environmental and ecological problems related to surface water and groundwater, for example impact of land use change and anthropogenic effects (Refsgaard *et al*., 1998).

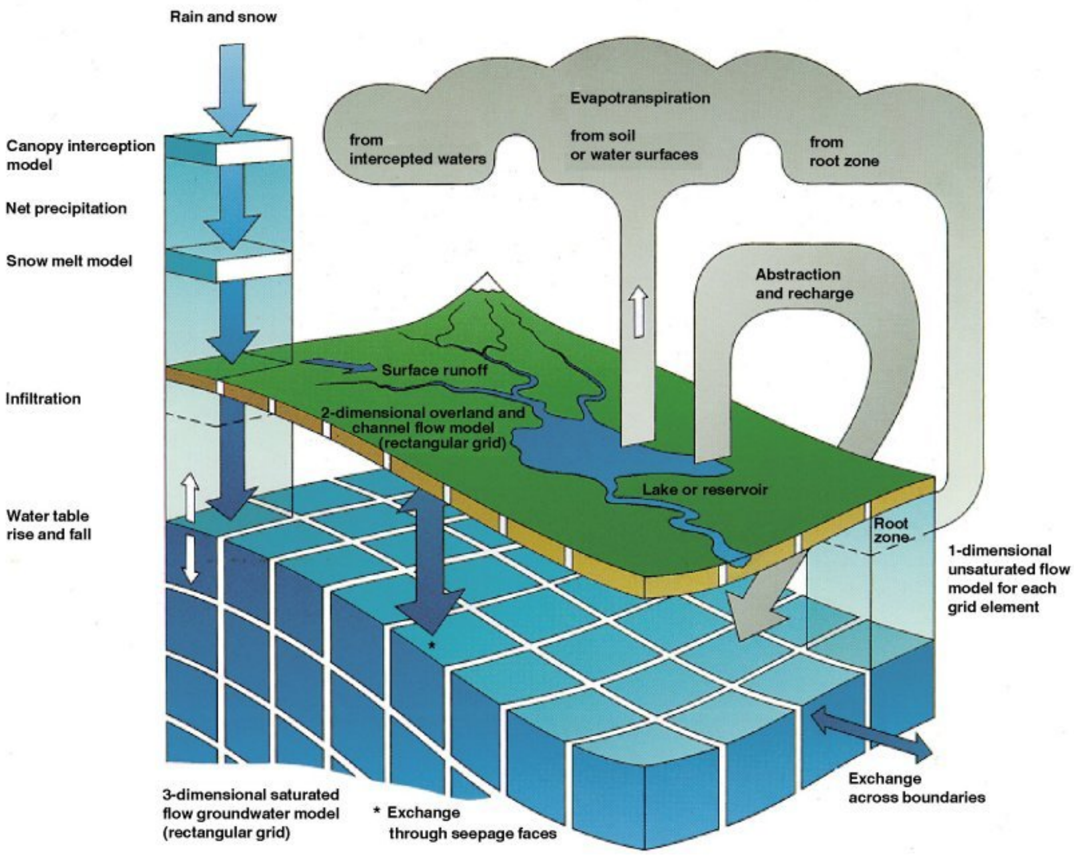


Figure 2-2 Hydrological processes in MIKE SHE (DHI, 2010)

Refsgaard and Kjelds (2001) selected MIKE SHE to be the best modeling system to simulate groundwater-surface water related issues. Additionally, MIKE SHE can provide the best and most comprehensive description interaction with a full dynamic coupled description of the hydrological processes.

2.4.2 MIKE 11

MIKE 11 is used for simulating the channel flow, water quality and sediment transport. MIKE 11 includes comprehensive modules to model complex channel networks, lakes and reservoirs, and river structures, such as gates, sluices, and weirs. The hydrodynamic (HD) module is the core of MIKE 11; moreover, MIKE 11 includes the add-on modules for hydrology, advection-dispersion, models for various aspects of water quality, cohesive sediment transport, and non-co cohesive sediment transport (DHI, 2010).

The hydrodynamic (HD) module consists of an implicit, finite difference computation of unsteady flows in rivers. The module is simulated for the unsteady flows in branched and looped river networks, and quasi two-dimensional flows in floodplains. The module solves the equations of conservation of continuity and momentum (the 'Saint Venant' equations). The solutions to the equations are based on four assumptions. Firstly, the water is incompressible and homogeneous. Secondly, the small of bottom slope caused the cosine of the angle it makes with the horizontal could be equaled to 1. Thirdly, the wave lengths are greater than the water depth by assuming the flow can be to flow parallel to the bottom everywhere. Finally, the flow is sub-critical when actual water depth is higher than critical depth. (Kamel, A.H., 2008).

The sediment transport in channel system can be simulated from two main modules. Firstly, advection-dispersion module (AD) is suitable for cohesive sediment such as silts and clays. Secondly, sediment transport module (ST) is proper for non-cohesive sediment such as gravels and sands.

2.5 Cadmium transport in the Mae Tao Creek

The cadmium contamination due to sediment transport was studied in the Mae Tao Creek, Mae Sot district, Tak province by Karoonmakphol (2009) and Tharathammathigorn (2010). Karoonmakphol (2009) demonstrated the cadmium contaminated sediment transport via bed load in the Mae Tao creek. The researchers applied the MIKE SHE coupled with MIKE 11 to simulate the hydrodynamic results which were daily time series of water depth and water discharge, and sediment transport using the Meyer-Peter and Muller model in 2009. According to grain size distribution, the size distribution of the bed load in studied area shown that the Mae Tao Creek was mostly covered with sand particles. The accumulated sediment transport at the downstream of the Mae Tao Creek in 2009 was computed to 24.522 m^3, whereas 99.77 % of sediment transport occurred in the wet season. The cadmium transport amount could be estimated as 1.599 kg spreading out from the Mae Tao Creek. The results revealed that cadmium distribute during wet season more than dry season. However there was some level of uncertainty in the results due to insufficient information. Tharathammathigorn (2010) also evaluated the cadmium transport in the Mae Tao Creek due to sediment transport from May 2010 to February 2011. However this study divided sediment transport into bed load and suspended sediment, selected MIKE 11 to investigate the channel flow, and sediment transport using Van Rijn model. The simulated results demonstrated the difference between the dry and wet seasons. The total of accumulated sediment transport at the downstream of the Mae Tao Creek was approximately 760.17 m^3 during the study period, and mainly occurred in the wet season with 78.46% of sediment transport. In addition, 86.86% of sediment that transport was suspended sediment that concluded that the suspended sediment was a dominant transport of cadmium transport in the creek. The cadmium was distributed out from the Mae Tao creek for 20.74 kg during May 2010 to February 2011. However the over prediction may be occurred due to model limitations such as neglecting in hydraulic structure.

According to the previous study, this study will consider agricultural land use and hydraulic structure in Mae Tao subcatchment to define their effect on the hydrology in model and the more reasonable result will be gotten.

CHAPTER III

METHODOLOGY

This study aims to clarify the possibility that agricultural land use and hydraulic structure can affect to cadmium contamination due to sediment transport in the Mae Tao Creek. Since the agricultural land use, it has a possibility that the hydrological process of the creek by changing of crop type and existing of hydraulic structure could impact the sediment transport, contributing to a change in cadmium transport. So, this study set up four scenarios that were current agricultural land use, conversion of rice to sugarcane, without weir in the creek and having weir in the creek. The study of the effects of agricultural land use on the transport of cadmium in the Mae Tao Creek consisted of four main phases which are:

1. Data collection: the land usage, topography and meteorology were obtained from the government departments. The leaf area index which used to identify the vegetation type in land usage was reviewed from the literature.

2. Field observation: suspended sediment and bed load were collected to estimate the cadmium concentration during the dry and wet seasons. In addition to bed load, the grain size distribution and soil classification were also determined. At station MT 01 and MT 04 was measured the water depth daily to verify model. Hydraulic structure existence between station MT 02 and MT 03 was measured the parameter to estimate its effect on cadmium transport.

3. Model simulation: once the required information were collected and analyzed, mathematic model was applied from MIKE SHE and MIKE 11. Simulation processes were divided into hydrodynamic simulation and sediment transport simulation. The hydrodynamic part was firstly simulated applying MIKE SHE coupled with MIKE 11 and calibrated by daily water level at station MT 04. The sediment transport was later computed with inputting the simulated hydrodynamic result into MIKE 11.

4. Cadmium transport estimation: cadmium transport in the Mae Tao Creek was calculated from observed cadmium concentration and simulated sediment transport.

The methodology scope of the study is illustrated in Figure 3-1.

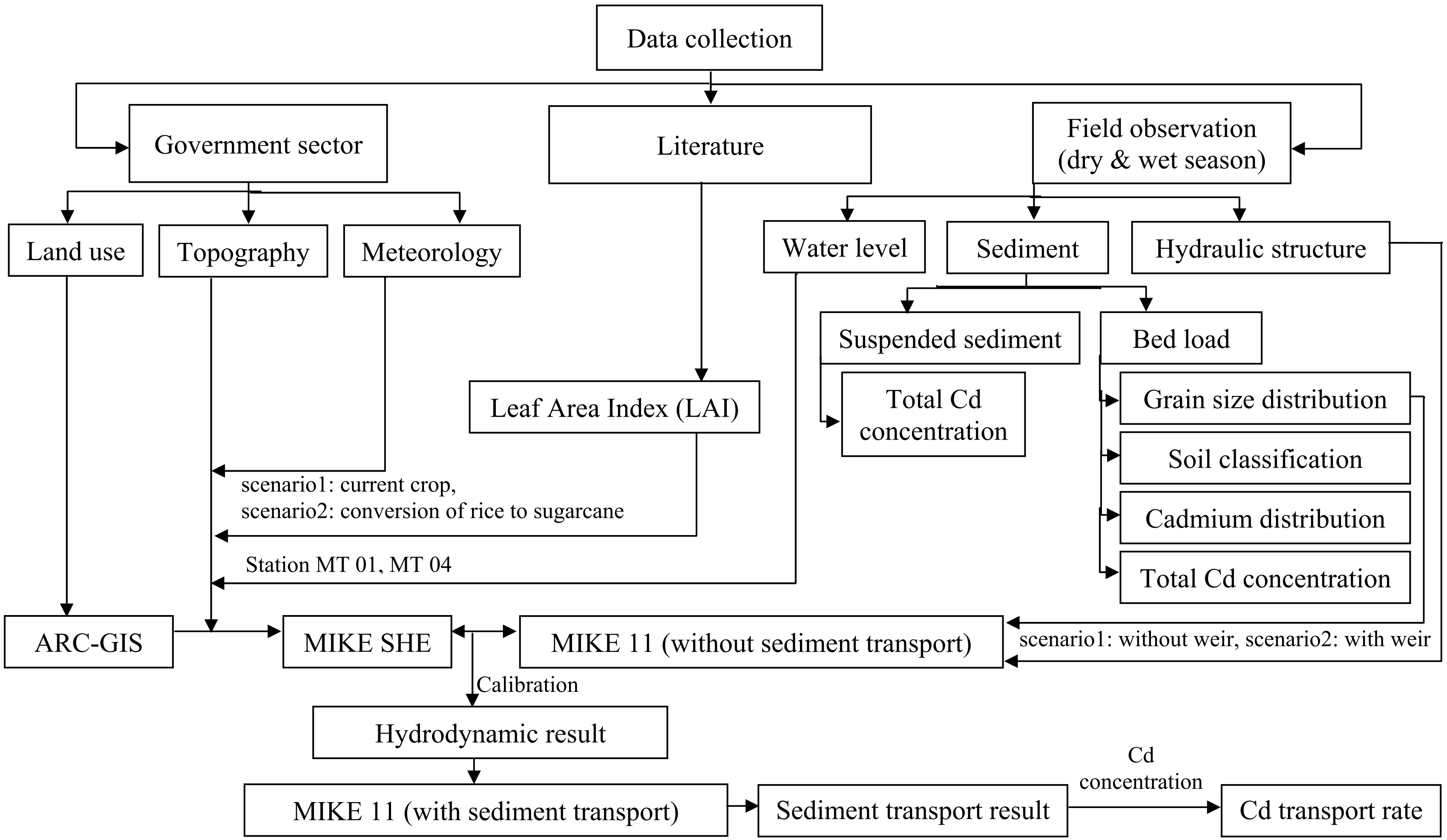


Figure 3-1 Methodology scope of the study of effects of agricultural land use on the transport of cadmium in the Mae Tao Creek, Thailand

3.1 Data collection

Input data required for MIKE SHE were obtained from the government departments, field observation, and literature.

- Topography: Mae Tao subcatchment was obtained from the map sheet 4742III of series L7018, edition 1-RTSD with a scale of 1:50,000 (Appendix A). Elevation in the study area ranged from 200-950 m, as shown in Figure 3-2.

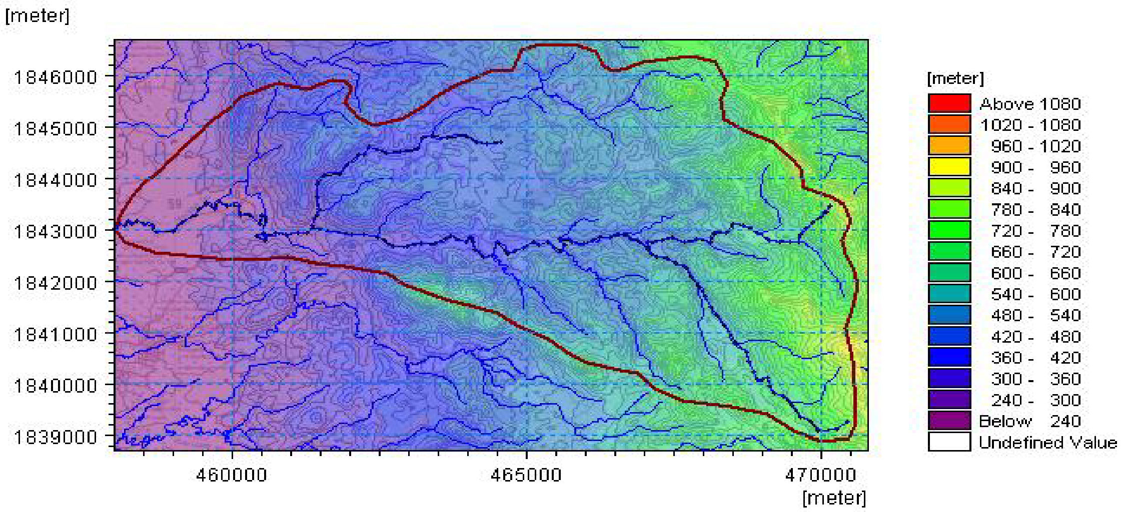


Figure 3-2 Topography of the Mae Tao Creek

- Meteorological data: Evaporation and precipitation rate data in year 2010-February 2012 (presented in Appendix B) were collected from the Thai Meteorological Department (TMD). Mae Sot meteorological station located at Tha Sai Luat Sub district, Mae Sot district, UTM Easting: 457098, UTM Northing: 1841791.

3.2 Field observation

Ten observing stations were located along the Mae Tao Creek at upstream, junctions and downstream locations, as displayed in Figure 3-3. The stations were ranged from downstream to upstream of main Mae Tao Creek, Mae Tao left, and Mae Tao right. The positions of observing stations show in Table 3-1. At each station, the observation during dry and wet seasons of water quality measurement including pH, dissolved oxygen, conductivity, and temperature. Suspended sediments and bed load were sampled and analyzed for cadmium content, grain size distribution, and soil classification.

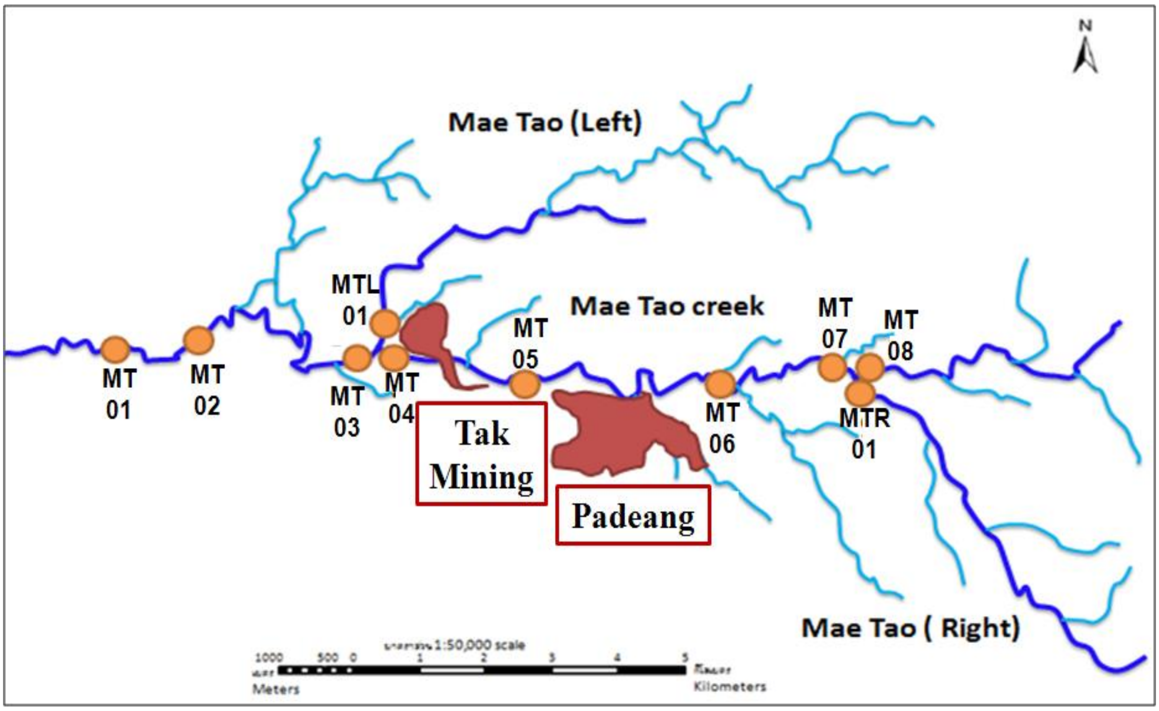


Figure 3-3 The ten observing stations and two zinc mines along the Mae Tao Creek

Table 3-1 The positions of each station along the Mae Tao Creek

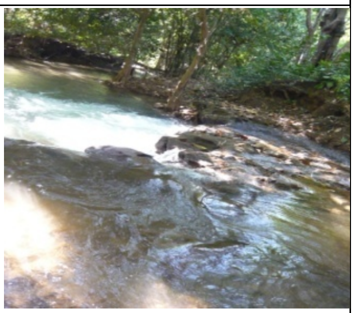
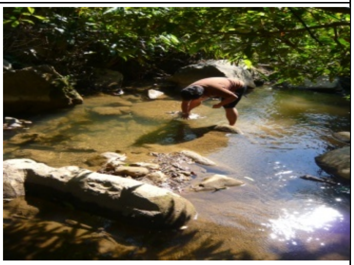
Station	Easting	Northing	Description	Field observation
MT 01	457998	1843017	- Village area - Location at downstream of Mae Tao subcatchment - Observation station of water level	
MT 02	459400	1843330	- Village area	
MT 03	461274	1843034	- Connection between station MT 04 and station MTL 01 - Receiving converged water from station MT 04	
MT 04	461374	1843110	- Location at downstream from Tak mining Company Limited's mine - Observation station of water level	
MTL 01	461438	1843286	- Mae Tao Left - Receiving converged water from Mae Tao Left	

Table 3-1 The positions of each station along the Mae Tao Creek (continued)

Station	Easting	Northing	Description	Field observation
MT 05	462046	1842870	Location between Tak Mining and Padaeng	
MT 06	465638	1842718	Location above two zinc mines	
MT 07	466937	1842750	- Connection between station MTR 01 and station MT 08 - Receiving water from station MTR 01 and station MT 08	
MTR 01	467228	1842559	Mae Tao Right	
MT 08	467088	1842736	Location at upstream of the main Mae Tao Creek	

3.3 Physical properties of sediment

3.3.1 Sample collection and preparation

At each station, suspended sediment and bed load were collected and analyzed for their composition during the dry and wet seasons. The suspended sediments were collected for estimating the total cadmium concentration. The bed load samples were collected for estimating the grain size distribution, soil classification, total cadmium concentration and the distribution of cadmium concentration.

Suspended sediment

- At the center of the stream, two liters of water were collected to take suspended sediment by using a polyethylene container.
- The collected water was filter with a pre-weighed filter paper (GFC WATTMAN) by coupling with the vacuumed pump. The filter paper with retained sediment was placed in a Petri dish.
- The suspended sediment on the filter paper was dehydrated in an oven at 60°C for 24 hours and weighted.

Bed load

- About 2 kg of bed load were collected at the top layer of sediment (0-5 cm) and contained in a polyethylene container.
- The bed load was dehydrated at 105°C for 24 hours in an oven, and allowed to cool at room temperature.
- A mortar and pestle were used to grind the bed load samples before analyzing of grain size distribution, soil classification and cadmium concentration. The cadmium and zinc distribution was investigated from various size of bed load which 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).

3.3.2 Grain size distribution

The bed load was analyzed grain size distribution by 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)
- Weighing apparatus
- Cleaning implements

B) Methods

- The grinded bed load of each station and each select sieve were weighed.
- The sieves were set up by ranking from the smallest sieve (no. 200) at the bottom to the largest sieve (no. 3/4'') at the top of the sieve set.
- The bed load was added to the top of sieve set and sieved for around 30 minutes.
- Each sieve which contained the bed load was weighed.

Note: The grain size analysis should be repeated if the sample loses more than 2% of its weight. Moreover, the hydrometer analysis is recommended if there is more than 10% of sample passing sieve No. 200.

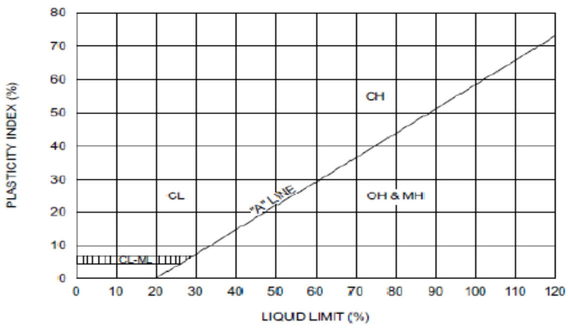
3.3.3 Soil Classification

The sediments from each station were classified by following the Unified Soil Classification System (USCS) (ASTM D2487).

Table 3-2 The soil classification

% sample passing sieve No.200	**Classification**	**Equation**
Less than 50%	Coarse-grained particles - Gravel (G) - Sand (S)	$CF = \frac{C}{F} = \frac{\%\ \text{coarser than 4-mesh sieve}}{\%\ \text{coarser than 200-mesh sieve}}$ (3.1) - If the CF (coarse fraction) is less than 50%, the sample will be classified as sand (S). - If the CF is greater than 50%, the sample will be classified as gravel (G).

Table 3-2 The soil classification (continued)

% sample passing sieve No.200	**Classification**	**Equation**
More than 50%	Fine-grained particles - Inorganic silt (M) - Inorganic clay (C) - Organic silt or clay (O) - Peat (Pt)	$PI = 0.73\ (LL-20)$ (3.2) (PI= plasticity index, LL= liquid limit)  **Figure 3-4** Plasticity chart and the A line (ASTM D 2487) - If the ratio between 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 LL and PI is above A-line, the sample is classified as inorganic clay (C).

3.3.4 Measurement of cadmium concentration

1) Suspended sediment (EPA method 3050B)

A) Instruments

- Hot plate
- Whatman disc filter paper No.41
- Graphite furnace atomic absorption spectrometry (GFAAS)
- GFAAS sample vessels
- Polyethylene bottles
- Weighing apparatus
- Glassware and others

B) Materials

- 65% Nitric acid
- Hydrochloric acid
- 30% Hydrogen peroxide
- Standard cadmium concentration
- Standard zinc concentration
- Deionized water

C) Methods

- Before analyzing, the laboratory glassware and plasticware were cleaned with deionized water and 10% nitric acid for 2 hours, and rinsed with deionized water.
- The sediment on filtered paper was weighed and heated to 95±5°C with 10 ml of 1:1 nitric acid for 10 to 15 minutes without boiling (covering with a watch glass).
- The nitric acid was added to the cooling solution about 5 ml and refluxed for 30 minutes. (The replicate of this step must be done when the brown fumes are occurred.)
- The solution was heated at 95±5°C without boiling for 2 hours.
- The 2 ml of water and 3 ml of 30% hydrogen peroxide mixed along with 1 ml of 30% hydrogen peroxide were added to the cooling solution until being of unchanged solution.
- The solution was heated at 95±5°C without boiling for 2 hours.
- Each sample was filtrated with Whatman disc filter paper No. 41 and adjusted the volume to 50 ml before placing into a polyethylene bottle.
- The filtered solutions were analyzed by graphite furnace atomic absorption spectrometry. Detection limit for GFAAS is 0.0001 ng/mL for cadmium measurement and 0.00005 ng/mL for zinc measurement.

2) Bed load (EPA method 3051)

A) Instruments

- Microwave digestion system: Mileston Ethos SEL
- Whatman disc filter paper No. 5

- PTFE vessels and covers
- Polyethylene bottles
- Sieve No. 65, 100, 150, 200
- Weighing apparatus
- Flame atomic absorption spectroscopy (FLAAS)
- FLAAS sample vessels
- Glassware and others

B) Materials

- 65% Nitric acid
- Hydrochloric acid
- Standard cadmium concentration
- Standard zinc concentration
- Deionized water

C) Methods

- Before analyzing, the laboratory glassware and plasticware were cleaned with deionized water and 10% nitric acid for 2 hours, and rinsed with deionized water.
- The sieving sediment from each sieve (No. 65, 100, 150, 200) was weighted around 0.5 g and placed in each PTFE vessels.
- Each PTFE vessels were added 9 ml of 65% nitric acid and 3 ml of hydrochloric acid.
- Each PTFE vessels were placed into a microwave system at 170±5 ºC for 8 minutes and remain at 170 ºC for 7 minutes, and allowed them cool down to the room temperature.
- Each cooled sample was filtrated with Whatman disc filter paper No. 5 and adjusted the volume to 50 ml before placing into a polyethylene bottle.
- The filtered samples were analyzed by flame atomic absorption spectroscopy. Detection limit for FLAAS is 1 ng/mL for cadmium measurement and 2ng/mL for zinc measurement.

Note: The cadmium and zinc concentration used the t-distribution to estimate a standard deviation at the 80% confidence level.

3.4 Effects on sediment transport

Agricultural land use and hydraulic structure were selected as the factors that play a significant role in cadmium contaminated sediment transport via the suspended sediment and bed load in the Mae Tao Creek.

- **Scenarios**

In this study, there are setting scenarios to demonstrate the effect on sediment transport by focusing on the agricultural land use changing and hydraulic structure operation.

The effect of agricultural land use:

- Current agricultural land use: setup the land use by following the current crop type such as rice, corn, forest etc.
- Conversion of rice to sugarcane plantation: is based on Thailand's policy for management of cadmium contamination

The effect of hydraulic structure operation:

- Without hydraulic structure operation
- With hydraulic structure operation: by open gate's weir

3.4.1 Agricultural Land Use

Land use module in MIKE SHE is used to define the items on the land surface that affect the hydrology in study area, focusing on vegetation distribution. There are two relevant time series parameters: Leaf Area Index (LAI) and Root Depth that are used to define the distribution of vegetation across the model area.

LAI is defined as the area of leaves per area of the ground. The role cannot control either leaves control or the significance of this index is photosynthesis, respiration, rain interception. Thus, LAI is a key parameter in many models to characterize the relationship of vegetation and atmosphere especially of the water cycles (GCOS, 2004). LAI is a dynamic parameter because its value of each crop bases on many factors that are species component, stage of development, season, environment and organization process. According to various factors and determination methods, The LAI value is broadly in literature such as range value of 2-4 for annual crops and 6-8 for deciduous forest (Jonckheere *et al.*, 2004).

LAI can be investigated by two major measurements, one direct and one indirect method, as shown in Table 3-3 (see review in Jonckheere *et al.*, 2004; Breda, 2003).

Table 3-3 Summarize of LAI measurement method

Procedure	LAI measurement
Direct method: 1) Leaf collection	There are two methods of leaf collection: harvesting methods and Non-harvest methods. a) Harvesting methods: - *Destructive sampling*: leaves are harvested and removed from a sampling area. - *Model tree method*: destructive sampling is applied for collecting vegetation out of the stand from which the leaf area and vertical distribution of leaf area is estimated leaf by leaf. This method is available for agricultural crop and forest system. b) Non-harvest method: - *Leaf litter collections*: litter traps are predestined box that design to collect the leaves during leaf fall season by non-cover on the top and lateral sides with precluding wind. This approach is applied for deciduous forest.
2) Leaf area determination	Leaf area can be estimated by two techniques: planimetric approach and gravimetric method. - *Planimetric method*: it relies on the relationship between individual leaf area and area, which is covered by the leaf in a horizontal surface. Planimeter is applied for measuring the leaf boundary, and then its area can be calculated. - *Gravimetric method*: it relies on the relationship between dry weight of leaves and leaf area. Leaf mass per area (LMA) is primarily evaluated from a sub sample.

Table 3-3 Summarize of LAI measurement method (continued)

Procedure	**LAI measurement**
	When LMA is completely determined, the whole sample is dehydrated and the leaf area is determined from its dry weight and the sub sample LMA.
Indirect method: a) Indirect contact LAI measurements	- *Inclined point quadrat*: point quadrat is a long thin needle that is used to pierce a leaf canopy with known of elevation and angles, and contact between the needle and green canopy component is counted. LAI is calculated from equations of a radiation penetration model. - *Allometric techniques for forests*: these techniques base on correlation between leaf area and dimensions of woody component, which sustain the green leaf biomass such as stem diameter, height of tree. This correlation depends on species vegetation, site condition, season and canopy structure.
b) Indirect non-contact measurements	Indirect non-contact methods apply the determination of transmission of light trough plant canopies. Instruments have been developed to determine in real time LAI of leaf canopies for 20 years. They consist of two major groups, which are classified on whatever they measure: a first category includes instruments by basing on gap fraction distribution, and a second category includes instruments by basing on gap size distribution.
	- *Gap fraction distribution*: LAI can be determine by using canopy image analysis approach (i.e. Digital Plant Canopy Imager CI 100, MVI), or comparing light measurement above canopy with light measurement below canopy (i.e. Accupar, Demon, Licor LAI-2000 Plant Canopy Analyzer). - *Gap size distribution*: this analysis determines LAI by evaluating the proportions of individual ground area, which

Table 3-3 Summarize of LAI measurement method (continued)

Procedure	LAI measurement
	are directly illuminated and converting them to the LAI value. The Tracing Radiation and Architecture of Canopies (TRAC) instrument and hemispherical photography are examples of instrument based on this analysis.

This study obtained land use map from Land Development Department, 2007. The land use map can be converted to a shape file using ArcGIS and then interpolated in MIKE SHE (see Appendix A, Figure A-2). In MIKE SHE, three vegetation parameters need to be specified by consisting of LAI, root depth and crop coefficient. In this study, the values of these parameters were determined from MIKE SHE manual (see Appendix D, Table D-2). Moreover, the leaf area index and root depth should be specified at the end of each crop state. The developments of LAI and root depth between the specified values are then interpolated linearly by the model (DHI, 2010).

3.4.2 Hydrodynamic

- **Water depth**

At station MT 01 and station MT 04 were setup vertical staff gauge. At station MT 01, the water depth was record three times on the morning, afternoon and evening every day. At station MT 04, the water depth was record two times on the morning and evening every day.

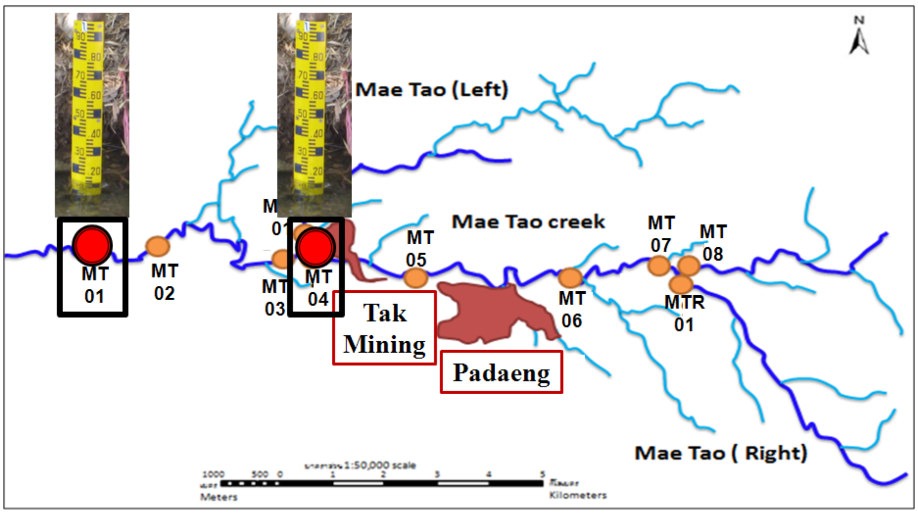


Figure 3-5 Water depth stations at MT 01 and MT 04

- **Hydraulic structure**

The discovering of concrete weir that located between station MT 02 and station MT 03, as displayed in Figure 3-6 was measured the hydraulic structure parameters that illustrated in Figure 3-7.

Figure 3-6 Hydraulic structure location

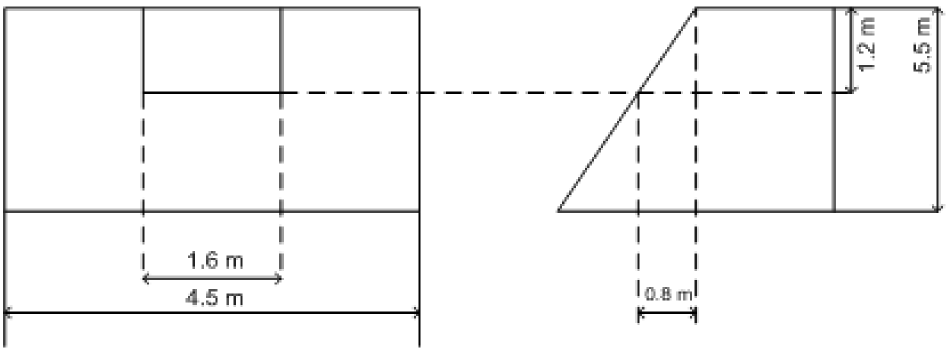


Figure 3-7 Hydraulic structure measurement

3.5 Hydrodynamic simulation

- **MIKE SHE (DHI, 2010d, 2010e, 2010f)**

1) Overland Flow (OL)

If there is higher precipitation rate than infiltration capacity' soil, ponded surface water is generated. It is available as surface runoff to streams. The movement and quantity is depended on topography and the losses from evaporation and infiltration along the flow route.

Overland flow module simulates the movement of ponded surface water across the topography. It can be used for calculating flow on a flood plain or runoff to streams by using the diffusive wave approximation of the Saint Venant equations. The Saint Venant equations are applied for the diffusive wave approximation by reducing momentum losses and lateral inflows perpendicular to the flow direction because of local and convective acceleration. The expression for the two-dimensional diffusive wave approximation to simulate surface runoff, and the velocities and depths relation:

$$uh = K_x \left(-\frac{\partial z}{\partial x}\right)^{\frac{1}{2}} h^{\frac{5}{3}} \quad (3.3)$$

$$vh = K_y \left(-\frac{\partial z}{\partial y}\right)^{\frac{1}{2}} h^{\frac{5}{3}} \quad (3.4)$$

$$z = z_g + h \quad (3.5)$$

where

u	=	flow velocity in x-direction	(m/s)
v	=	flow velocity in y-direction	(m/s)
K_x	=	Strickler coefficient in x-direction	($m^{1/3}$)
K_y	=	Strickler coefficient in y-direction	($m^{1/3}$)
h	=	flow depth (above ground surface)	(m)
z	=	flow depth (referred to datum)	(m)
z_g	=	ground surface level (referred to datum)	(m)

The Strickler roughness coefficient is equivalent to the Manning M because of the control of surface roughness to the overland flow rate. The value of *n* is typically in the range of 0.01-0.10 (smooth channels-thickly vegetated channels), which correspond to the value of M between 100 and 10.

$$K = M = \frac{1}{n} \quad (3.6)$$

where

M	=	Manning M	($m^{1/3}$)
n	=	Manning n	($m^{-1/3}$)

The expression for a finite-difference from of the velocity term:

$$\frac{\partial y}{\partial x}(uh) \cong \frac{1}{\Delta x}[(uh)_{east} - (uh)_{west}] \quad (3.7)$$

$$\frac{\partial y}{\partial x}(vh) \cong \frac{1}{\Delta y}[(vh)_{north} - vh_{south}] \quad (3.8)$$

where

$(uh)_{eas}$	= discharge per unit length across the eastern boundary	(m/s)
$(uh)_{west}$	= discharge per unit length across the western boundary	(m/s)
$(vh)_{north}$	= discharge per unit length across the northern boundary	($m^{1/3}$)
$(vh)_{south}$	= discharge per unit length across the southern boundary	($m^{1/3}$)
Δx	= side of length in x-direction	(m)
Δy	= side of length in y-direction	(m)

The expression for the flow between grid squares:

$$Q = \frac{K\Delta x}{\Delta x^{\frac{1}{2}}}(Z_u - Z_D)^{\frac{1}{2}} h_u^{\frac{5}{3}} \quad (3.9)$$

where

Q	=	water discharge	(m^3/s)
K	=	appropriate Strickler coefficient and water depth	($m^{1/3}$)
Z_U	=	higher depth of the two water levels (referred to datum)	(m)
Z_D	=	lower depth of the two water levels (referred to datum)	(m)
h_u	=	depth of water that can freely flow into the next cell	(m)
	=	actual water depth minus detention storage	

The overland flow equation is calculated from successive over-relaxation (SOR) method to avoid an internal water balance error and divergence of the solution scheme.

$$\sum|Q_{out}| \leq \sum Q_{in} + i\Delta x^2 + \frac{\Delta x^2 h(t)}{\Delta t} \quad (3.10)$$

where

$\sum Q_{out}$	=	sum of outflows	(m^3/s)
$\sum Q_{in}$	=	sum of inflows	(m^3/s)
i	=	net input to overland flow (net rainfall less infiltration)	(m/s)
$h(t)$	=	water depth	(m)
Δt	=	time difference	(s)

2) Evapotranspiration (ET)

Total evapotranspiration can be calculated from weather and vegetative data because of canopy interception, drainage from the canopy to the soil surface, canopy evaporation, soil evaporation and transpiration from the vegetation. The primary evapotranspiration model is relied on empirically derived equations that follow a study by Kristensen and Jensen (1975).

A) Canopy Interception

Interception is defined as process whereby precipitation is retained on vegetation. The intercepted water directly evaporated no storing to the soil moisture. The interception process i s modeled as an interception storage that relies on the vegetation type and its development stage, which is characterized by leaf area index (LAI).

$$I_{max} = C_{int} \cdot LAI \tag{3.11}$$

where

I_{max}	=	size of the interception storage capacity	(mm)
C_{int}	=	interception coefficient (typical value is about 0.05)	(mm)
LAI	=	leaf are index (typical value is between 0 and 7)	(-)

B) Evaporation from the canopy

The amount of evaporation from the canopy is time-step dependent. The total amount of water stored in the canopy in temperature climates is insignificant correlation to the precipitation, but the semi-arid climates are significant.

$$E_{can} = min(I_{max}, E_p \Delta t) \tag{3.12}$$

where

E_{can}	=	canopy evaporation	(m)
E_p	=	potential evapotranspiration	(m/s)

C) Plant Transpiration

The plant transpiration relies on the density of the crop material, the soil moisture content in root zone, and the root density.

$$E_{at} = f_1(LAI) \cdot f_2(\theta) \cdot RDF \cdot E_p \tag{3.13}$$

$$f_1(LAI) = C_2 + C_1 \cdot LAI \tag{3.14}$$

$$f_2(\theta) = 1 - \left(\frac{\theta_{FC}-\theta}{\theta_{FC}-\theta_w}\right)^{\frac{C_3}{E_p}} \tag{3.15}$$

$$RDF_i = \frac{\int_{z_1}^{z_2} R(z)dz}{\int_0^{L_R} R(z)dz} \tag{3.16}$$

where

E_{at}	=	actual plant transpiration	(m^3/s)
$f_l(LAI)$	=	function based on leaf are index	(-)
$f_2(\Theta)$	=	function based on soil moisture content in root zone	(-)
RDF	=	root distribution function	(-)
Θ_{FC}	=	volumetric moisture content at field capacity	(-)
Θ_w	=	volumetric moisture content at the wilting point	(-)
Θ	=	actual volumetric moisture content	(-)
C_1	=	empirical evapotranspiration parameter	(-)
C_2	=	empirical evapotranspiration parameter	(-)
C_3	=	empirical evapotranspiration parameter	(mm/d)
z_1	=	depth below the ground surface bounded above layer I	(m)
z_2	=	depth below the ground surface bounded above layer i	(m)
L_R	=	maximum root depth	(m)

The roots extraction for transpiration varies over the growing season, and relies on the climatic conditions and the soil moisture conditions.

$$logR(z) = logR_0 - AROOT \cdot z \tag{3.17}$$

where

$R(z)$	=	root extraction vary logarithmically with depth	(-)
R_0	=	root extraction at the soil surface	(-)
$AROOT$	=	root mass distribution	(-)
z	=	depth below ground surface	(-)

D) Soil Evaporation

The following functions described the soil evaporation:

$$E_s = E_p \cdot f_3(\theta) + \left(E_p - E_{at} - E_p \cdot f_3(\theta)\right) \cdot f_4(\theta) \cdot (1 - f_1(LAI)) \tag{3.18}$$

$$f_3(\theta)\begin{cases} C_2; \theta > \theta_W \\ C_2 \frac{\theta}{\theta_W}; \theta_r \leq \theta \leq \theta_W \\ 0; \theta < \theta_r \end{cases} \quad (3.19)$$

$$f_4(\theta) = \begin{cases} \frac{\theta - \frac{\theta_W + \theta_{FC}}{2}}{\theta_{FC} - \frac{\theta_W + \theta_{FC}}{2}}; \theta \geq \frac{\theta_W + \theta_{FC}}{2} \\ 0; \theta < \frac{\theta_W + \theta_{FC}}{2} \end{cases} \quad (3.20)$$

where

E_s	=	soil evaporation	(m/s)
E_{at}	=	actual transpiration	

C_1; is used in the plant transpiration function, and is about 0.3. C_1 effects the distribution between the soil evaporation and transpiration: for example; the soil evaporation has a larger relative to the transpiration from a smaller C_1 values in agricultural crop and grass.

C_2; is used in the plant transpiration function, and is about 0.2 for agricultural crops and grass grown on clayey loamy soils. A larger percentage of the actual evapotranspiration will be soil evaporation.

C_3; is used in the plant transpiration and soil moisture function, and is estimated generally 20 mm/day.

3) Unsaturated Flow (UZ)

Unsaturated zone is usually heterogeneous and based on cyclic fluctuations in soil moisture that water is replenished with rainfall, removed by evapotranspiration and recharge to the ground water table. Because of the major role during infiltration of gravity, unsaturated flow is primarily vertical. Thus, unsaturated flow in MIKE SHE is calculated only vertically in one-dimension that sufficient on very steep hill slopes with contrasting soil properties in the soil profiles.

A simplified gravity flow is used to calculate vertical flow in the unsaturated zone. This procedure assumes a uniform vertical gradient and ignores capillary forces. The driving force for water movement in the unsaturated zone is shown as following:

$$h = z + \psi \quad (3.21)$$

where

h	=	hydraulic head	(m)
z	=	gravitational head	(m)
ψ	=	pressure head	(m)

The gravitation head, z (positive upwards) is elevation of a point above the datum. Atmospheric pressure is defined as reference level for pressure head component (ψ), which is negative under unsaturated conditions because of capillary force and short range adsorption forces between the water molecules and the soil matrix. However, the pressure head is not calculated and the driving force is due entirely to gravity in the gravity floe module. So the vertical gradient of the hydraulic head is one.

The volumetric flux is based on Darcy's law:

$$q = -K(\theta)\frac{\partial h}{\partial z} = -K(\theta) \quad (3.22)$$

where

q	=	volumetric flux	(m/s)
$K(\Theta)$	=	unsaturated hydraulic conductivity	(m/s)

If the soil matrix is incompressible and soil water has a constant density, the continuity equation will be:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} - S(z) \quad (3.23)$$

where

Θ	=	actual volumetric moisture content	(-)
S	=	root extraction sink term	(1/s)
t	=	time	(s)

4) Saturated Flow (SZ)

The saturated subsurface flow is calculated from a fully three-dimensional flow in a heterogeneous aquifer by playing between unconfined and confined conditions.

The spatial and temporal variations of the hydraulic head are expressed by the three-dimensional Darcy equation.

The three dimensional ground water flow is calculated follow by following the 3D finite difference method by the groundwater discharge to the surface water. A three-dimensional saturated porous media is defined the governing flow by:

$$\frac{\partial y}{\partial x}\left(K_{xx}\frac{\partial y}{\partial x}\right)+\frac{\partial y}{\partial x}\left(K_{yy}\frac{\partial y}{\partial x}\right)+\frac{\partial y}{\partial x}\left(K_{zz}\frac{\partial h}{\partial z}\right)-Q=S\frac{\partial h}{\partial t} \quad (3.24)$$

where

K_{xx}	=	hydraulic conductivity along x axis	(m/s)
K_{yy}	=	hydraulic conductivity along y axis	(m/s)
K_{zz}	=	hydraulic conductivity along z axis	(m/s)
h	=	hydraulic head	(m/s)
Q	=	source/sink terms	(1/s)
S	=	specific storage coefficient	(1/m)

The potential flow is followed Darcy's law:

$$Q=(\Delta h)C \quad (3.25)$$

where

Δh	=	piezometric head difference	(m)
C	=	conductance	(m^2/s)

Horizontal conductance between node I and i-1:

$$C_{i-\frac{1}{2}}=\frac{KH_{i-1,j,k}KH_{i,j,k}(\Delta z_{i-1,j,k}+z_{i,j,k})}{(KH_{i-1,j,k}+KH_{i,j,k})} \quad (3.26)$$

where

$C_{i-\frac{1}{2}}$	=	horizontal conductance	(m^2/s)
KH	=	horizontal hydraulic conductivity	(m/s)
Δz	=	saturated layer thickness of the cell	(m)

The vertical conductance between two cells is calculated from the middle of layer k to the middle of the layer k+1. Thus,

$$C_v=\frac{\Delta x^2}{\frac{\Delta z_k}{2K_{z,k}}+\frac{\Delta z_{k+1}}{2K_{z,k+1}}} \quad (3.27)$$

where

C_v	=	vertical conductance between two cells	(m^2/s)

There are two dewatering conditions:

- Dewatered cell below, the actual flow between cell k and k+1 will be:

$$q_{k+\frac{1}{2}} = C_{v,k+\frac{1}{2}}(z_{top,k+1} - h_k) \tag{3.28}$$

- Dewatered cell above, the actual flow from cell *k*-1 to *k* will be:

$$q_{k-\frac{1}{2}} = C_{v,k-\frac{1}{2}}(h_{k-1} - Z_{top,k}) \tag{3.29}$$

where

$q_{k+\frac{1}{2}}$	=	the actual flow from cell *k* to *k+1*	(m^3/s)
$q_{k-\frac{1}{2}}$	=	the actual flow from cell *k-1* to *k*	(m^3/s)

The storage capacity is calculated from:

$$\frac{\Delta w}{\Delta t} = \frac{S2(h^n - z_{top}) + S1(z_{top} - h^{n-1})}{\Delta t} \tag{3.30}$$

- Confined cells $S = \Delta x^2 \Delta z S_{art}$ (3.31)
- Unconfined cells $S = \Delta x^2 S_{free}$ (3.32)

where

$\frac{\Delta w}{\Delta t}$	=	storage capacity	(-)
n	=	time step	(-)
S1	=	storage capacity at the start of the iteration at time step n	(1/m)
S2	=	storage capacity at the last iteration	(1/m)
S	=	storage capacity for the cells	(1/m)

5) Channel Flow (OC)

- **MIKE 11 (DHI, 2010a, 2010b, 2010c)**

1) Hydrodynamic module

A) Continuity equation

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{3.33}$$

where

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

x = distance (m)

t = time (s)

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

$$\frac{\partial A}{\partial t} \approx \frac{A_j^{n+1} - A_j^n}{\Delta t} \tag{3.34}$$

$$\frac{\partial Q}{\partial x} \approx \frac{\left(\frac{Q_{j+1}^{n+1} + Q_{j+1}^{n}}{2}\right) - \left(\frac{Q_{j-1}^{n+1} + Q_{j-1}^{n}}{2}\right)}{\Delta x_j + \Delta x_{j+1}} \tag{3.35}$$

where

Δt = time difference between time step n and $n + 1$ (s)

Δx = distance between point j and $j - 1$ (m)

B) Momentum equation

$$\frac{\Delta M}{\Delta t} = \frac{\Delta(M \cdot U)}{\Delta x} + \frac{\Delta P}{\Delta x} - \frac{F_f}{\Delta x} + \frac{F_s}{\Delta x} \tag{3.36}$$

where

$\frac{\Delta M}{\Delta t}$ 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

Two main momentum equation selections are diffusive wave.

- Diffusive wave is suitable for relatively steady backwater effects and slowly propagating flood waves. The momentum flux term is ignored because of indifferent tidal flows.

$$\frac{\Delta M}{\Delta t} = \frac{\Delta P}{\Delta x} - \frac{F_f}{\Delta x} + \frac{F_s}{\Delta x} \tag{3.37}$$

3.6 Sediment transport simulation

- **MIKE 11 (DHI, 2010a, 2010b, 2010c)**

A) Sediment continuity equation

The sediment continuity equation is the sufficient for erosion, deposition, and transport of the non-cohesive sediment to evaluate the bed level changes.

$$\frac{\partial s}{\partial x} + (1-\varepsilon)w \cdot \frac{\partial z}{\partial t} = 0 \qquad (3.38)$$

$$s = (q_b + q_s)w \qquad (3.39)$$

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

According to the Van Rijn model, the sediment is divided into bed load and suspended load by basing on the relative magnitudes of the bed shear velocity and the particle fall velocity.

- Suspended and bed load transport: the velocity of bed shear is more than the particle fall
- Bed load transport: base on rolling and saltation. The rolling occurred when the value of the bed-shear velocity just exceeds the critical value, and saltation is the increasing values of the bed-shear velocity.
- Suspended load transport: base on the depth-integration of the product of the local concentration and flow velocity

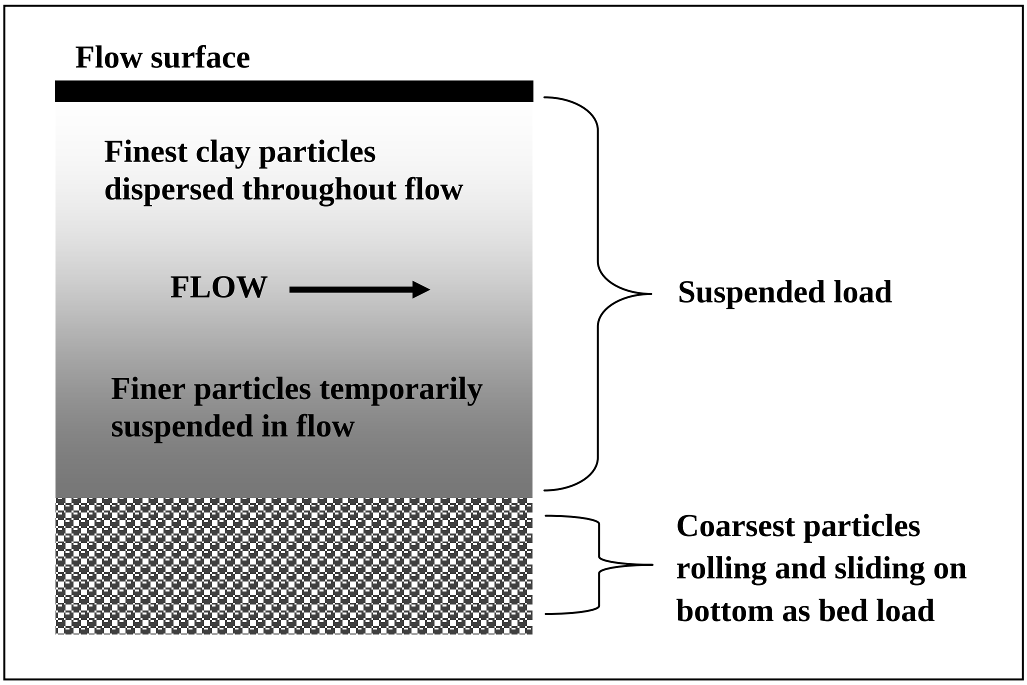


Figure 3-8 Suspended sediment and bed load classification (PCD, 2011)

Bed load (Rijn, 1984a)

An expression for bed load transport rate:

$$q_b = u_{bs}\delta_b c_b \tag{3.40}$$

where

q_b	=	bed load transport rate	(m^3/s)
u_{bs}	=	the product of particle velocity	(m/s)
δ_b	=	saltation height	(m)
c_b	=	the bed load concentration	

The particle velocity and saltation height expressions use the dimension particle diameter and transport stage parameter to express the bed load transport.

$$D_* = d_{50}[\frac{s-1}{v^2}g]^{\frac{1}{3}} \tag{3.41}$$

$$T = \frac{(u'_g)^2 - (u'_{f,cr})^2}{(u'_{f,cr})^2} \tag{3.42}$$

where

D_* = the dimension particle diameter

D_{50}	=	the dimension of which 50% are finer	(mm)
u'_g	=	the bed shear velocity, related to grains	(m/s)
$u'_{f,cr}$	=	Shields critical bed shear velocity	(m/s)
T	=	transport stage parameter	

The influence of bed forms is eliminated when drag dose not contribute to bed load transport:

$$u'_g = \frac{\sqrt{g}}{C'} u \tag{3.43}$$

$$C' = 10\log\left(\frac{R}{3d_{90}}\right) \tag{3.44}$$

where

u	=	the mean flow velocity	(m/s)
C'	=	Chezy's coefficient related to skin friction	($m^{0.5}$/s)
R	=	the hydraulic radius (or resistance radius) related to the bed (m)	
$3d_{90}$	=	considered to be the effective roughness height of the plane bed	

An expression for particle velocity and saltation height by solving the equations of motion to a solitary particle:

$$\frac{u_{bs}}{u'_f} = 9 + 2.6\log(D_*) - 8\frac{\theta_c}{\theta}^{0,5} \tag{3.45}$$

$$\frac{u_{bs}}{[(s-1)gd]^{0,5}} = 1.5T^{0,6} \tag{3.46}$$

$$\frac{\delta_b}{d} = 0.3D_*^{0,7}T^{0,5} \tag{3.47}$$

$$C_b = \frac{q_b}{u_{bs}}\delta_b \tag{3.48}$$

where

u_{bs}	=	particle mobility	(m/s)
(δ_b)	=	saltation height	(m)
(c_b)	=	bed load concentration	

An extensive analysis of flume measurements of bed load transport yielded for the bed load concentration:

$$\frac{c_b}{c_0} = 0.18\frac{T}{D_*} \tag{3.49}$$

where

c_0	=	the maximum bed concentration (0.65)

Combining of an expression for the particle mobility, saltation height, the bed load concentration expresses the bed load transport:

$$\frac{q_b}{\sqrt{(s-1)gd_{50}^3}} = \frac{0{,}0537^{2{,}1}}{D_*^{0{,}3}} \tag{3.50}$$

$$q_b = \frac{0{,}0537^{2{,}1}}{D_*^{0{,}3}} \tag{3.51}$$

Suspended load (Rijn, 1984b)

The suspended load transport is computed from a reference concentration of bed load transport, expressions, so it expressed by the dimension particle diameter and transport stage parameter.

$$D_* = d_{50}\left[\frac{(s-1)g}{v^2}\right]^{\frac{1}{3}} \tag{3.52}$$

$$T = \frac{(u'_g)^2(u'_{f,cr})^2}{(u'_{f,cr})^2} \tag{3.53}$$

where

D_*	=	the dimensionless particle diameter	
T	=	transport stage parameter	
u'_g	=	the bed shear velocity related to the grains	(m/s)
$u'_{f,cr}$	=	the critical bed shear velocity	(m/s)

An expression for a reference level by all sediment transport is bed load:

$$a = 0.5H \tag{3.54}$$

where

a	=	reference level	(m)
H	=	the (known) bed from height	(m)

$$a = k \tag{3.55}$$

where

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

$$a = 0.01D \tag{3.56}$$

where

D	=	water depth	(m)

An expression for the reference concentration:

$$q_b = c_b u_{bs} \delta_b = c_a u_a a \tag{3.57}$$

$$u_a = \alpha u_{bs} \tag{3.58}$$

where

c_a	=	reference concentration	
c_b	=	the bed concentration	
u_{bs}	=	the velocity of bed load particles	(m/s)
δ_b	=	the saltation height	(m)
u_a	=	the effective velocity at reference level a	(m/s)

An expression for combining α_2 = 2.3 with the expressions for δ_b and c_b (as functions of D_* and T):

$$c_a = 0{,}0015 \frac{d_{50}}{a} \frac{T^{1.5}}{D_*^{0.3}} \tag{3.59}$$

An expression for relating particle size, d_s to the d_{50} and geometric standard deviation, σ_s, of the bed material

$$\frac{d_s}{d_{50}} = 1 + 0{,}011(\sigma_s - 1)(T - 25) \text{ for} T < 25 \tag{3.60}$$

$$\sigma_s = 0{,}5 \frac{d_{84}}{d_{50}} + \frac{d_{50}}{d_{16}} \tag{3.61}$$

The expressions for fall velocity by using d_s value:

$$w = \begin{cases} \frac{1}{18} \frac{(s-1)gd^2}{v} \; for \; d < 0{,}1 \; mm \\ \frac{10v}{d}\left\{\left[1 + \frac{0.01(s-1)gd^3}{v^2}\right]^{0,5} - 1\right\} \; for \; 0{,}1 \; mm \leq d \leq 1{,}0 \; mm \\ 1{,}1[(s-1)gd]^{0,5} \; for \; 1{,}0 \; mm < d \end{cases} \tag{3.62}$$

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

$$\frac{u_f}{w} = \frac{u}{d_s}, for \; 1 < d_s \leq 10 \tag{3.63}$$

$$\frac{u_f}{w} = 0{,}4, for \; 10 < d_s \tag{3.64}$$

An expression for a suspended parameter Z which expresses the influence of the upward turbulent fluid forces and the downward gravitational forces:

$$Z = \frac{w}{\beta_{Ku'_f}} \tag{3.65}$$

$$\beta = 1 + 2\left[\frac{w}{u'}\right]^2 for\ 0{,}1 < \frac{w}{u'_f} < 1 \quad (3.66)$$

where

u_f	=	the overall bed shear velocity	(m/s)
K	=	von Karman's constant	
β	=	a coefficient related to the diffusion of sediment particles	

An expression for a modified suspension number *Z*, which is defined from a single correction factor *y*:

$$Z' = Z + \psi \quad (3.67)$$

$$\psi = 2{,}5\left[\frac{w}{u'_f}\right]^{0.8}\left[\frac{c_a}{c_0}\right]^{0.4} \quad (3.68)$$

where

c_0	=	the maximum bed concentration (0.65)
ψ	=	a function of the main hydraulic parameter

An expression for the suspended load

$$q_s = \int_a^D cudy \quad (3.69)$$

where

q_s	=	the suspended load	(m^3/s)
u	=	the current velocity	(m/s)
c	=	the concentration of suspended sediment	
a	=	the thickness of the bed layer which can be approximated by 2 *d*	
D	=	the flow depth	(m)

At a distance *y* above bed level by the logarithmic velocity profile

$$u = 2{,}5u'_f ln\left(\frac{30y}{k}\right) \quad (3.70)$$

$$k = 2.5d \quad (3.71)$$

$$c = c_a\left(\frac{D-y}{y}\frac{a}{D-a}\right)^Z \quad (3.72)$$

$$z = w/(0.4'_f) \quad (3.73)$$

where

u	=	the current velocity	(m/s)
y	=	a distance *y*	(m)

u'_f	=	the friction velocity and the equivalent sand roughness	(m/s)
c_a	=	the concentration at the bed	
D	=	depth of water	(m)
y	=	distance from bed level	(m)
Z	=	the Rouse number	
w	=	the settling velocity of the suspended material	(m/s)

Combining the expression describing the velocity and concentration profiles with the expression for Z and y gives the following expression:

$$q_s = FuDc_a \tag{3.74}$$

$$F = \frac{\left[\frac{a}{D}\right]^{Z'} - \left[\frac{a}{D}\right]^{1.2}}{\left[1-\frac{a}{D}\right]^{Z'}[1,2-Z']} \tag{3.75}$$

(C) Additional equations

Relative density or specific gravity of sediment

$$S = \frac{\rho_{sediment}}{\rho_{water}} \tag{3.76}$$

where

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

3.7 Computer modeling

- **Simulation**

ArcGIS is applied to work and manage the land use map, before interpolating the data into the model. For simulations, the hydrodynamic simulation is simulated using MIKE SHE and calibrated with the observed water level. The sediment transport is simulated using MIKE 11 by inputting the hydrodynamic result.

- **Sensitivity Analysis**

To investigate a sensitivity of model parameter that had impact on hydrodynamic model, the sensitivity analysis was computed by following the study of Lanhart *et al*., 2002. Sensitivity index (*I*) was estimated for assessing the model parameter sensitivity by defining as a ratio of relative change between model output and model parameter. I was calculated by equation as shown in Equation (3.77) and expressed the sensitivity of model, which classified into four classes as displayed in Table 3-4.

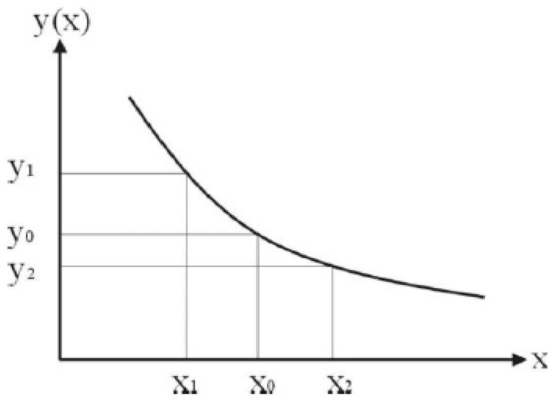


Figure 3-9 The correlation between model output (y) and model parameter (x)

$$I = \frac{(y_2 - y_1)/y_0}{2\Delta x/x_0} \tag{3.77}$$

$$\Delta x = x_0 - x_1 \tag{3.78}$$

$$\Delta x = x_2 - x_0 \tag{3.79}$$

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

Table 3-4 Sensitivity classes

Class	Sensitivity index (I)	Sensitivity
I	0.00 - 0.04	Small to negligible
II	0.05 - 0.19	Medium
III	0.20 – 0.99	High
IV	≥ 1.00	Very high

The parameters, which affected in the water discharge were analyzed the sensitivity in this study. The parameters (x) that were applied to sensitivity analysis contained overland flow, unsaturated flow and saturated zone parameters (see values in Appendix D, Table D-1). The Δx was determined as a half of parameter x by applying for all parameter. The model output (y_0, y_1, and y_2) are water discharge in June 2011 because there was highest precipitation for determining the effect of parameters change to water discharge.

- **Uncertainty Analysis**

Concentration of suspended sediment was an important key to estimate calculation factor in sediment transport module. It was observed for one time during the dry season and the other one during the wet season so the calculation factor was identified as high uncertainty input for sediment transport simulation.

The calculation factor is applied to compute sediment transport rates as correction factors in sediment transport module. The calculation factor can be calculated from the ratio of measured suspended sediment concentration and simulated suspended sediment, and approximated as 1. The concentration profile of suspended sediment is fluctuated with water depth, as displayed in Figure 3-6. Thus, the reference concentration can be estimated from Equation (3.80). For the uncertainty analysis, the highest and lowest water depths were used to calculate the calculation factor, which was applied to simulate the possible accumulated sediment transport.

$$\frac{c}{c_a} = \left[\frac{a}{d-a}\right]^z \left[\int_a^{0.5d} \left[\frac{d-z}{z}\right]^z ln\left(\frac{z}{z_0}\right) + \int_{0.5d}^{d} [e]^{-4z\left(\frac{z}{d}-0.5\right)} ln\frac{z}{z_0} dz\right] \tag{3.80}$$

where

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

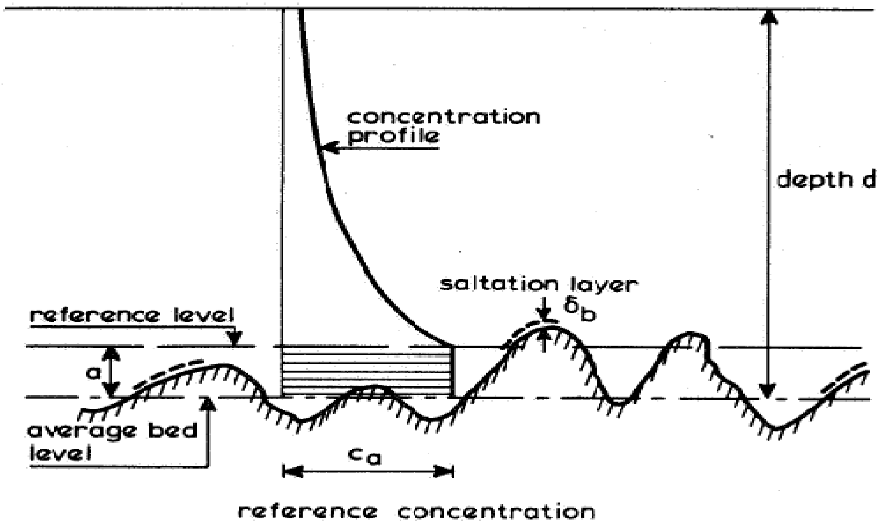


Figure 3-10 Sketch of concentration profile (Rijn, 1984b)

3.8 Estimation of cadmium migration

The cadmium transport in the stream sediment (mg/season) calculated from the following equation.

$$\text{Cadmium transport} = [(S_{bd} \times \rho_{bd}) \times [Cd]_{bd}] + [(S_{ss} \times \rho_{ss}) \times [Cd]_{ss}] \qquad (3.81)$$

where

S_{bd}	=	accumulated bed load transport	(m^3/season)
S_{ss}	=	accumulated suspended sediment transport	(m^3/season)
ρ_{ss}	=	density of suspended sediment	(kg/m^3)
ρ_{bd}	=	density of bed load	(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

Field observations during the dry and wet seasons of 2011 investigated the water quality which at the ten stations along the Mae Tao Creek, as displayed in Figure 4-1. The water quality had the same pattern for dry and wet season, respectively. The pH values of water at all of the stations were slightly alkali which is 7.56 to 8.37 in the dry season and 7.68 to 8.36 in the wet season. The slightly alkali pH values are indicating that cadmium was in an insoluble form at the ten stations and were influenced by adsorption to sediments (Huynh-Ngoc *et al*., 1988).

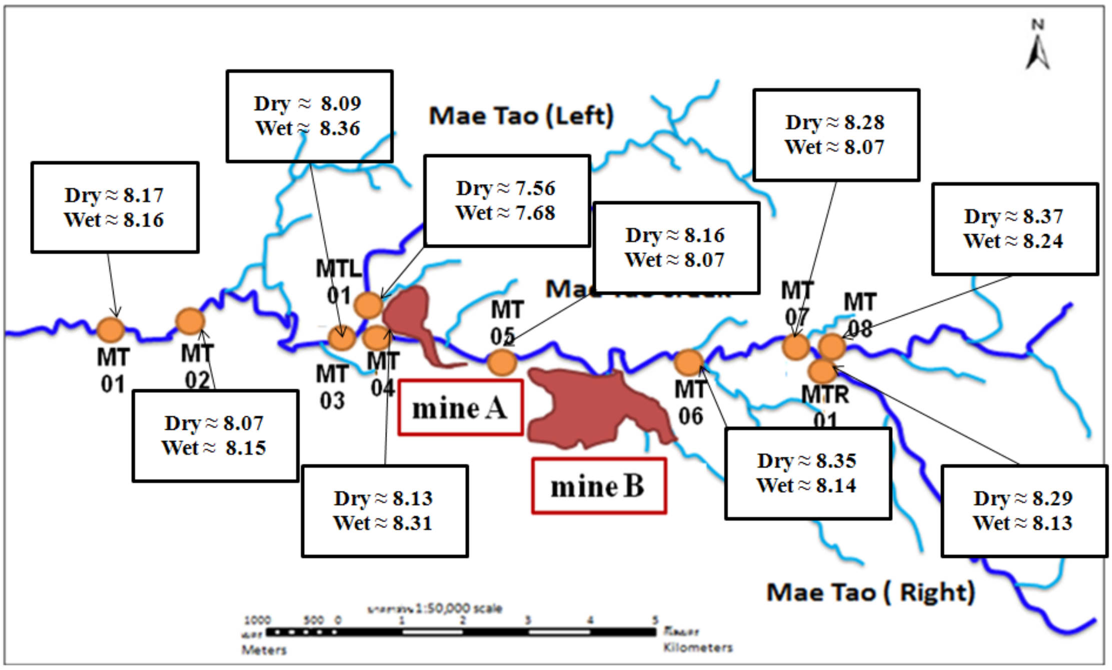


Figure 4-1 The water pH at each station in the study area both dry and wet season

4.2 Laboratory results

4.2.1 Grain size distribution

Bed load samples were determined for the grain size distribution following ASTM C136-06 and ASTM D422-63. Consequently, their mean diameter and standard deviation at ten stations are shown in Table 4-1 for dry season and Table 4-3 for wet season.

The Unified Soil Classification System (USCS) method was considered to classify the characteristics of the bed load samples. Results of sample percentage passing sieve No. 200 were less than 50% in all stations, so the bed load is classified as coarse-grained particles. The coarse-grained particles were completely classified as sand or gravel type by coarse fraction (CF), as shown in Equation (3.1). The results showed that the CF values were less than 0.5 almost sampling stations. Thus, the bed sediment in the Mae Tao Creek could be almost categorized as sand, but classified as gravel in a few station during both the dry and wet seasons, as shown in Table 4-2 and Table 4-4.

Table 4-1 Grain-size distribution of sediment at each station (dry season)

Mesh No.	Sieve Opening (mm)	Mean size (mm)	Weight of sediment (g)									
			MT 01	MT 02	MT 03	MT 04	MTL01	MT 05	MT 06	MT 07	MTR01	MT 08
Sample weight before sieving			1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
3/4"	19.000	19.000	7.91	13.28	0.00	44.89	0.00	0.00	56.85	27.73	0.00	0.00
3/8"	9.500	14.250	29.77	3.55	1.86	236.79	77.02	3.98	196.42	79.27	60.06	121.29
#4	4.750	7.125	68.28	15.78	8.97	254.65	216.55	17.46	151.34	89.88	139.09	174.97
#10	2.000	3.375	237.87	41.94	60.64	184.91	251.83	90.62	122.92	101.23	194.40	195.69
#20	0.850	1.425	291.19	69.60	230.07	85.86	143.32	127.13	85.40	99.80	158.06	146.90
#35	0.500	0.675	240.18	157.88	426.25	56.35	83.34	122.26	93.03	193.49	126.92	118.96
#65	0.231	0.366	77.00	513.87	200.04	54.50	95.09	164.25	170.71	281.15	150.48	115.51
#100	0.150	0.191	13.52	96.35	19.17	18.02	33.73	60.79	63.57	54.06	51.62	49.05
#150	0.100	0.125	18.28	67.13	22.47	29.03	53.45	141.39	46.03	50.34	70.65	54.33
#200	0.075	0.088	2.22	3.42	1.52	9.90	7.03	44.52	2.97	4.69	10.32	4.50
receiver	-	0.075	9.92	12.75	21.77	24.60	36.78	212.70	8.97	14.51	33.66	14.62
Total (g)			996.12	995.53	992.74	999.49	998.12	985.08	998.19	996.14	995.27	995.81
Loss (g)			3.88	4.47	7.26	0.51	1.88	14.92	1.81	3.86	4.73	4.19
Loss (%)			0.39	0.45	0.73	0.05	0.19	1.49	0.18	0.39	0.47	0.42
%Passing Sieve No.200			0.99	1.28	2.18	2.46	3.68	21.27	0.90	1.45	3.37	1.46
Mean Diameter (mm)			2.48	0.98	1.00	6.86	3.81	0.87	5.65	3.04	2.90	4.00
S.D. (mm)			3.26	2.60	1.17	5.98	4.14	1.62	6.46	5.03	3.88	4.74

Table 4-2 Bed sediment classification of each station by USCS (dry season)

Mesh No.	Sieve Opening (mm)	Mean size (mm)	Weight of sediment (g)									
			MT 01	MT 02	MT 03	MT 04	MTL01	MT 05	MT 06	MT 07	MTR01	MT 08
Sample weight before sieving			1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
3/4"	19.000	19.000	7.91	13.28	0.00	44.89	0.00	0.00	56.85	27.73	0.00	0.00
3/8"	9.500	14.250	29.77	3.55	1.86	236.79	77.02	3.98	196.42	79.27	60.06	121.29
#4	4.750	7.125	68.28	15.78	8.97	254.65	216.55	17.46	151.34	89.88	139.09	174.97
#10	2.000	3.375	237.87	41.94	60.64	184.91	251.83	90.62	122.92	101.23	194.40	195.69
#20	0.850	1.425	291.19	69.60	230.07	85.86	143.32	127.13	85.40	99.80	158.06	146.90
#35	0.500	0.675	240.18	157.88	426.25	56.35	83.34	122.26	93.03	193.49	126.92	118.96
#65	0.231	0.366	77.00	513.87	200.04	54.50	95.09	164.25	170.71	281.15	150.48	115.51
#100	0.150	0.191	13.52	96.35	19.17	18.02	33.73	60.79	63.57	54.06	51.62	49.05
#150	0.100	0.125	18.28	67.13	22.47	29.03	53.45	141.39	46.03	50.34	70.65	54.33
#200	0.075	0.088	2.22	3.42	1.52	9.90	7.03	44.52	2.97	4.69	10.32	4.50
receiver	-	0.075	9.92	12.75	21.77	24.60	36.78	212.70	8.97	14.51	33.66	14.62
Total (g)			996.12	995.53	992.74	999.49	998.12	985.08	998.19	996.14	995.27	995.81
%Passing Sieve No.200			0.99	1.28	2.18	2.46	3.68	21.27	0.90	1.45	3.37	1.46
F = % Coarser than #200			98.62	98.28	97.10	97.49	96.13	77.24	98.92	98.16	96.16	98.12
C = % Coarser than #4			10.60	3.26	1.08	53.63	29.36	2.14	40.46	19.69	19.92	29.63
CF = Coarse Fraction			0.11	0.03	0.01	0.55	0.31	0.03	0.41	0.20	0.21	0.30
Categorization			sand	sand	sand	gravel	sand	sand	sand	sand	sand	sand

Table 4-3 Grain-size distribution of sediment at each station (wet season)

Mesh No.	Sieve Opening (mm)	Mean size (mm)	Weight of sediment (g)									
			MT 01	MT 02	MT 03	MT 04	MTL01	MT 05	MT 06	MT 07	MTR01	MT 08
Sample weight before sieving			1000.0	1000.0	1000.0	500.0	1000.0	1000.0	500.0	500.0	1000.0	1000.0
3/4"	19.000	19.000	0.00	0.00	0.00	0.00	0.00	6.61	29.75	0.00	80.80	0.00
3/8"	9.500	14.250	0.00	20.99	0.88	2.97	177.65	66.60	136.10	0.00	104.95	66.53
#4	4.750	7.125	0.00	141.74	6.99	8.16	350.46	134.03	111.81	0.00	249.93	160.07
#10	2.000	3.375	2.72	363.40	38.61	58.00	282.82	173.75	76.83	12.88	250.91	156.80
#20	0.850	1.425	23.89	205.44	140.85	113.17	75.97	181.48	52.95	53.35	120.85	84.33
#35	0.500	0.675	180.96	138.14	313.48	147.76	33.68	217.81	50.96	85.30	90.08	131.82
#65	0.231	0.366	526.54	105.96	408.44	130.90	36.89	169.82	32.78	184.60	69.96	292.15
#100	0.150	0.191	148.68	15.09	53.05	18.93	12.99	22.66	5.03	73.17	16.32	59.52
#150	0.100	0.125	96.24	7.25	29.69	14.18	14.22	20.21	3.20	68.03	11.73	36.39
#200	0.075	0.088	4.15	0.21	1.69	1.22	2.00	1.37	0.15	3.58	0.95	2.11
receiver	-	0.075	12.66	1.56	4.47	2.91	11.65	3.95	0.33	14.46	2.81	8.19
Total (g)			995.82	999.76	998.14	498.18	998.33	998.26	499.87	495.36	999.26	997.89
Loss (g)			4.18	0.24	1.86	1.82	1.67	1.74	0.13	4.64	0.74	2.11
Loss (%)			0.42	0.02	0.19	0.36	0.17	0.17	0.03	0.93	0.07	0.21
%Passing Sieve No.200			1.27	0.16	0.45	0.58	1.17	0.39	0.07	2.89	0.28	0.82
Mean Diameter (mm)			0.40	2.96	0.77	1.23	6.14	3.10	7.37	0.54	5.93	2.96
S.D. (mm)			0.30	2.85	0.98	1.67	4.67	4.15	6.28	0.64	5.86	4.08

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

Mesh No.	Sieve Opening (mm)	Mean size (mm)	Weight of sediment (g)									
			MT 01	MT 02	MT 03	MT 04	MTL01	MT 05	MT 06	MT 07	MTR01	MT 08
Sample weight before sieving			1000.0	1000.0	1000.0	500.0	1000.0	1000.0	500.0	500.0	1000.0	1000.0
3/4"	19.000	19.000	0.00	0.00	0.00	0.00	0.00	6.61	29.75	0.00	80.80	0.00
3/8"	9.500	14.250	0.00	20.99	0.88	2.97	177.65	66.60	136.10	0.00	104.95	66.53
#4	4.750	7.125	0.00	141.74	6.99	8.16	350.46	134.03	111.81	0.00	249.93	160.07
#10	2.000	3.375	2.72	363.40	38.61	58.00	282.82	173.75	76.83	12.88	250.91	156.80
#20	0.850	1.425	23.89	205.44	140.85	113.17	75.97	181.48	52.95	53.35	120.85	84.33
#35	0.500	0.675	180.96	138.14	313.48	147.76	33.68	217.81	50.96	85.30	90.08	131.82
#65	0.231	0.366	526.54	105.96	408.44	130.90	36.89	169.82	32.78	184.60	69.96	292.15
#100	0.150	0.191	148.68	15.09	53.05	18.93	12.99	22.66	5.03	73.17	16.32	59.52
#150	0.100	0.125	96.24	7.25	29.69	14.18	14.22	20.21	3.20	68.03	11.73	36.39
#200	0.075	0.088	4.15	0.21	1.69	1.22	2.00	1.37	0.15	3.58	0.95	2.11
receiver	-	0.075	12.66	1.56	4.47	2.91	11.65	3.95	0.33	14.46	2.81	8.19
Total (g)			995.82	999.76	998.14	498.18	998.33	998.26	499.87	495.36	999.26	997.89
%Passing Sieve No.200			1.27	0.16	0.45	0.58	1.17	0.39	0.07	2.89	0.28	0.82
F = % Coarser than #200			98.32	99.82	99.37	99.05	98.67	99.43	99.91	96.18	99.65	98.97
C = % Coarser than #4			0.00	16.27	0.79	2.22	52.81	20.72	55.53	0.00	43.57	22.66
CF = Coarse Fraction			0.00	0.16	0.01	0.02	0.54	0.21	0.56	0.00	0.44	0.23
Categorization			sand	sand	sand	sand	gravel	sand	gravel	sand	sand	sand

4.2.2 Cadmium distribution

Cadmium has high accumulation potential in small particles of sediments (Salomons, 1980; Groot *et al*., 1982; Lucas *et al*., 1986), and the large grain particles such as 0.204 mm of mean diameter usually low have accumulation of heavy metal (Forstner & Salomons 1980). Hence, cadmium distribution was investigated by bed load sieving with sieve No. 65, 100, 150 and 200 both in dry and wet seasons.

Results for cadmium distribution in each choosing bed load particles are displayed in Table 4-5 for dry season and wet season. The results showed that the cadmium concentrations were distribution in every fraction both the dry and wet season. The smallest size (0.075- mm mesh opening) and sand size particle (0.231-mm mesh opening) of bed load were the highest accumulated cadmium. Even though, heavy metals are naturally occur in the coarse-grained particles such as sand, they have the highest concentration in the fine-grained particle especially silt and clay both on natural and contamination metals (Groot *et al*., 1982).

Table 4-5 Cadmium concentrations distribute in bed load in dry and wet seasons

Station	Grain size (mm)	Dry season	Wet season
MT 01	0.151 - 0.231	14.87 ± 1.25	20.32 ± 2.53
	0.101 - 0.150	25.80 ± 10.87	25.13 ± 5.75
	0.076 - 0.100	14.36 ± 5.30	20.14 ± 7.28
	≤0.075	6.99 ± 2.54	27.76 ± 3.07
MT 02	0.151 - 0.231	15.94 ± 7.05	30.18 ± 22.25
	0.101 - 0.150	17.11 ± 1.63	17.10 ± 2.61
	0.076 - 0.100	27.52 ± 4.84	20.44 ± 7.09
	≤0.075	29.15 ± 1.41	17.47 ± 5.33
MT 03	0.151 - 0.231	6.59 ± 3.34	8.24 ± 6.00
	0.101 - 0.150	11.76 ± 9.48	15.46 ± 5.28
	0.076 - 0.100	10.96 ± 1.48	18.43 ± 1.78
	≤0.075	11.14 ± 0.14	19.62 ± 2.40
MT 04	0.151 - 0.231	49.59 ± 31.34	38.19 ± 2.11
	0.101 - 0.150	17.27 ± 6.45	152.25 ± 30.62

Table 4-5 Cadmium concentrations distribute in bed load in dry and wet seasons (continued)

Station	Grain size (mm)	Dry season	Wet season
MT 04	0.076 - 0.100	7.04 ± 1.08	64.67 ± 8.26
	≤0.075	5.54 ± 1.04	31.66 ± 2.82
MTL 01	0.151 - 0.231	3.22 ± 0.56	3.68 ± 0.79
	0.101 - 0.150	3.52 ± 0.45	1.66 ± 0.25
	0.076 - 0.100	3.80 ± 0.56	0.98 ± 0.48
	≤0.075	3.90 ± 0.80	1.08 ± 0.11
MT 05	0.151 - 0.231	24.49 ± 3.10	28.42 ± 7.77
	0.101 - 0.150	11.95 ± 9.69	32.03 ± 4.74
	0.076 - 0.100	3.43 ± 1.97	15.87 ± 3.23
	≤0.075	2.41 ± 0.62	13.55 ± 1.12
MT 06	0.151 - 0.231	2.64 ± 0.58	2.37 ± 0.98
	0.101 - 0.150	2.47 ± 0.14	2.21 ± 0.14
	0.076 - 0.100	1.84 ± 0.31	2.01 ± 0.19
	≤0.075	2.10 ± 0.95	0.05*
MT 07	0.151 - 0.231	1.32 ± 0.09	2.15 ± 0.26
	0.101 - 0.150	0.89 ± 0.14	1.72 ± 0.35
	0.076 - 0.100	0.84 ± 0.32	2.00 ± 0.55
	≤0.075	1.42 ± 0.42	2.64 ± 0.39
MTR 01	0.151 - 0.231	1.24 ± 0.32	2.29 ± 0.74
	0.101 - 0.150	0.66 ± 0.21	3.33 ± 0.54
	0.076 - 0.100	0.91 ± 0.52	5.79 ± 3.69
	≤0.075	1.39 ± 0.11	3.27 ± 1.70
MT 08	0.151 - 0.231	1.42 ± 0.13	1.72 ± 0.33
	0.101 - 0.150	1.34 ± 0.30	0.93 ± 0.19
	0.076 - 0.100	1.29 ± 0.11	1.57 ± 0.04
	≤0.075	1.36 ± 0.20	6.17 ± 5.71

Note: *Limit bed load samples

4.2.3 Total cadmium in the suspended sediment and bed load

- **Total cadmium in the suspended sediment**

Suspended sediments were compiled from ten stations along the Mae Tao Creek and prepared for the total cadmium measurement by following EPA method 3051B in both dry and wet season. Then, the total cadmium concentrations were completely analyzed by graphite furnace atomic absorption spectrometry (GFAAS).

Figure 4-2 shows the total cadmium concentrations in suspended sediment during the dry and wet seasons. The cadmium concentration in the suspended sediment ranged from 2.55 to 12.80 mg/kg in the dry season and ranged from 5.76 to 112.40 mg/kg in the wet season. Analysis results of suspended sediments were different from the bed load results. This may be affected by the limited amount of collected samples of suspended sediment. High amount of precipitation before collecting samples during the dry season and wet seasons may be a factor for significant high concentrations. High cadmium contaminations in suspended sediments were detected at upstream of the Mae Tao Creek or before entering the zinc mining area. It may be caused from weathering and human activities could have increased the erosion by resulting in high level of cadmium contamination releasing to the environment. It was indicated that deforestation for crop plantations increased soil and ore erosions due to lack of trees covering ore potential area (PCD, 2011).

At present, Thailand does not establish a standard for heavy metal concentrations in sediments. Consequently, the Probable Effect Levels (PELs) standard of the Canadian Environmental Quality Guidelines established by the Canadian Council of Ministers of the Environment was applied to compare the results (PCD, 2011). In comparison with the PELs standard which allowed a level of cadmium contamination lower than 3.5 mg/kg (CCME, 2002), only suspended sediment samples at station located upstream of zinc mines area during dry season complied with the standard.

- **Total cadmium concentration in bed load**

Bed load sediments were collected and prepared for total cadmium measurement during both seasons. Bed load sizes were selected to estimate the total cadmium concentrations from bed load sieving with sieve No. 65, 100, 150 and 200. The bed load samples that remain on each sieve were digested by following the EPA method 3051. Then, the laboratory was completely analyzed by flame atomic absorption spectrometry (FLAAS).

Figure 4-3 shows the total cadmium concentrations in bed load during the dry and wet season. The average total cadmium concentrations in the bed load ranged from 1.00 to 19.63 mg/kg in the dry season and 1.79 to 81.98 mg/kg in the wet season. In comparison with the PELs standard, bed load sediments in the upstream of zinc mining area had cadmium concentrations lower than the standard both seasons. Furthermore, cadmium levels in Mae Tao Left (MTL 01) collected from the wet season complied with the standard.

The result of the total cadmium concentrations in bed load sediments showed a similar trend during the dry and wet seasons. Cadmium contribution in bed load before the two zinc mines presented the low concentration as shown in station MT 06, MT 07, MTR 01 and MT 08. On the other hand, cadmium became high concentration at downstream of mining area, as presented in station MT 01, MT 02, MT 03, MT 04. The total cadmium concentrations at station MT 06 and station MT 05 showed that the cadmium increased when passing the first mine (Padaeng Industry Public Company Limited's mine). Moreover, the total cadmium concentration at station MT 04 showed that the cadmium still had high levels when passing the second mine (Tak Mining Company Limited's mine). The concentrations of cadmium in bed load sediment along the ten sampling stations in the Mae Tao Creek have higher concentrations in wet season. The causes of high cadmium accumulated sediment in the wet season may affect by surface runoff and rainfall during storm season. The high precipitation rate caused the greater transport of sediments. Consequently, the most significant sources for cadmium contamination were rainfall rate and anthropogenic activities such as deforestation and mining activities.

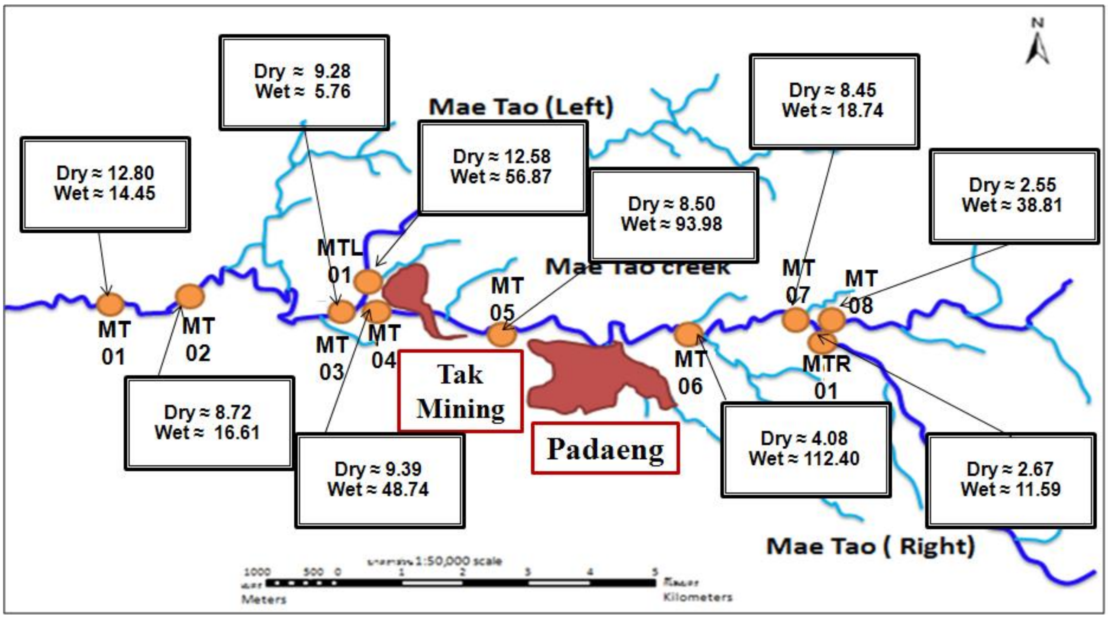


Figure 4-2 Cadmium concentration in suspended sediment at each station during the dry and wet seasons

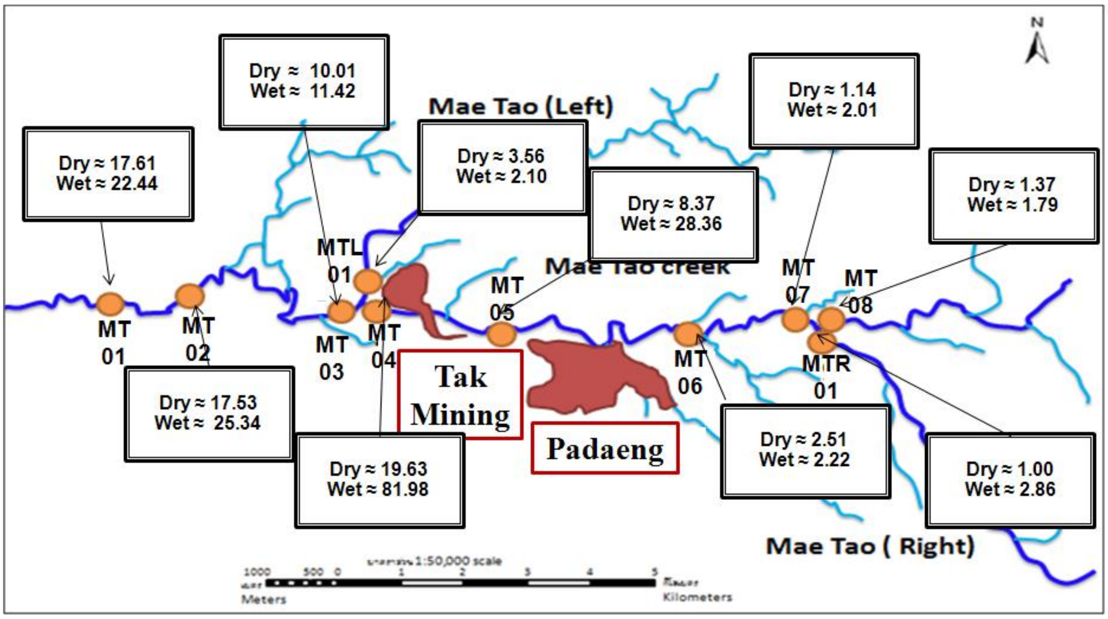


Figure 4-3 Cadmium concentration in bed load at each station during the dry and wet seasons

Table 4-6 The total cadmium concentration in suspended sediment and bed load

Station	Suspended sediment				Bed load	
	Dry season		Wet season		Dry season	Wet season
	Dry weight (mg/L)	Total Cd concentration (mg/kg)	Dry weight (mg/L)	Total Cd concentration (mg/kg)	Total Cd concentration (mg/kg)	Total Cd concentration (mg/kg)
MT 01	2.08	12.80 ± 5.82	7.30	14.45 ± 8.93	17.61 ± 5.03	22.44 ± 4.09
MT 02	4.02	8.72 ± 1.32	29.33	16.61 ± 0.86	17.53 ± 3.57	25.34 ± 9.77
MT 03	8.68	9.28 ± 0.58	34.50	5.76 ± 0.75	10.01 ± 4.12	11.42 ± 3.46
MT 04	4.35	9.39 ± 1.46	15.12	48.74 ± 9.76	19.63 ± 12.40	81.98 ± 14.6
MTL01	9.75	12.58 ± 1.67	5.08	56.87 ± 45.80	3.56 ± 0.49	2.10 ± 0.39
MT 05	2.15	8.5 ± 2.04	3.20	93.98 ± 37.50	8.37 ± 4.21	28.36 ± 3.94
MT 06	3.75	4.08 ± 2.35	3.03	112.4 ± 11.40	2.51 ± 0.47	2.22 ± 0.47
MT 07	1.55	8.45 ± 1.96	38.23	18.74 ± 5.77	1.14 ± 0.22	2.01 ± 0.32
MTR01	4.70	2.67 ± 0.16	84.90	11.59 ± 11.60	1.00 ± 0.27	2.86 ± 1.69
MT 08	5.10	2.55 ± 0.59	13.95	38.81 ± 12.80	1.37 ± 0.16	1.79 ± 2.32

4.3 Simulation results

4.3.1 Hydrodynamic simulation

4.3.1.1 Model calibration

Hydrodynamic simulation of the Mae Tao Creek was calibrated with the measured water depth at station MT 04 from March 2011 to February 2012. The simulated and measured water level at station MT 04 as shown in Figure 4.4, statistic calculations were generated for estimating the reliability of model calibration. Correlation coefficient (R) is a measure of linear dependency between simulated and measured values, and is closer value to 1.00 for the better match. Root mean square error (RMSE) will tend to be 0 if there is a perfect match of the observation and simulation. This study obtained the R value of 0.61and the RMSE value of 10.33 m. The high significant values may be influenced by noise of beginning period of simulation.

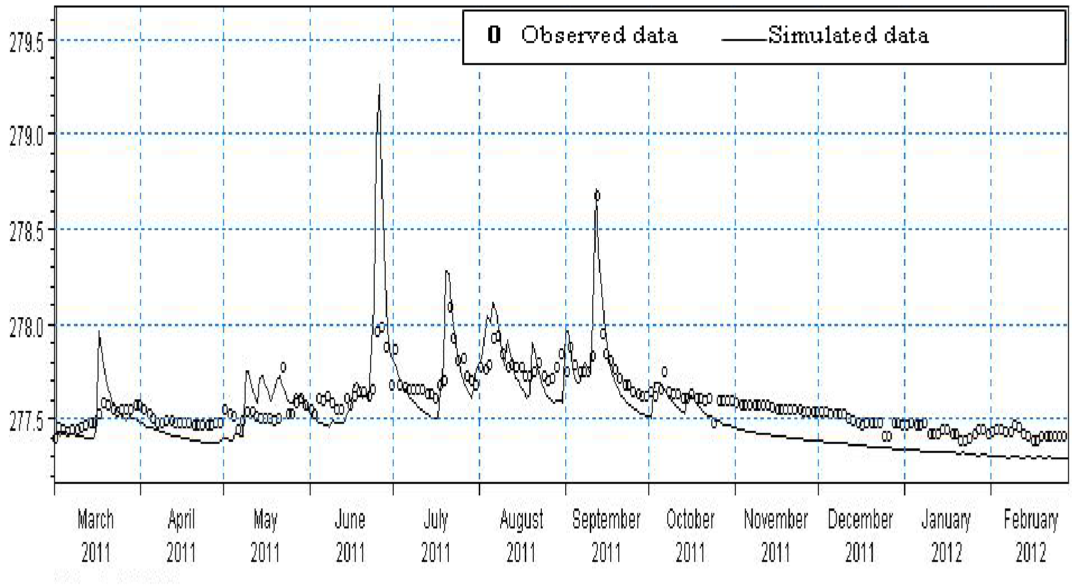
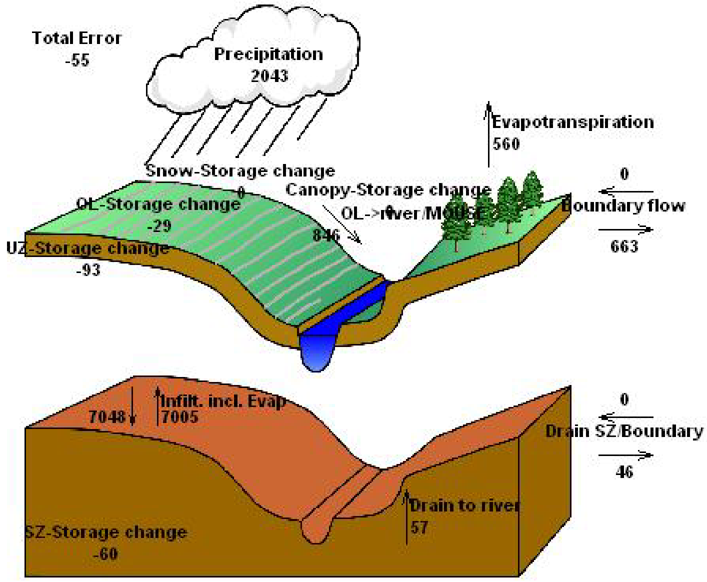


Figure 4-4 Observed and simulated water level at station MT 04 (m)

4.3.1.2 Hydrodynamic results

MIKE SHE coupled with MIKE 11 was applied to estimate the hydrodynamic results, which were water depth and water discharge. Water depth and water discharge focused on 9 stations along main of Mae Tao Creek, Mae Tao Right and Mae Tao Left, which except station MT 01 for using as downstream boundary condition. The simulated results revealed that high amount of water discharge obtained from downstream and consequently came down until upstream of the main Mae Tao Creek. The Mae Tao Left and the Mae Tao Right had less discharge than the main Mae Tao Creek. According to the greater water depth and water discharge in wet season, precipitation was a major impact for influencing instability of the amount of water along the creek. The example of precipitation factor was first peak in March after shortly heavy rainfall and other peaks in May to October related to wet season (see precipitation rate in Appendix B, Figure B-1).

(a)



(b)

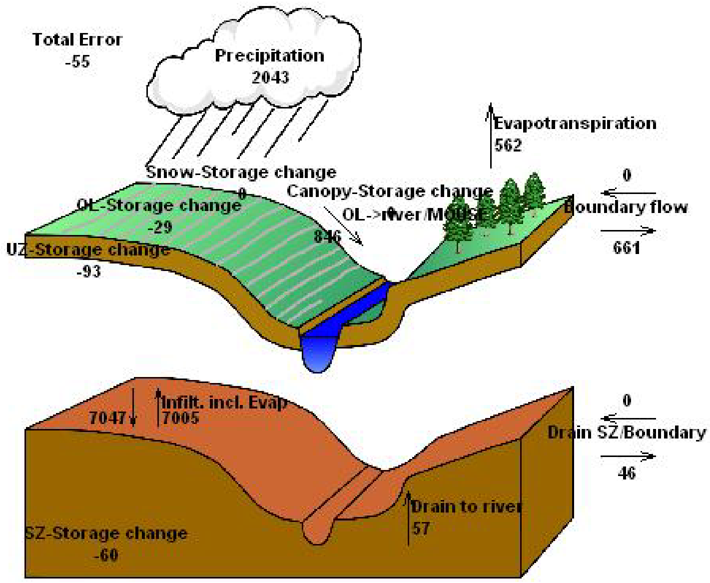


Figure 4-5 Total water balance chart of the Mae Tao subcatchment (mm)

(a) Current agricultural land use

(b) Agricultural land use change: conversion of rice to sugarcane

According to Figure 4-5 (a) and (b), there is changing of crop type from rice to sugarcane. The result showed that conversion of rice plantation to sugarcane plantation brought to increasing of annual evapotranspiration from 560 mm. to 562 mm in sugarcane condition. Moreover, case of sugarcane plantation detected the decreasing of boundary flow from unsaturated zone in water balance chart from 663 mm in current land use to be 661 mm. In fact that the plantation of sugarcane abundantly required water demand and growing period, and its leaf area index was higher than rice. Nevertheless, sugarcane obtained growth time to be mature development over 300 days, while rice took shorter growing period such over 100 days. The longer mutual developing time of sugarcane planting was resulted in taking much water requirement. Moreover, sugarcane has greater leaf area index than rice (see Appendix D, Table D-2). These reasons influenced a rising up of annual evapotranspiration in assume agricultural land use, which contributed to a reducing in water flows.

4.3.2 Sensitivity analysis

The sensitivity of model's parameters affecting water discharge was calibrated using Equation (3.77) and evaluated by sensitivity classes as displayed in Table 3-4. The results in Table 4-7 showed the effect of parameters in overland flow, unsaturated flow and saturated zone to water discharge. Sensitivity analysis showed that simulating hydrodynamic focusing on water discharge of the Mae Tao Creek sensitive to the process in saturated zone especially a drainage level to the river, and the process in overland flow to the river. The drainage level is determined from the saturated zone layer from which drain water is extracted. If surface drainage is routed by drain levels, the drainage routing is calculated from the drainage level in each cell. So, the drain flow will continue until crossing a river.

Table 4-7 Sensitivity of parameters in MIKE SHE

Parameters	Sensitivity index (I)	Sensitivity
Overland flow		
- Manning number	0.09	Medium
- Detension storage	0.00	Small to negligible
Unsaturated Flow		
- Saturated hydraulic conductivity	0.01	Small to negligible
- Groundwater depths used for UZ classification	0.00	
Saturated Zone		
- Lower level	0.00	Small to negligible
- Horizontal Hydraulic Conductivity	0.01	
- Vertical Hydraulic Conductivity	0.00	
- Specific yield	0.00	
- Specific storage	0.00	
- Initial potential head	0.00	
- Drainage level	0.19	Medium
- Drainage time constant	0.00	Small to negligible

4.3.3 Sediment transport results

After calibrating the hydrodynamic results from MIKE SHE model, sediment transport module was added on MIKE 11 with hydrodynamic results for simulating sediment transport results along the Mae Tao Creek. Both wet and dry season, total sediment transport was estimated by dividing into suspended sediment and bed load. The study periods were from May 2011 to October 2011 as the wet season, and November 2011 to February 2012 as the dry season.

During the wet season, the total sediment transport was computed as 532.60 m^3 that was transported by water discharge of 388.36x10^5 m^3. Whereas 8.03 m^3 of the sediment was occurred in the dry season, it was transported by 15.39x10^5 m^3 of water discharge. Therefore, 540.63 m^3 of the total sediment both suspended sediment and bed load was transported with a water discharge of 403.75x10^5 m^3. The sediment transport was mainly contained during wet season with 98.52% of total, and transported via suspended sediment with of 72.75% of total. The results revealed that instability of sediment transport depended on discharge rate. According to wet season, high water discharge which affected from high rainfall caused the sediment to be high available of transport along river system. The small amount of bed load was transported because the proportion of total sediment in sand-bed channels contained a few of bed load (Simons and Senturk, 1977).

Sediment transport in the wet season

From May 2011 to October 2011, sediment transport along Mae Tao Creek was simulated as wet season. The results showed that both suspended sediment (Figure 4-6) and bed load (Figure 4-7) had a great transport rate when the rainfall was occurred. So the highest transport rates occurred in June 2011.

Figure 4-6 displayed transport rate of suspended sediment at downstream. Highest suspended sediment rate obtained from 25th June 2011, which had the highest precipitation. The highest rate was 3.63x10^{-4} m^3/s with a water discharge of 20.45 m^3/s. The volume of accumulated suspended sediment was determined as 387.46 m^3. According to Figure 4-7, bed load transport rates downstream were presented by having the highest period liked the period of suspended sediment. The highest bed load transport rate was 0.21x10^{-4} m^3/s, and accumulated amount was 145.14 m^3. Thus, accumulated total sediment transport, consisted of suspended and bed load sediment, was estimated at 532.60 m^3 at downstream during the wet season of 2011, as shown in Figure 4-8.

Sediment transport in the dry season

Sediment transport via suspended sediment and bed load was simulated by applying the period from November 2011 to February 2012 as the dry season. Transport rates of suspended sediment and bed load at downstream are displayed in Figure 4-9 and Figure 4-10, respectively. Figure 4-11 presented the total sediment transported downstream in dry season. The accumulated total sediment transport during dry season was 8.03 m^3 that composed of accumulated suspended sediment transport with 6.59 m^3 and accumulated bed load transport with 1.44 m^3.

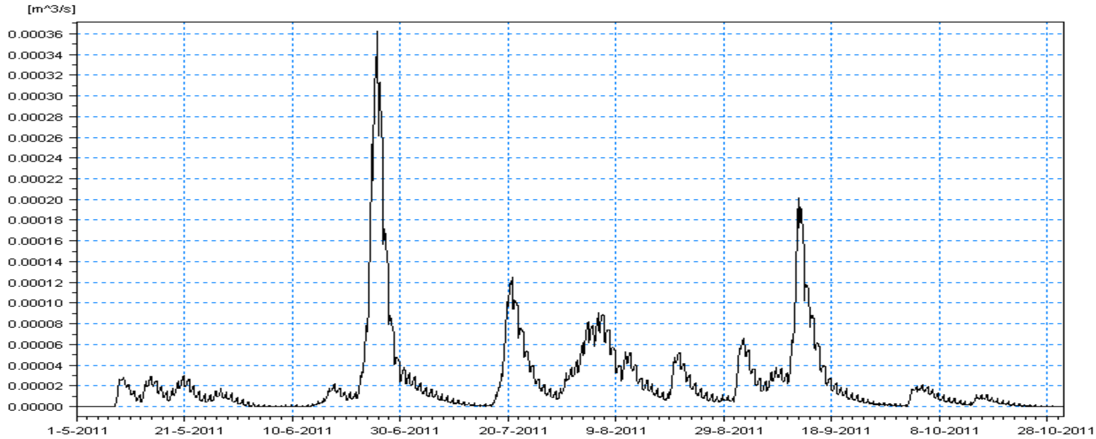


Figure 4-6 Suspended sediment transport rate at downstream in wet season (m^3/s)

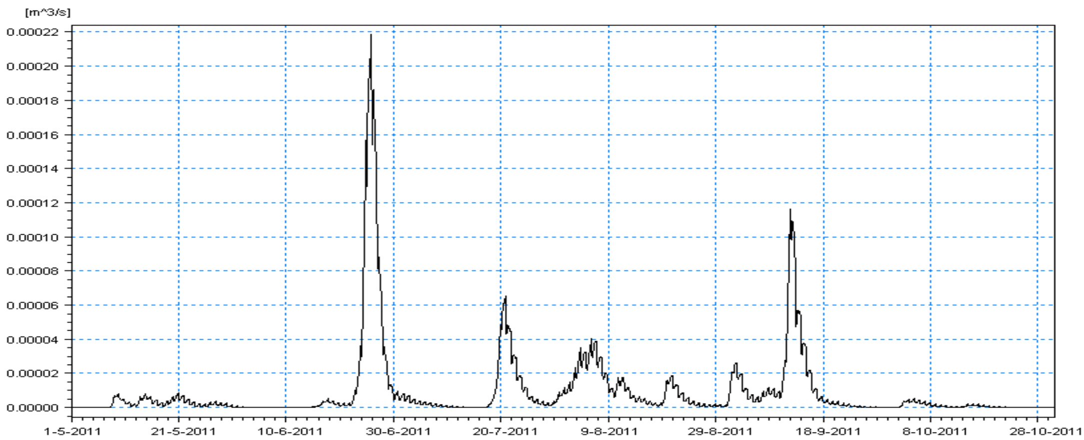


Figure 4-7 Bed load transport rate at downstream in wet season (m^3/s)

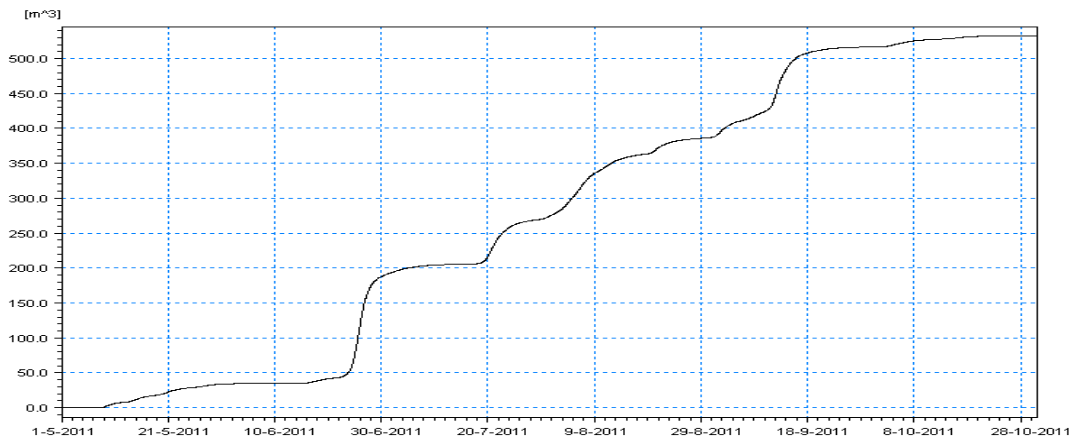


Figure 4-8 Accumulated sediment transport at downstream in wet season (m^3)

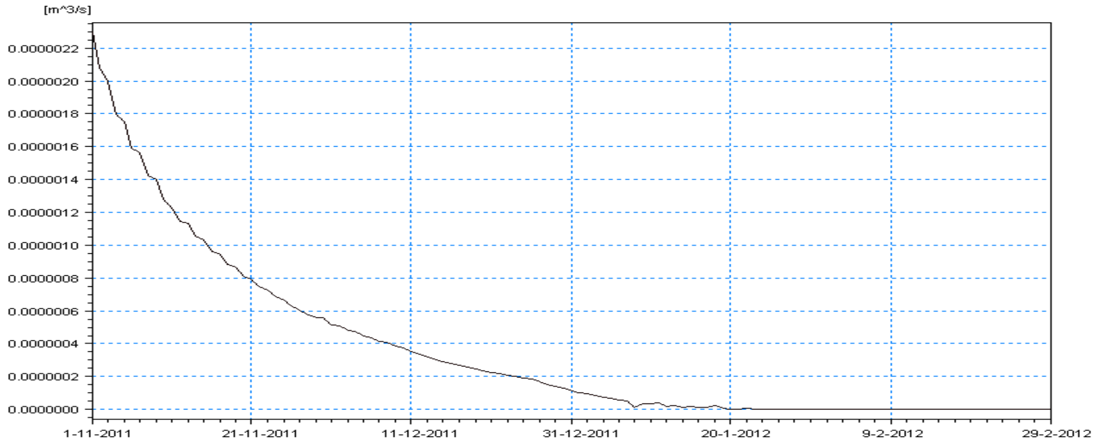


Figure 4-9 Suspended sediment transport rate at downstream in dry season (m^3/s)

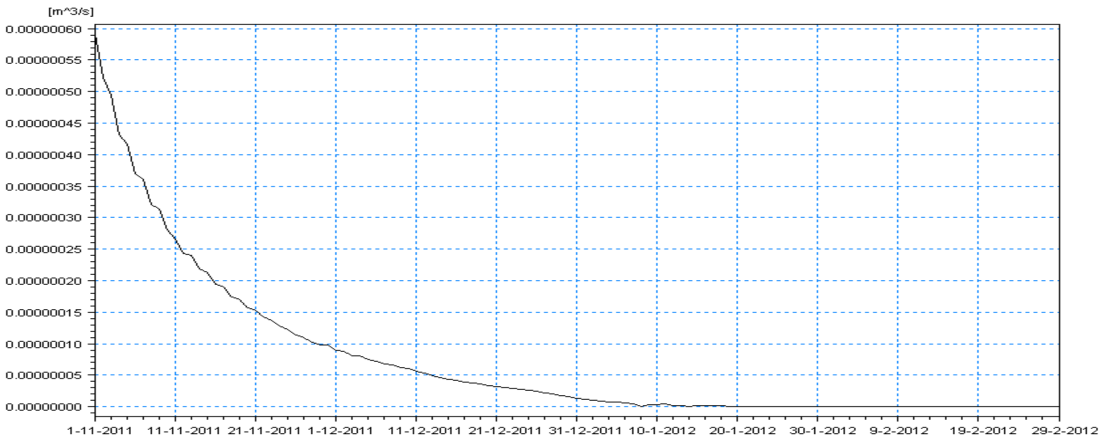


Figure 4-10 Bed load transport rate at downstream in dry season (m^3/s)

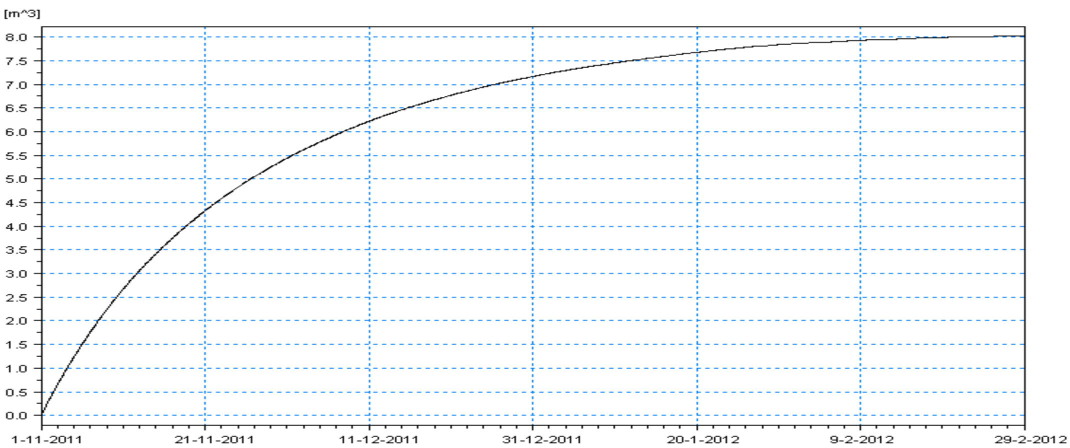


Figure 4-11 Accumulated sediment transport at downstream in dry season (m^3)

Sediment transport rate illustrated similar pattern to moving of water discharge, as displayed in Figure 4-12 and Figure 4-13. During May 2011 to February 2012, the rate of sediment transport generated highest peak in June and the other peaks were followed in July to October related to high discharge occurrence. After storm event, the sediment transport rate gently became down until the end of the study period. This is a good agreement that discharge as a result of wet season can affect variations in the rate of sediment transport. Therefore, high flow seasonal played significant role on total sediment input into downstream of river system.

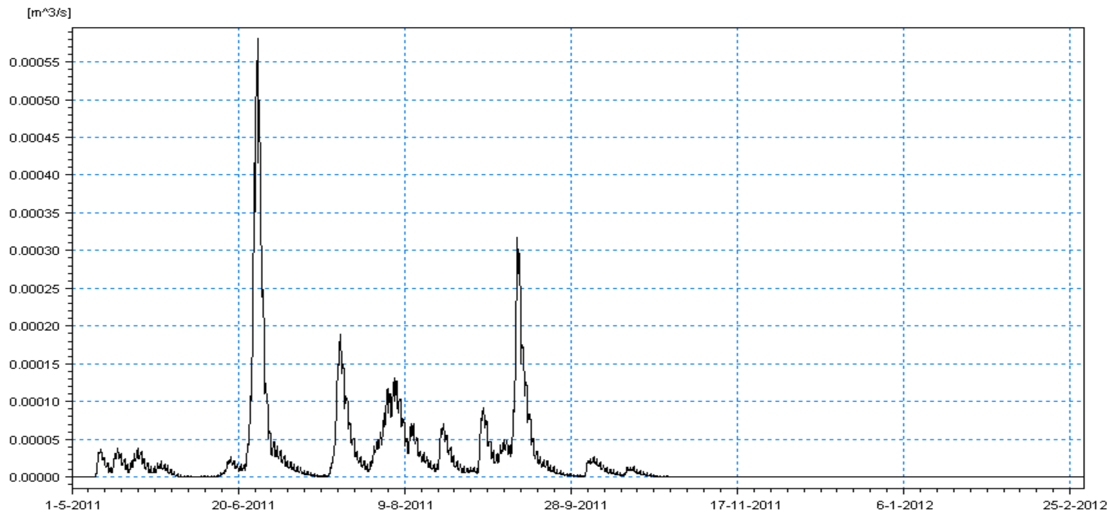


Figure 4-12 Total sediment transport rate at downstream (m^3/s)

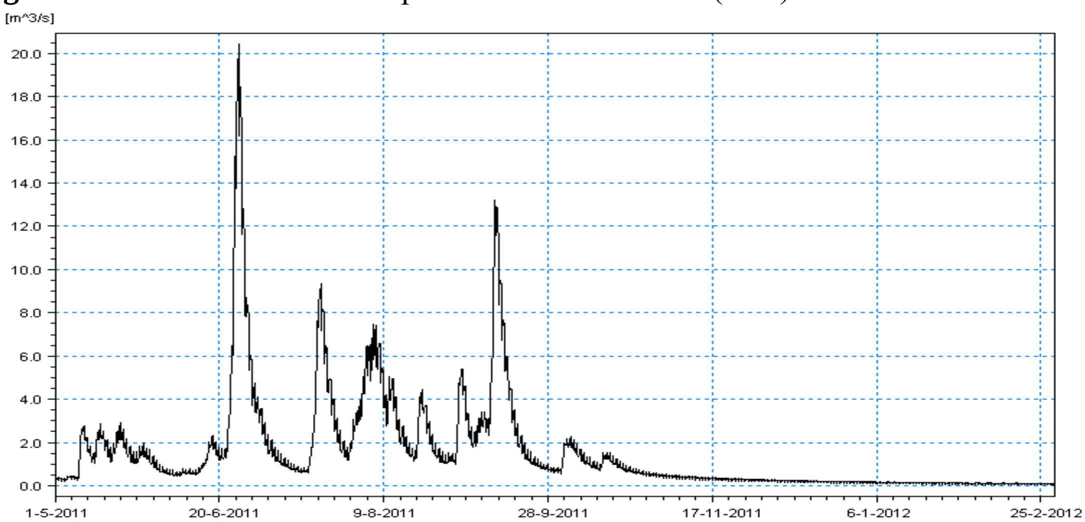


Figure 4-13 Discharge rate at downstream (m^3/s)

4.4 Cadmium transport estimation

The amount of cadmium transport (kg) at downstream could be computed from accumulated sediment transport (kg) from model and cadmium concentration that measured from the field (mg/kg), as presented in Equation (3.81). At downstream station of the Mae Tao Creek, station MT 02 was chosen as significant sampling site to estimate cadmium transport amount distributed to a village area. Because of high uncertainty of sediment transport results, the uncertainty analysis determined the minimum and maximum of sediment transport to examine the boundary of cadmium transport.

Agricultural land use scenarios

In this study, land use scenarios were developed by directions of national policy. The impacts of agricultural land use on the accumulated cadmium transport in the Mae Tao Creek. The effect of agricultural land use was divided into two scenarios. The first one was original condition that based on current crop types in the study area, and the last one was the setting condition by replacing rice plantation with sugarcane plantation. Scenario with switch of rice to sugarcane was set by relying on the Royal Thai Government's policy for management of cadmium contamination.

- *Scenario 1: current agricultural land use*

The results from original condition (current agricultural land use) are shown in Table 4-8 and Table 4-9. The amount of sediment transport, which was estimated from accumulated sediment transport and sediment density, was equal to 866,090.89 kg from May 2011 to February 2012. It was simulated from wet season as 853,230.27 kg and from dry season as 12,860.62 kg, as mentioned in Table 4-8. So, the total amount of cadmium transport at downstream of the Mae Tao Creek during this period was computed to 16.33 kg. It was separated into wet and dry season with 16.20 kg and 0.13 kg, respectively, as shown in Table 4-9. The result revealed that suspended sediment was a greater transport than bed load so the cadmium transport in the Mae Tao Creek was mainly controlled by suspended sediment transport.

Moreover, the wet season caused the sediment become available for transport that resulting in high distribution of cadmium contaminated in the storm event.

Table 4-8 Possible values of total sediment transport (current agricultural land use)

Period	Sediment	Minimum total sediment transport (kg)	Simulate total sediment transport (kg)	Maximum total sediment transport (kg)
Wet season	Suspended sediment	90,189.63	620,716.87	1,013,307.04
	Bed load	33,784.00	232,513.40	379,573.14
	Total	123,973.63	853,230.27	1,392,880.19
Dry season	Suspended sediment	1,534.30	10,559.61	17,238.33
	Bed load	334.33	2,301.01	3,756.35
	Total	1,868.64	12,860.62	20,994.68

Table 4-9 Possible values of cadmium transport (current agricultural land use)

Period	Sediment	Minimum cadmium transport (kg)	Simulate cadmium transport (kg)	Maximum cadmium transport (kg)
Wet season	Suspended sediment	1.50	10.31	16.83
	Bed load	0.86	5.89	9.62
	Total	2.36	16.20	26.45
Dry season	Suspended sediment	0.01	0.09	0.15
	Bed load	0.01	0.04	0.07
	Total	0.02	0.13	0.22
Total		**2.38**	**16.33**	**26.67**

- *Scenario 2: conversion of rice to sugarcane*

In this scenario, effects of agricultural land use were determined by basing on substitution of rice plantation with sugarcane plantation. Table 4-10 and Table 4-11 described the downstream results of sediment transport and cadmium transport from assume condition from May 2011 to February 2012. When assume agricultural land use compared with original land use (scenario 1), it could be observed the different in the amount of total sediment transport both suspended sediment and bed load. According to Table 4-10 showing the total sediment transport at downstream, the results presented a significant effect on decreasing from original condition's results. They obtained relatively small changes by reducing from 853,230.27 kg to 853,069.89 kg during wet season, and from 12,860.62 kg to 12,830.24 kg during dry season. In addition to decrease of the amount of sediment transport, it could be hypothesized that a long growing time of sugarcane could have effect the water flow. Sugarcane plantation obtained a great water demand and took long growth period to be maturity, while rice plantation took shorter of mutual growing time. So, the long period in sugarcane growth was gained a lot of water requirement that may be had impact a decrease in water flow, responding for sediment transport reduction. However, the decrease in amount of sediment transport was small different from previously scenario that could not be contributed to take much change in cadmium transport reduction. The results in Table 4-11 expressed the amount of accumulated cadmium from land use changing that was transported downstream.

Table 4-10 Possible values of total sediment transport (conversion of rice to sugarcane)

Period	Sediment	Minimum total sediment transport (kg)	Simulate total sediment transport (kg)	Maximum total sediment transport (kg)
Wet season	Suspended sediment	90,172.84	620,601.25	1,013,118.33
	Bed load	33,777.50	232,468.64	379,500.10
	Total	123,950.34	853,069.89	1,392,618.43
Dry season	Suspended sediment	1,530.92	10,536.34	17,200.36
	Bed load	333.30	2,293.90	3,744.75
	Total	1,864.22	12,830.24	20,945.11

Table 4-11 Possible values of cadmium transport (conversion of rice to sugarcane)

Period	Sediment	Minimum cadmium transport (kg)	Simulate cadmium transport (kg)	Maximum cadmium transport (kg)
Wet season	Suspended sediment	1.50	10.31	16.83
	Bed load	0.86	5.89	9.62
	Total	2.36	16.20	26.45
Dry season	Suspended sediment	0.01	0.09	0.15
	Bed load	0.01	0.04	0.07
	Total	0.02	0.13	0.22
Total		**2.38**	**16.33**	**26.67**

Hydraulic structure scenario

From the field observation, concrete weir was found between station MT 02 and station MT 03 at the Mae Tao Creek. Hydraulic structure was considered as the other one of factors that would play significant role in cadmium contaminated sediment transport via the suspended sediment and bed load in the Mae Tao Creek. Effects of hydraulic structure on cadmium transport were evaluated on two conditions: with and without hydraulic structure.

Changes in sediment and cadmium transport according to hydraulic structure construction scenarios were summarized in Table 4-12. As having construction of hydraulic structure condition at downstream of the Mae Tao Creek, the results reported that this condition attributed to decrease of total accumulated sediment transport at downstream of hydraulic structure location explicitly in bed load transport. This is in good agreement that coarse sediment such as sand and gravel may be disrupted and decreased by the impoundment construction (Taylor *et al*., 2008). From May 2011 to February 2012, the amount of total accumulated sediment transport when passing the weir was equal to 691,826.72 kg in scenario of having hydraulic structure. While, the scenario in removal of hydraulic structure, it resulted in increase of total accumulated sediment transport amount for 954,378.11 kg. Thus, the cadmium transport in hydraulic structure removal condition could be estimated at 18.06 kg, and came down when having hydraulic structure operation as 12.86 kg, as displayed in Figure 4-14.

Due to high uncertainty of sediment transport simulations, the possible of sediment transport and cadmium transport in hydraulic structure scenarios were estimated from uncertainty analysis as minimum and maximum values, as showed in Table 4-13, 4-14, 4-15 and 4-16.

Table 4-12 Sediment and cadmium transport results from comparison between without hydraulic structure and with hydraulic structure

		Sediment transport (kg)		Cadmium transport (kg)	
Period	**Sediment**	**No having hydraulic structure**	**Having hydraulic structure**	**No having hydraulic structure**	**Having hydraulic structure**
Wet season	**Suspended sediment**	648,800.81	521,023.86	10.78	8.65
	Bed load	273,502.95	162,805.12	6.93	4.13
	Total	922,303.76	683,828.98	17.71	12.78
Dry season	**Suspended sediment**	23,860.88	6,647.47	0.21	0.06
	Bed load	8,213.47	1,350.27	0.14	0.02
	Total	32,074.35	7,997.74	0.35	0.08
Total				**18.06**	**12.86**

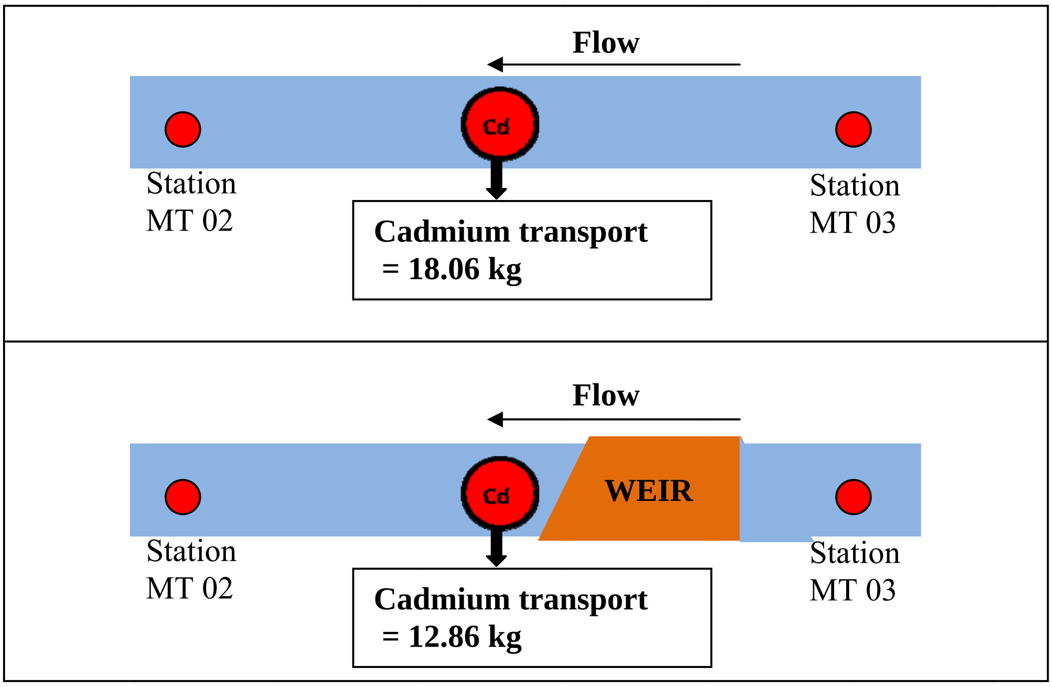


Figure 4-14 Comparison of cadmium transport between without and with weir

Table 4-13 Possible values of sediment transport (without hydraulic structure)

Period	Sediment	Minimum total sediment transport (kg)	Simulate total sediment transport (kg)	Maximum total sediment transport (kg)
Wet season	**Suspended sediment**	94,270.21	648,800.81	1,059,153.44
	Bed load	39,739.74	273,502.95	446,487.69
	Total	134,009.95	922,303.76	1,505,641.13
Dry season	**Suspended sediment**	3,466.97	23,860.88	38,952.38
	Bed load	1,193.41	8,213.47	13,408.32
	Total	4,660.38	32,074.35	52,360.70

Table 4-14 Possible values of cadmium transport (without hydraulic structure)

Period	Sediment	Minimum cadmium transport (kg)	Simulate cadmium transport (kg)	Maximum cadmium transport (kg)
Wet season	**Suspended sediment**	1.57	10.78	17.59
	Bed load	1.01	6.93	11.31
	Total	2.57	17.71	28.91
Dry season	**Suspended sediment**	0.03	0.21	0.34
	Bed load	0.02	0.14	0.24
	Total	0.05	0.35	0.57
Total		**2.62**	**18.06**	**29.48**

Table 4-15 Possible values of sediment transport (with hydraulic structure)

Period	Sediment	Minimum total sediment transport (kg)	Simulate total sediment transport (kg)	Maximum total sediment transport (kg)
Wet season	Suspended sediment	75,704.32	521,023.86	850,560.31
	Bed load	23,655.44	162,805.12	265,775.87
	Total	99,359.76	683,828.98	1,116,336.18
Dry season	Suspended sediment	965.87	6,647.47	10,851.86
	Bed load	196.19	1,350.27	2,204.29
	Total	1,162.07	7,997.74	13,056.15

Table 4-16 Possible values of cadmium transport (with hydraulic structure)

Period	Sediment	Minimum cadmium transport (kg)	Simulate cadmium transport (kg)	Maximum cadmium transport (kg)
Wet season	Suspended sediment	1.26	8.65	14.13
	Bed load	0.60	4.13	6.73
	Total	1.86	12.78	20.86
Dry season	Suspended sediment	0.01	0.06	0.09
	Bed load	0.00	0.02	0.04
	Total	0.01	0.08	0.13
Total		**1.87**	**12.86**	**21.00**

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Cadmium contaminated sediment transport in the Mae Tao Creek was studied by focusing on the effect from agricultural land use changes and hydraulic structure. The input data, which was obtained from government departments, field observation and literature, was applied into MIKE SHE coupled with MIKE 11 model to simulate hydrodynamic and sediment transport results during May 2011 to February 2012.

The assessment of hydrodynamics in the Mae Tao Creek was carried out by calibrating with the observed water depth at station MT 04. Statistics for a simulation were applied to evaluate the performance of the simulated hydrodynamic results by using correlation coefficient (R) and root mean square error (RMSE). The values of R and RMSE were generated with 0.61 and 10.33 m, respectively. According to results, wet season influenced the higher water depth and discharge than dry season. Water discharge was great amount at downstream highly increased along the Mae Tao Creek by taking highest discharge at downstream. Moreover, a drainage level in the saturated zone and the process in overland flow to the river were the significant compartment that majorly affected the water discharge from sensitivity analysis.

As classification of field sediment belonged to sand size particle, non-cohesive sediment transport module in MIKE 11 could be applied to assess a sediment transport. The sediment transport was simulated both wet and dry season for the period of May 2011 to October 2011 and November 2011 to February 2012, respectively. Total sediment transport was divided into suspended sediment and bed load. During May 2011 to February 2012, the total accumulated sediment transport was simulated to 540.63 m^3, which explicitly occurred in the wet season by 98.52%. It could be explained that the wet season had greater rainfall leading to have more discharge and velocity than the dry season, contributing to high available transport of sediment in the creek.

According to field observation, the cadmium contaminated along the Mae Tao Creek had higher concentrations in wet season both in suspended sediment and bed load. The higher cadmium accumulated sediment could be affected by rainfall rate and anthropogenic activities. It could be demonstrated that rainfall rate and anthropogenic activities played significant role on conversion of surface covering zinc ore potential area, conducing to the cadmium releasing into environment. Station MT 02 located at downstream was identified as significant site to estimate cadmium transport amount distributed to a village area. Suspended sediment had the cadmium concentrations of 16.61 mg/kg and 8.72 mg/kg for wet and dry season, respectively. Bed load contained cadmium values with 25.34 mg/kg and 17.53 mg/kg for wet and dry season, respectively.

The distribution of cadmium contaminated via sediment transport in the Mae Tao Creek mainly generated in the wet season. According to high transport capacity of suspended sediment, the cadmium transport was dominant by suspended sediment transport. From May 2011 to February 2012, cadmium was transported out of the Mae Tao Creek about 16.33 kg by occurring in wet season with 16.20 kg and in dry season with 0.13 kg.

The impact of agricultural land use and hydraulic structure on the accumulated cadmium transport in the Mae Tao Creek was studied. Conversion of rice in current agricultural land use to sugarcane plantation presented a decreasing on accumulated sediment both suspended sediment and bed load. The small change in sediment transport slightly affected the cadmium transport because the area of land use change was small when compared to the whole study area. As scenarios of hydraulic structure, with the hydraulic structure at downstream of the Mae Tao Creek leaded a decreasing of accumulated sediment transport both suspended sediment and bed load after passing the weir, contribution to a lowering in cadmium transport. From May 2011 to February 2012, the cadmium transport amount of removal hydraulic structure's condition was simulated at 18.06 kg, and came down when having hydraulic structure operation as 12.86 kg.

5.2 Recommendations

To accomplish the investigation of cadmium transport via suspended sediment and bed load, cadmium concentration was a key factor to define the transport. Cadmium transport in the Mae Tao Creek was evaluated in two seasons which are dry and wet season. However, the accessibility to sediment collection during wet season had limitation from the extensive flood occurrence. According to the important of cadmium concentration, more of sediment samples should be collected in each season. Additionally, the cadmium concentrations would be collected from the agricultural area receiving water from the Mae Tao Creek to more understanding on source and cadmium contamination in the area. In accordance with the assessment impacts of land use, leaf area index of each crop was defined by basing on literature. The leaf area index should be measured at the study area to obtain more reliable simulated results. The sediment density was obtained from literature reviews that caused the high uncertainty in this study. To improve the cadmium transport result, more effort should be focused on estimating accurate density of sediment both in suspended sediment and bed load to be used in cadmium transport estimation. Moreover, other eating crop type in study area would be taken into account for further discussion.

As result from this study found that weir in the Mae Tao Creek may reduce a lot of contaminate sediment to downstream which is the more dense resident area. It would be worth to do more study on using such structure to manage cadmium contaminate. More extensive field survey at structure may require to refine and validate the simulation result. Further recommend for future study is extended to ECOLab model in MIKE 11 that would be taken into simulation to describe heavy metal transport with sediment and river flow.

REFERENCES

Akkajit, P., and Tongcumpou, C. 2010. Fractionation in cadmium contaminated soil: Relation and effect on bioavailable cadmium. Geoderma. 156: 126-132.

American Society for Testing and Materials (ASTM) International. 2009. ASTM C136 - 06 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates [Online]. Available from: http://www.astm.org/Standards/C136.htm/ [2012, May 1]

American Society for Testing and Materials (ASTM) International. 2009. ASTM D422 - 63(2007) Standard Test Method for Particle-Size Analysis of Soils [Online]. Available from: http://www.astm.org/Standards/D422.htm/ [2012, May 1]

Arnason, J.G., and Fletcher, B.A. 2003. A 40+ year record of Cd, Hg, Pb, and U deposition in sediments of Patroon Reservoir, Albany County, NY, USA. Environmental Pollution. 123: 383–391.

Breda, N.J. 2003. Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. Journal of Experimental Botany. 54: 2403-2417.

Butts, M.B., Payne, J.T., and Overgaard, J. 2004. Improving streamflow simulations and firecasts with multimodel ensembles. Proc. of the 6th International Conference on Hydroinformatics, eds. Liong, Phoon and Babovic, 21-24 June, 2004. 1189-1196.

Canadian Council of Ministers of the Environment. 2006. Canadian soil quality guidelines for the protection of environmental and human health: summary tables (Updated November, 2006). In Canadian environmental quality guidelines, 1999 Canadian Council of Ministers of the Environment, Winnipeg.

CCME. 2002. Recommended Canadian Soil Quality Guidelines. CCME 1-895-925-92-4.

Chanpo, S. 2005. Distribution and relationship between zinc and cadmium in soil in Mae Ku Creek, Mae Ku sub-district, Mae Sot district, Tak province. Master's Thesis, Graduate School, Chulalongkorn University, Thailand

Chanthachot, W., et al. 2005. Analysis of heavy metals in soil along Mae Tao river, Tak province by neuclear technique. 31st Congress on Science and Technology of Thailand at Suranaree University of Technology, 18-20 October

Chen, C.W., Kao, C.M., Chen, C.F., and Dong, C.D. 2007. Distribution and accumulation of heavy metals in the sediments of Kaohsiung Harbor, Taiwan. Chemosphere. 66: 1431–1440.

Codex Alimentarius Commission. 2002. Report of the 34th Session of the Codex Committee on Food Additives and Contaminants, 11-15 March. Rotterdam. (Mimeographed)

DHI Water • Environment • Health 2010. MIKE 11 Reference Manual. Hørsholm, Denmark: DHI.

DHI Water • Environment • Health 2010. MIKE 11 Short Introduction Tutorial version 2010. Hørsholm, Denmark: DHI.

DHI Water • Environment • Health 2010. MIKE 11 User Guide. Hørsholm, Denmark: DHI.

DHI Water • Environment • Health 2010. MIKE SHE-Basic Excercises. Hørsholm, Denmark: DHI.

DHI Water • Environment • Health 2010. MIKE User Manual-Volume 1: User Guide. Hørsholm, Denmark: DHI.

DHI Water • Environment • Health 2010. MIKE SHE User Manual-Volume 2: Reference Guide. Hørsholm, Denmark: DHI.

European Economic Commission. 1986. Council Directive 86/ 278/EEC on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture, 12 June. (Mimeographed)

Forstner, U. and Salomons, W. 1980. Trace metal analysis on polluted sediments. Part: Assessment of sources and intensities. Environ. Technol. Lett. 1: 494-505.

GCOS. 2004. Implementation plan for the Global Observing System for Climate in support of the UNFCCC. Report GCOS – 92 (WMO/TD No. 1219).

Groot, A.J., Zschuppe, K.H., and Salomons, W. 1982. Standardization of methods of analysis for heavy metals in sediments. Hydrobiologia. 92: 689-695.

Honda, R., et al. 2010. Cadmium induced renal dysfunction among residents of rice farming area downstream from a zinc-mineralized belt in Thailand. Toxicology Letters. 198: 26–32.

Huynh-Ngoc, L., Whitehead, N.E., and Oregioni, B. 1988. Cadmium in the Rhone River. Wat. Res. 22: 571-576.

IARC. 1993. Cadmium and cadmium compounds. Beryllium, Cadmium, Mercury and Exposures in the Glass Manufacturing Industry. IARC Monographs on the Evaluation of Carcinogenic Risk of Chemicals to Humans 58: 119-239.

International Cadmium Association. 2009. Cadmium [Online]. Available from: http://www.cadmium.org [2012, May 1]

International Programme on Chemistry Safety: IPCS. 1992. Environmental Health Criteria 135: Cadmium: Environmental Aspect. World Health Organization (WHO), Geneva, Switzerland.

Jain, C.K. 2004. Metal fractionation study on bed sediments of River Yamuna, India. Water Research. 38: 569–578.

Joint FAO/WHO Expert Committee on Food Additives: JECFA. 2003. Report of the 61st Session of JECFA, 10–19 June. Rome: JECFA. (Mimeographed)

Joint FAO/WHO Expert Committee on Food Additives : JECFA. 2005. Report of the 64th Meeting of the JECFA, 8-17 February. Rome: JECFA. (Mimeographed)

Jonckheere, I., et al. 2004. Review of methods for *in situ* leaf area index determination Part I. Theories, sensors and hemispherical photography. Agricultural and Forest Meteorology. 121: 19–35.

Kamel, A. H. 2008. Application of a Hydrodynamic MIKE 11 Model For The Euphrates River in Iraq. Slovak Journal of Engineering. 2:1 – 7

Karoonmakphol, P. 2009. Evaluation of cadmium contamination due to sediment transport in Mae Tao Creek, Mae Sot district, Tak province. Master's Thesis, Graduate School, Chulalongkorn University.

Karoonmakphol, P., and Chaiwiwatworakul, P. 2010. Evaluation of Cadmium Contamination Due to Bed Load Sediment Transport in Mae Tao Creek, Mae Sot District, Tak Province, Thailand. Chemistry and Chemical Engineering (ICCCE), 2010 International Conference on. Kyoto. 114 – 118.

Kido, T., et al. 1988. Progress of renal dysfunction in inhabitants environmentally exposed to cadmium. Archives of Environmental Health. 43: 213–217.

Krissanakriangkrai, O. 2007. Assessment on environmental impact and health risk from aquatic animals in cadmium contaminated area in Mae Sot district, Tak province. Research Funding of Naresuan University and Office of the National Research Council of Thailand.

Lenhart, T., Eckhardt, K., Fohrer, N.H., and Frede, H.G. 2002. Comparison of two different approaches of sensitivity analysis. Physics and Chemistry of the Earth. 27: 645–654.

Llewellyn, TO. 1994. Cadmium. (Materials Flow). U.S. Department of Interior, Bureau of Mines.

Lucas, M.F., Caldeira, M.F., Hall, A., Duarte, A.C., and Lima, C. 1986. Distribution of mercury in sediments and fishes of the Lagoon of Aveiro, Portugal. Water Science and Technology. 18: 141-148.

Mahidol University, Faculty of Environment and Resource Studies. 2006. Specification of pollution standard and environmental management of mining industry and metallurgy of zinc, Tak province. Bangkok (in Thai)

Maneewong, P. 2005. Cadmium distribution in stream sediment and suspended solids along Huai Mae Tao and Huai Mae Ku, Mae Sot district, Tak province. Master's Thesis, Graduate School, Chulalongkorn University.

Ministry of Industry, Department of Primary Industries and Mines. 2006. Study of the causes of cadmium contamination in soil in Mae Sot district, Tak province. Bangkok (in Thai)

Ministry of Industry, Department of Primary Industries and Mines, Office of Primary Industries and Mines Khet 3 (Northern part). 2009. Report of water quality and stream sediment monitoring at Doi Padaeng zinc mining in Mae Sot district, Tak province. Bangkok (in Thai)

Ministry of Natural Resources and Environment, Pollution Control Department. 1998. Cadmium. 2nd edition. Bangkok: Integrated Promotion Technology (in Thai)

Ministry of Natural Resources and Environment, Pollution Control Department. 2009. Thai Environment Regulations. [online]. Available from: http://www.pcd.go.th/info_serv/en_regulation.html [2012, May 1]

Ministry of Natural Resources and Environment, Pollution Control Department. 2011. Survey and Assessment of Cadmium Distribution and Sources of Contamination in Mae Tao River Basin, Mae Sod District, Tak Province. Bangkok (in Thai)

Morgan, R.P.C. 1986. Soil Erosion and conservation. Longman, Harlow.

National Toxicology Program, Department of Health and Human Services, 2011. Cadmium and Cadmium Compounds. Report on Carcinogens. 12: 80-83.

NEPC. 1999. National environment protection (assessment of site contamination) measure schedule B (1) guideline on the investigations levels for soil and groundwater. National Environment Protection Council, Australia.

Nogawa, K., et al. 1983. The relationship between Itai-itai disease among inhabitants of the Jinzu River basin and cadmium in rice. Toxicology Letters. 17: 263–266.

Nogawa, K., Kido, T. 1993. Biological monitoring of cadmium exposure in Itai-itai disease epidemiology. International Archives of Occupational and Environmental Health. 63: 43–46.

Numman, C. 2006. Cadmium from mining: the tragedy of local people. Report of ten environmental situations in 2005: 9-114. Bangkok (in Thai)

OSPAR Commission. 2002. Cadmium. OSPAR Background Document on Cadmium.

Padaeng Industry Public Company Limited. 2009. The report of environmental impact assessment and environmental quality monitoring on zinc mining project 2/2552 during July-December 2552. Bangkok (in Thai)

Phaenark C., Pokethitiyook P., Kruatrachue M., and Ngernsansaruay, C. 2009. Cd and Zn Accumulation in Plants from the Padaeng Zinc Mine Area. International Journal of Phytoremediation. 11: 479-495.

Plachy, J. 2001. Cadmium. Geological Survey Minerals Yearbook. U.S.

Refsgaard, J.C., et al. 1998. An Integrated Model for the Danubian Lowland – Methodology and Applications. Water Resources Management. 12: 433-465.

Refsgaard, A. and Kjelds, J. 2001. MIKE SHE groundwater model selected as best management tool in US [Online]. Available from:

http://www.dhigroup.com/News/NewsArchive/2001/MIKESHEGroundwater ModelSelectedAsBestManagementToolInUS.aspx [2012, May 1]

Rijn, L.C. van,. 1984a. Sediment transport, Part I: Bed load transport. Journal of Hydraulic Engineering. 110: 1434-1456.

Rijn, L.C. van,. 1984b. Sediment transport, Part II: Suspended load transport. Journal of Hydraulic Engineering. 110: 1613-1641.

Salomons, M. 1980. Biochemical processes affecting metal concentrations in lake sediments (Ijsselmeer, The Netherlands). Science of the Total Environment. 16: 217-229.

Simmons, D.B., Senturk, F. 1977. Sediment Transport Technology. Water Resources Publications, Fort Collins.

Simmons, R.W., et al. 2003. The relative exclusive of zinc and iron from rice grain in relation to rice grain cadmium to soybean: Implication for human health. Journal of Plant and Soil. 257: 163-170.

Simmons, R.W., Pongsakul, P., and Klinphoklap, D.S. 2005. Elevated levels of cadmium and zinc in paddy soil and elevated of cadmium in rice grain downstream of a zinc mineralized area in Thailand: Implications for health. Journal of Environmental Geochemistry and Health. 27: 501-511.

Simmons, R. W., Sukreeyapongse, O., Noble, A.D., and Chinabut, N. 2005. Report of LDD-IWMI Land Zoning and Cd Risk Assessment Activities Undertaken in Phatat Pha Daeng and Mae Tao Mai Sub-districts, Mae Sot, Tak Province, Thailand (2004-2005).

Simmons, R. W., Noble, A. D., Pongsakul, P., Sukreeyapongse, O., and Chinabut, N. 2008. Analysis of field-moist Cd contaminated paddy soils during rice grain fill allows reliable prediction of grain Cd levels. Plant Soil. 302: 125-137.

Somboon, P. 1999. Distribution of cadmium and zinc in soil from zinc mining activitiy: a case study of zinc mine, Mae Sot District, Tak Province. Master’s

Thesis, Department of Technology of Environmental Planning for Rural Development, Faculty of Science, Mahidol University.

Sriprachot, A. 2006. Distribution of cadmium in contaminated soil. Graduate School, Kasetsart University.

Taylor, K.G., Owens, P.N., Batalla, R.J., and Garcia, C. 2008. Sediment and Contaminant Sources and Transfers in River Basins. Sustainable Management of sediment Resources: Sediment Management at the River Basin Scale. 83-135.

Tharathammathigorn, W. 2010. Transport modeling of cadmium contaminated suspended sediment and bed load in Mae Tao Creek, Thailand. Master's Thesis, Graduate School, Chulalongkorn University.

Tohyama, C., Shaikh, Z.A., Nogawa, K., Kobayashi, E., and Honda, R. 1982. Urinary metallothionein as a new index of renal dysfunction in ''Itai-itai'' disease patients and other Japanese women environmentally exposed to cadmium. Archives of Toxicology. 50: 159–166.

Unhalekhaka, U., and Kositanont, C. 2008. Distribution of Cadmium in Soil around Zinc Mining Area. Thai Journal Toxicology. 23: 170-174.

U.S. EPA Standard Method 3015A. 1998. Microwave Assisted Acid Digestion of Aqueous Samples and Extracts [online]. Available from: http:// www.epa.gov/ sw-864/pdfs/3015a.pdf. [2012, May 1]

U.S. EPA Standard Method 3050B. 1996. Acid Digestion of Sediment, Sludge, and Solids [online]. Available from: http://www.epa.gov/sw-864/pdfs/3050b.pdf. [2012, May 1]

Vorosmarty, C.J. Meybeck, M., Fekete, B., and Sharma, K. 1997. The potential impact of neo-Castorization on sediment transport by the global network of rivers. Human Impact on Erosion and Sedimentation. (Proc. Rabat Symposium, April 1997). 245: 261-273.

World Bank Group, United Nations Environment Programme, United Nations Industrial Development Organization. 1998. Cadmium. Pollution Prevention and Abatement Handbook. 212-214.

Yunus, K., et al. 2011. Heavy Metal Concentration in the Surface Sediment of Tanjung Lumpur Mangrove Forest, Kuantan, Malaysia. Sains Malaysiana. 40(2): 89–92.

APPENDICES

APPENDIX A

Topographic map of study area

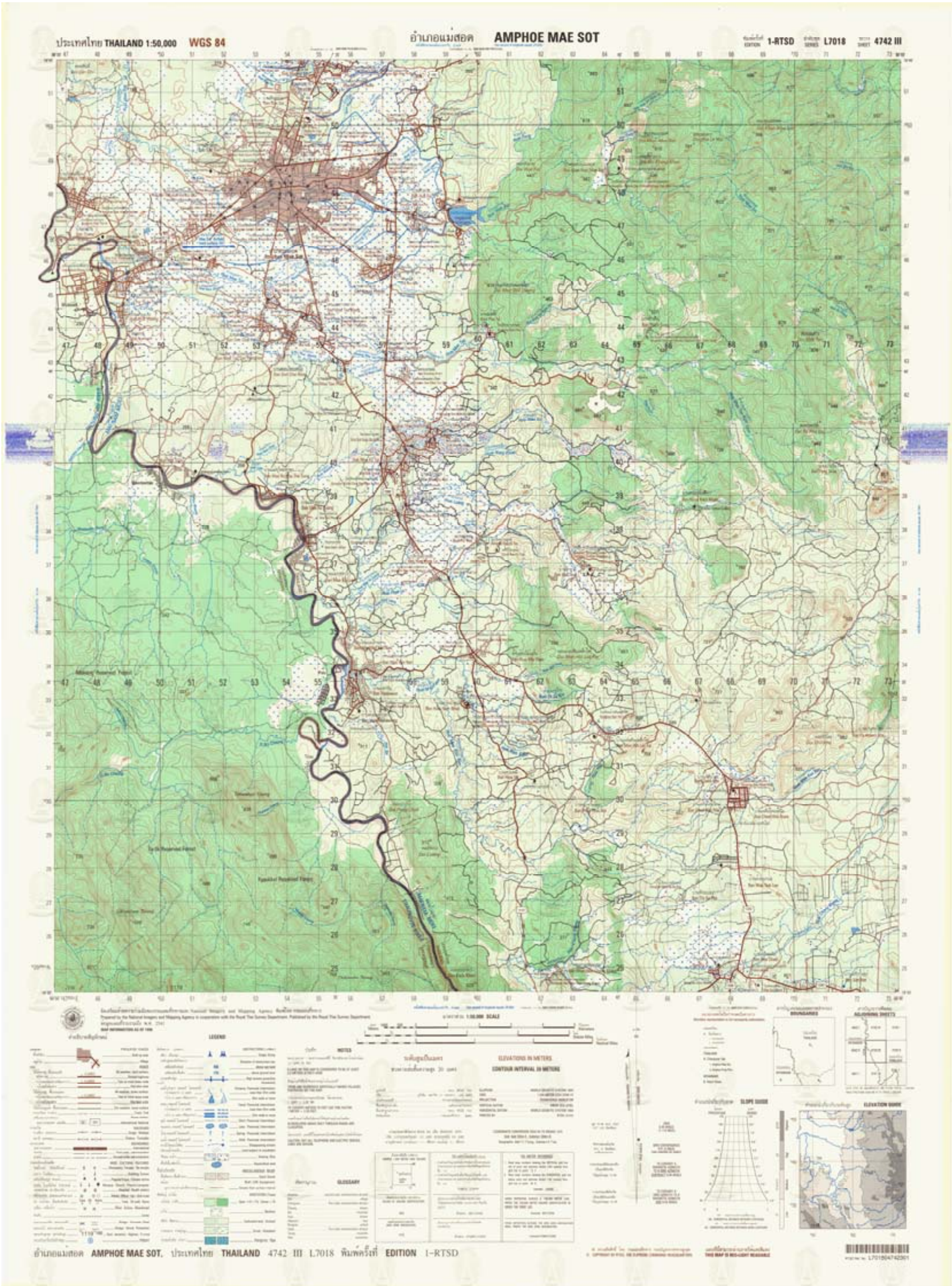


Figure A-1 The topographic map 1:50,000 scale, sheet 4742III, series L7018, edition 1-RTS

Land use map of study area

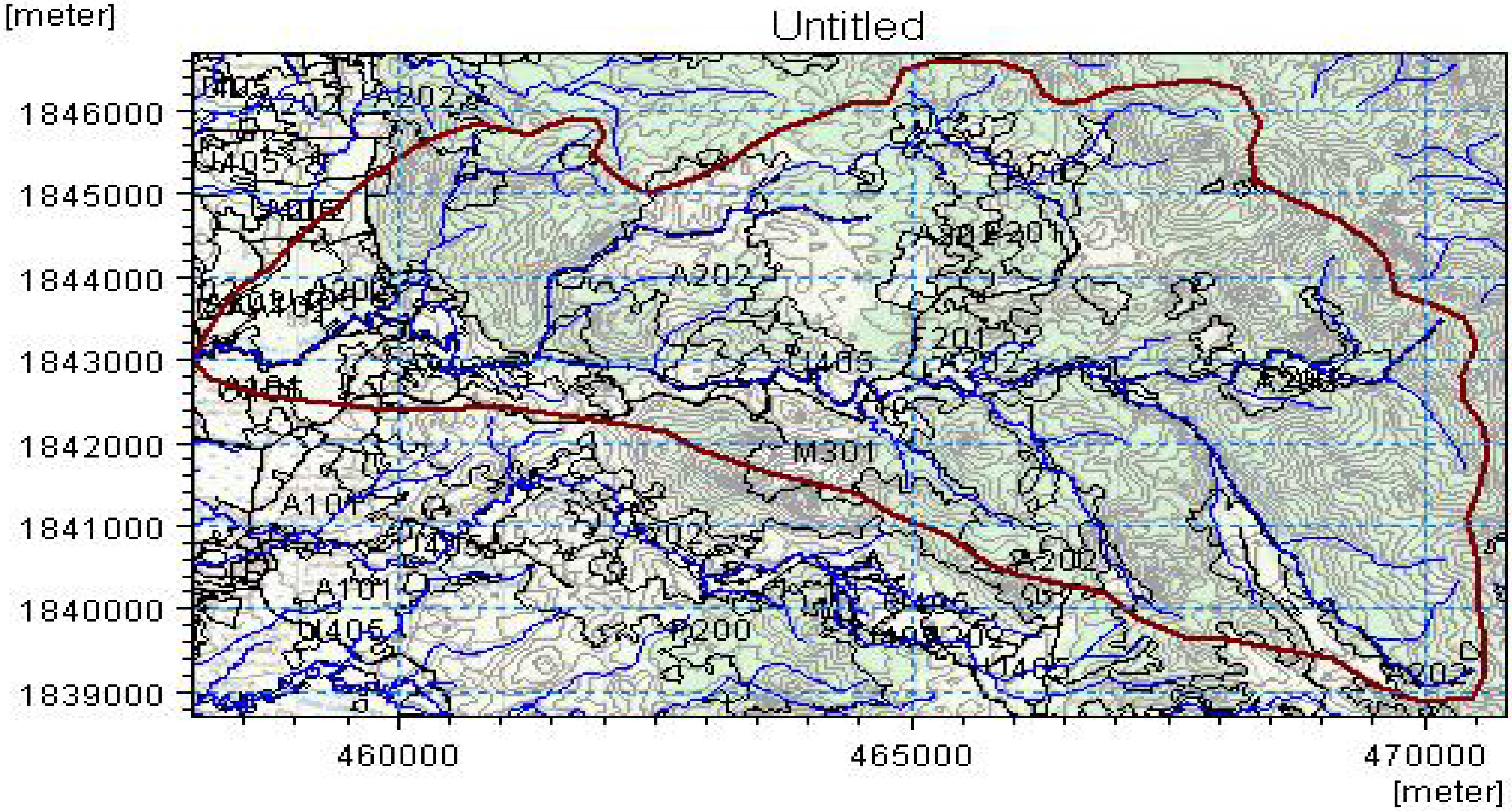


Figure A-2 The shape file of land use for MIKE SHE (Land Development Department, 2007)

Table A-1 Land use classification (Land Development Department, 2007)

Code	Land use classification
A101	Rice paddy
A202	Corn
A301	Mixed perennial
A401	Mixed orchard
A412	Tamarind
A413	Longan
A602	Corn
A616	Upland rice
F100	Disturbed evergreen forest
F200	Disturbed deciduous forest
F201	Dense deciduous forest
M301	Mine
M403	Rock out crop
M405	Landfill
U201	Village
U405	Road
U502	Factory
W101	River, Canal
W102	Lake
W202	Farm pond

APPENDIX B

Rainfall rate and evaporation rate in year 2011 – February 2012

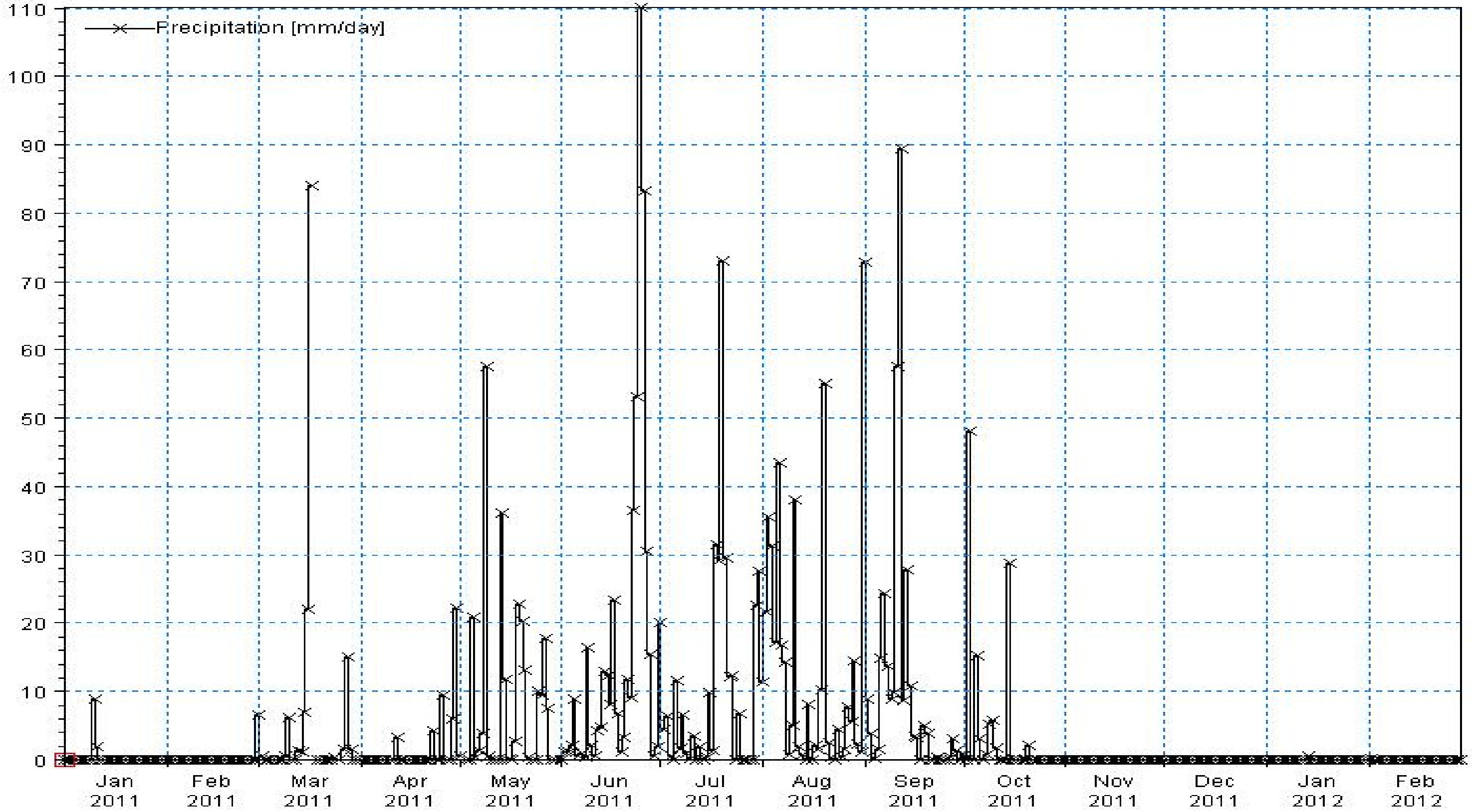


Figure B-1 Rainfall rate in year 2011 – February 2012 (millimeter/day)

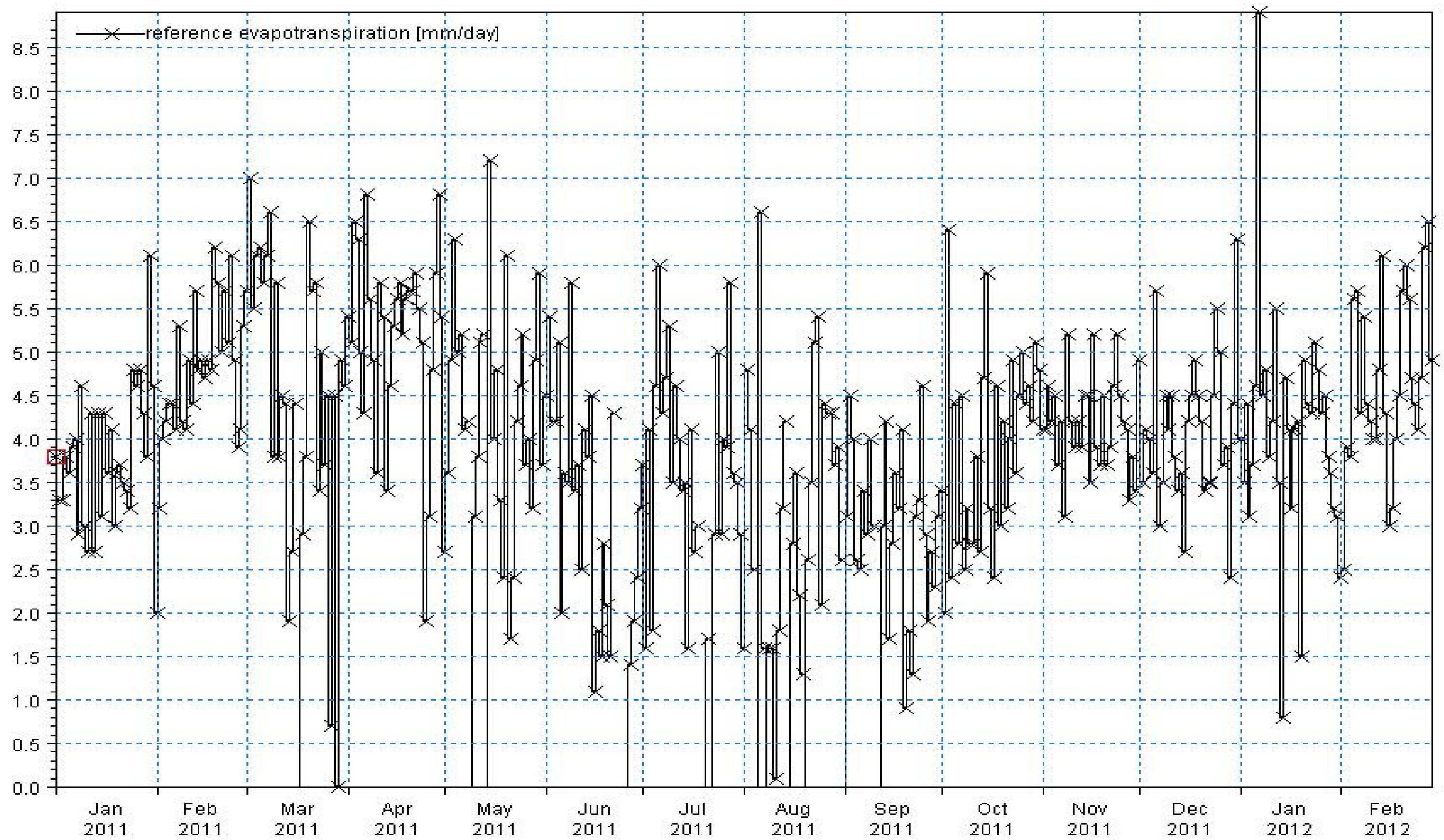


Figure B-2 Evaporation rate in year 2011 – February 2012 (millimeter/day)

APPENDIX C

Field observation results

Table C-1 The water quality data at each station in April 2011 (dry season)

Station	pH	DO (mg/L)	EC (µS)	T (°C)
MT 01	8.17 ± 0.01	7.99 ± 0.01	140.1 ± 0.09	25.3 ± 0.05
MT 02	8.07 ± 0.01	8.39 ± 0.01	136.9 ± 0.05	24.9 ± 0.05
MT 03	8.09 ± 0.03	8.50 ± 0.04	441.0 ± 0.00	24.8 ± 0.05
MT 04	8.13 ± 0.01	7.99 ± 0.01	441.0 ± 0.00	24.6 ± 0.05
MTL 01	7.56 ± 0.07	6.18 ± 0.01	647.0 ± 2.50	25.2 ± 0.20
MT 05	8.16 ± 0.00	5.25 ± 0.02	443.0 ± 0.00	23.2 ± 0.05
MT 06	8.35 ± 0.00	9.13 ± 0.03	461.0 ± 0.00	24.7 ± 0.05
MT 07	8.28 ± 0.00	6.54 ± 0.03	443.0 ± 0.00	23.7 ± 0.20
MTR 01	8.29 ± 0.00	8.31 ± 0.02	490.0 ± 0.00	24.9 ± 0.05
MT 08	8.37 ± 0.06	6.54 ± 0.01	402.0 ± 0.00	23.1 ± 0.05

Table C-2 The water quality data at each station in December 2011 (wet season)

Station	pH	DO (mg/L)	EC (µS)	T (°C)
MT 01	8.16 ± 0.00	8.29 ± 0.00	207.0 ± 0.00	23.3 ± 0.09
MT 02	8.15 ± 0.00	8.46 ± 0.00	418.0 ± 0.00	23.2 ± 0.25
MT 03	8.36 ± 0.01	7.35 ± 0.00	203.0 ± 0.00	22.1 ± 0.14
MT 04	8.31 ± 0.01	7.61 ± 0.01	419.0 ± 0.00	22.1 ± 0.05
MTL 01	7.68 ± 0.07	7.99 ± 0.00	183.6 ± 0.19	22.9 ± 0.09
MT 05	8.07 ± 0.00	8.19 ± 0.07	210.0 ± 0.00	21.8 ± 0.00
MT 06	8.14 ± 0.01	8.43 ± 0.00	401.0 ± 0.00	21.0 ± 0.05
MT 07	8.07 ± 0.01	7.59 ± 0.01	460.0 ± 0.00	22.6 ± 0.05
MTR 01	8.13 ± 0.02	8.63 ± 0.03	452.7 ± 0.55	22.7 ± 0.14
MT 08	8.24 ± 0.00	8.42 ± 0.02	399.7 ± 0.55	21.9 ± 0.05

Note: pH = potential of the hydrogen ion
DO = dissolved oxygen (mg/L)
EC = conductivity of water (µS)
T = temperature (°c)

Table C-3 The total zinc concentration in the suspended sediment

Station	Dry season			Wet season		
	Dry weight (mg/L)	Total Zn concentration (mg/kg)	Cd/Zn Ratio (%)	Dry weight (mg/L)	Total Zn concentration (mg/kg)	Cd/Zn Ratio (%)
MT 01	2.08	28,098.35 ± 1,216.20	0.03	7.30	10,682.06 ± 3,541.14	0.14
MT 02	4.02	13,912.68 ± 1,834.36	0.06	29.33	4,685.35 ± 1,091.94	0.35
MT 03	8.68	35,935.35 ± 9,365.39	0.03	34.50	1,814.72 ± 1,825.01	0.32
MT 04	4.35	22,697.58 ± 13,007.34	0.04	15.12	9,905.89 ± 6,241.96	0.49
MTL01	9.75	31,786.76 ± 7,892.56	0.04	5.08	11,207.02 ± 5,552.42	0.51
MT 05	2.15	47,770.83 ± 23,069.36	0.02	3.20	13,942.37 ± 3,308.15	0.67
MT 06	3.75	15,816.67*	0.03	3.03	39,993.93 ± 4,776.09	0.28
MT 07	1.55	46,419.04 ± 278.34	0.02	38.23	2,669.56 ± 488.25	0.70
MTR01	4.70	17,669.12 ± 2,143.46	0.02	84.90	2,343.02 ± 2,206.48	0.49
MT 08	5.10	10,887.50*	0.02	13.95	6,187.28 ± 1291.55	0.63

Note: *Limit suspended sediment samples

Table C-4 The total zinc concentration in the bed load

Station	Dry season				Wet season			
	Total Zn concentration (mg/kg)			Cd/Zn Ratio (%)	Total Zn concentration (mg/kg)			Cd/Zn Ratio (%)
MT 01	1,680.74	±	1,302.39	1.05	1,703.02	±	136.27	1.32
MT 02	1,493.85	±	1,015.49	1.17	1,390.15	±	95.43	1.82
MT 03	960.30	±	660.14	1.04	872.77	±	247.38	1.31
MT 04	2,033.10	±	2,533.12	0.97	8,225.38	±	801.26	1.00
MTL01	94.25	±	67.94	3.78	69.05	±	14.00	3.05
MT 05	1,288.32	±	1,327.43	0.65	2,220.48	±	173.03	1.28
MT 06	28.28	±	21.73	8.89	55.21	±	30.45	4.02
MT 07	26.28	±	26.09	4.33	34.56	±	3.56	5.81
MTR01	18.18	±	13.51	5.51	148.70	±	25.74	1.93
MT 08	22.61	±	16.80	6.06	32.35	±	4.84	5.54

Table C-5 The distribution of zinc concentrations in the bed load (mg/kg)

Station	Grain size (mm)	Dry season			Wet season		
MT 01	0.151 - 0.231	1,978.63	±	73.57	1,736.23	±	127.74
	0.101 - 0.150	2,005.50	±	109.25	1,721.80	±	286.07
	0.076 - 0.100	1,237.65	±	86.06	1,191.11	±	98.99
	≤0.075	775.57	±	21.57	1,337.73	±	71.55
MT 02	0.151 - 0.231	1,518.33	±	37.54	1,492.81	±	99.32
	0.101 - 0.150	1,358.04	±	39.51	1,377.88	±	183.22
	0.076 - 0.100	1,904.71	±	26.31	1,024.33	±	107.35
	≤0.075	1,913.68	±	29.69	505.85	±	22.09
MT 03	0.151 - 0.231	1,129.51	±	263.14	714.65	±	375.48
	0.101 - 0.150	826.91	±	23.50	1,096.18	±	11.07
	0.076 - 0.100	878.20	±	13.12	1,115.82	±	82.76
	≤0.075	954.71	±	24.52	1,173.69	±	17.75
MT 04	0.151 - 0.231	3,894.75	±	673.56	825.79	±	15.89
	0.101 - 0.150	2,073.43	±	12.86	19,957.29	±	1,618.07
	0.076 - 0.100	1,168.49	±	42.16	3,523.27	±	189.91
	≤0.075	969.94	±	11.64	1,146.22	±	157.55
MTL 01	0.151 - 0.231	105.12	±	19.74	102.80	±	33.71
	0.101 - 0.150	72.84	±	15.51	48.72	±	5.39
	0.076 - 0.100	87.72	±	10.38	46.29	±	1.09
	≤0.075	116.64	±	2.61	60.12	±	5.22
MT 05	0.151 - 0.231	2,800.58	±	379.74	2,552.34	±	295.27
	0.101 - 0.150	1,368.08	±	25.67	2,148.13	±	305.04
	0.076 - 0.100	984.08	±	39.13	1,176.59	±	39.45
	≤0.075	866.81	±	6.96	1,047.76	±	22.64
MT 06	0.151 - 0.231	26.95	±	5.35	50.67	±	52.79
	0.101 - 0.150	25.57	±	8.12	56.52	±	38.03

Table C-5 The distribution of zinc concentrations in the bed load (mg/kg) (continued)

Station	Grain size (mm)	Dry season			Wet season		
MT 06	0.076 - 0.100	25.74	±	0.82	52.81	±	1.02
	≤0.075	52.40	±	5.61		1.14*	
MT 07	0.151 - 0.231	20.36	±	1.20	36.13	±	3.33
	0.101 - 0.150	22.91	±	0.86	29.42	±	1.48
	0.076 - 0.100	33.16	±	0.54	39.04	±	7.68
	≤0.075	57.75	±	0.80	49.67	±	2.16
MTR 01	0.151 - 0.231	15.54	±	0.78	62.60	±	14.77
	0.101 - 0.150	16.23	±	0.73	269.28	±	52.82
	0.076 - 0.100	18.64	±	0.96	202.98	±	31.04
	≤0.075	26.19	±	2.54	126.86	±	7.90
MT 08	0.151 - 0.231	22.09	±	2.51	33.74	±	8.63
	0.101 - 0.150	19.39	±	3.27	26.29	±	4.94
	0.076 - 0.100	25.06	±	2.73	26.78	±	3.86
	≤0.075	35.54	±	0.49	50.58	±	3.30

Note: *Limit bed load samples

APPENDIX D

Parameter values in MIKE SHE

Table D-1 The values of parameter in each compartment of MIKE SHE

Parameters in MIKE SHE	Value
Overland flow	
- Manning number	10 $m^{1/3}/s$
- Detention storage	0.01 mm
Unsaturated Flow	
- Saturated hydraulic conductivity	10^{-8} m/s
- Groundwater depths used for UZ classification	3 m
Saturated Zone	
- Lower level	-27 m
- Horizontal hydraulic conductivity	10^{-8} m/s
- Vertical hydraulic conductivity	10^{-4} m/s
- Specific yield	0.8 %
- Specific storage	10^{-4} m^{-1}
- Initial potential head	-3 m
- Drainage level	-1.5 m
- Drainage time constant	$10^{-6}s^{-1}$

Table D-2 Vegetation setup for land use compartment in MIKE SHE

Vegetation	End day	LAI	Root	Kc
Rice	0	1.5	200	1
	15	1.5	200	1
	30	4	600	1
	60	5	800	1.1
	80	5	1000	1
	120	4	1000	1
Sugarcane	0	2	500	1
	75	4	1000	1
	95	6	600	1.5
	145	6	1500	1.4
	250	6	1500	1.2
	300	3	1500	1
	366	1	1500	1
Corn	0	0.5	500	1
	30	0.5	500	1
	75	5	1000	1
	105	5	1000	1.1
	125	5	1000	1.1
	175	5	1000	1
Forest	0	6	800	1
	100000	6	800	1

Table D-3 The values of parameters in hydrodynamic module of MIKE 11

Hydrodynamics parameters (HD)		**Value**	**Unit**
Initial conditions	Water level	5	meter
	Discharge	1.4	m^3/s
Wind	Topographical Factor	1	-
	Friction Factor	0.0024	-
Bed Resistance	Resistance Number	0.01	$s/m^{1/3}$
Default Values	Delta	0.85	-
	Delhs	0.01	-
	Delh	0.1	-
	Alpha	1	-
	Theta	1	-
	Eps	0.0001	-
	Dh Node	0.01	-
	Zeta Min	0.1	-
	Struc Fac	0	-
	Inter1 Max	10	-
	Nolter	1	-
	MaxlterSteady	100	-
	FroudeMax	-1	-
	FroudeExp	-1	-
Quasi Steady	Relax	0.5	-
	Beta_Limit	10^{-8}	-
	Fac_0	2.5	-
	Qconv_Factor	0.001	-

Table D-3 The values of parameter in hydrodynamic module of MIKE 11 (continued)

Hydrodynamics parameters (HD)		Value	Unit
Quasi Steady	Hconv_Factor	0.01	-
	Min_Hconv_In_Branch	10^{-5}	meter
	Q_struc_Factor	0.05	-
	Hstop	0.0001	meter
Stratification	No.of layers	1	-
	Turbulence model (Viscosity)	0.003	m^2/s
	Corrections (reductions):		
	Baroclinic Pressure - Factor	1	-
	- Local bed slope	0	-
	Convection/Advection:		
	-Factor horizontal momentum	1	-
	- Factor vertical momentum	1	-
	- Factor advection	1	-
	Dispersion:		
	- Factor horizontal viscosity	1	-
	- Factor vertical viscosity	1	-
Flood Plain Resistance	Flood Plain Resistance	-99	$m^{1/3}/s$
Encroachment	Max no. of iterations	20	-
	Encroachment positions:		
	- Left offset	0	-
	- Right offset	0	-
	- Left position	0	-
	- Right position	0	-

Table D-4 The values of parameters in sediment transport module of MIKE 11

Sediment transport parameter (ST)		Value	Unit
Sediment Grain Diameter	Global Grain Diameter	0.001	meter
	St. Deviation	1	meter
Transport Model	Model Parameters:		
	-Rel. density	2.65	-
	-Kin. Viscosity	10^{-6}	m^2/s
Bed Shear Stress	Manning (M):		
	- Minimum	20	$m^{1/3}/s$
	- Maximum	40	$m^{1/3}/s$
	- Omega	1	$m^{1/3}/s$
Non Scouring Bed Level	Thickness of active layer	0.1	meter
	Non scouring bed level	-1.5	meter
Calibration Factors	Factor	0.117	-
Data for Graded ST	Min. depth of active layer	0.1	meter
	Init. Depth of passive layer	1	meter

APPENDIX E

Calculation method

Laboratory results

1. Grain size distribution of bed load

- **Loss (g)**

Loss weight of bed load samples after sieving is calculated from the difference between weight before sieving (g) and total weight after sieving (g). The bed load weight at each were displayed in Chapter IV, Table 4-3 for the dry season and in Chapter IV, Table 4-5 for the wet season.

Loss = Sample weight before sieving (g) – Total sample weight after sieving (g)

Station MT 01, dry season: Loss = 1000.0 - 996.12

Loss = 3.88 g

- **Loss (%)**

After the loss weight of bed load samples after sieving was calculated, percent loss of bed load in each station after sieving can be computed from the ratio of the loss weight (g) per sample weight before sieving (g). The bed load weight at each were displayed in Chapter IV, Table 4-3 for the dry season and in Chapter IV, Table 4-5 for the wet season.

$$\text{Loss (\%)} = \frac{\text{Loss (g)}}{\text{Sample weight before sieving (g)}} \times 100$$

Station MT 01, dry season: $\text{Loss} = \frac{3.88}{1000.0} \times 100$

Loss = 0.39 %

- **% Passing Sieve No. 200**

The amount of bed load passing sieve no. 200 is estimated from sample weight on receiver (g) per sample weight before sieving (g). The bed load weight at each mesh sieve in ten sampling station were displayed in Chapter IV, Table 4-3 for the dry season and in Chapter IV, Table 4-5 for the wet season.

$$\text{\% Passing Sieve No. 200} = \frac{\text{Sample weight on receiver (g)}}{\text{Sample weight before sieving (g)}} \times 100$$

Station MT 01, dry season:

$$\text{\% Passing Sieve No. 200} = \frac{9.92}{1000.0} \times 100$$

$$\text{\% Passing Sieve No. 200} = 0.99\ \%$$

- **Mean Diameter (mm)**

Mean diameter of bed load samples in each station was calculated from the pooled data of bed load from sieves No. 3/4'', 3/8'', 4, 10, 20, 35, 65, 100, 150, and 200. The mean size of each mesh and sample weight on each mesh were displayed in Chapter IV, Table 4-3 for the dry season and in Chapter IV, Table 4-5 for the wet season.

$$\text{Mean Diameter (mm)} = \frac{X_{3/4''}W_{3/4''} + X_{3/8''}W_{3/8''} + \ldots + X_{receiver}W_{receiver}}{\text{Sample weight after sieving (g)}}$$

where X = Mean size of each mesh

W = Sample weight on each mesh

Station MT 01, dry season:

$$\text{Mean Diameter} = \frac{(19.000 \text{x} 7.91)+(14.250 \text{x} 29.77)+\ldots+(0.075 \text{x} 9.92)}{996.12}$$

$$\text{Mean Diameter} = 2.48 \text{ mm}$$

2. Cadmium concentration

- **Cadmium concentration of suspended sediment and bed load**

Cadmium concentration for suspended sediment and bed load were computed from cadmium concentration result from the ratio of atomic absorption spectrometry (μg/L) and volume of digested sample (L) per weight of digested sample (g)

$$\text{Cadmium concentration (mg/kg)} = \frac{\text{AAS result (μg/L) x digested sample vol. (L)}}{\text{Weight of digested sample (g)}} \text{x}10^{-3}$$

Station MT 01, dry season: Cadmium concentration = $\frac{1.583\text{x}25}{0.0043} \text{ x } 10^{-3}$

Cadmium concentration = 9.20 mg/kg

- **Total cadmium concentration of bed load**

From bed load samples which were sieved with sieve No. 65, 100, 150 and 200, the total cadmium concentration is calculated by weighted average in which each quantity to be averaged is assigned a weight. Cadmium concentration of bed load in sieve No. 65, 100, 150 and 200 showed in Chapter IV, Table 4-1, and weight of bed load samples in sieve No. 65, 100, 150 and 200 displayed in Chapter IV, Table 4-3 for the dry season and in Chapter IV, Table 4-5 for the wet season.

Total cadmium concentration (mg/kg)

$$= \frac{C_{\#65}W_{\#65} + C_{\#100}W_{\#100} + X_{\#150}W_{\#150} + X_{\#200}W_{\#200}}{W_{\#65} + W_{\#100} + W_{\#150}W_{\#200}}$$

where C = Cadmium concentration of each mesh

W = Bed load weight on each mesh

Station MT 01, dry season:

Total cadmium concentration

$$= \frac{(14.87\text{x}13.52)+(25.80\text{x}18.28)+(14.36\text{x}2.22)+(6.99\text{x}9.92)}{43.94}$$

Total cadmium concentration = 17.61 mg/kg

- **Standard deviation from several cadmium measurement in bed load**

Just as several means may be combined to obtain a grand average, standard deviations also can be combined to obtain a single estimate. Pooled standard deviation is calculated from standard deviation of separate sets of cadmium measurement in sieve No. 65, 100, 150 and 200.

Pooled standard deviation = $\sqrt{\frac{s_{\#65}^2(n_{\#65}-1)+s_{\#100}^2(n_{\#100}-1)+s_{\#150}^2(n_{\#150}-1)+s_{\#200}^2(n_{\#200}-1)}{(n_{\#65}-1)+(n_{\#100}-1)+(n_{\#150}-1)+(n_{\#200}-1)}}$

where S = Standard deviation

n = Number of measurements

Station MT 01, dry season:

Pooled standard deviation = $\sqrt{\frac{(1.32^2)(3-1)+(11.49^2)(3-1)+(5.61^2)(3-1)+(2.68^2)(3-1)}{(3-1)+(3-1)+(3-1)+(3-1)}}$

Pooled standard deviation = 6.57

<u>Simulation results</u>

1. Sensitivity Analysis

The sensitivity index (I) was calculated to determine the sensitivity of input parameter in MIKE SHE model that effected water discharge (see parameter values in Appendix D, Table D-1). For example, the Manning' M used input value (x_0) equal to 10, then x_1 and x_2 were calculated equal to 5 and 15, respectively. The output (y) is water discharge in 26 June 2011due to the highest rainfall rate occurred in this period.

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

$$\Delta x = x_0 - x_1$$

$$\Delta x = x_2 - x_0$$

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

Manning number (10): $I = \frac{(27.27-24.91)/27.62}{2(5)/10}$

$I = 0.09$

2. Sediment transport (kg)

The sediment transport (kg) at downstream of the Mae Tao Creek is computed from the accumulated sediment (m^3) that simulated from model and density of sediment (kg/m^3). For example, suspended sediment transport at downstream (Station MT 02) during the wet season was calculated from accumulated suspended sediment (Station MT 02) in the wet season equal to 387.46 m^3 (see Chapter IV, Table 4-10) and density of sediment equal to$1.602x10^3 kg/m^3$.

Sediment transport = Accumulated sediment (m^3) x Sediment density (kg/m^3)

Station MT 02, suspended sediment in the wet season:

Sediment transport = (387.46 m^3) x ($1.602x10^3 kg/m^3$)

Sediment transport = 620,716.87 kg

3. Cadmium transport (mg)

After sediment transport amount value was computed, the cadmium transport could be estimated. The amount of cadmium transport (mg) is calculated from sediment transport (kg) and observed cadmium concentration from field observation (mg/kg), as shown in Chapter IV, Table 4-6. For instance, the cadmium transport due to suspended sediment at station MT 02 during the wet season was estimated from suspended sediment transport equal to 620,716.87 kg and Observed cadmium concentration in suspended sediment at station MT 02 equal to 16.61 mg/kg.

Cadmium transport (mg)

= Sediment transport (kg) x Observed cadmium concentration (mg/kg)

Station MT 02, suspended sediment in the wet season:

Cadmium transport = (620,716.87 kg) x (16.61 mg/kg) x 10^{-6}

Cadmium transport = 10.31 kg

BIOGRAPHY

Miss Thananporn Thamjedsada was born on May 2, 1988 in Yala. She graduated with a Bachelor's degree in Biochemistry from the department of Biochemistry, Faculty of Science, Chulalongkorn University in 2010. Thereafter, she has carried out this research as a part of studied for the Master's degree in Environmental Management at graduate school, Chulalongkorn University. Under the management of Center of Excellence for Environmental and Hazardous waste Management.