THE CONTAMINATION OF LEAD IN PATTANI RIVER SIMULATION BY WATER ANALYSIS SIMULATION PROGRAM (WASP) VERSION 6.2

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การคาดการณ์การปนเปื้อนของตะกั่วในแม่น้ำปัตตานี
ด้วยแบบจำลองทางคณิตศาสตร์ วอส 6.2

นาย พัทธพล ชัยกุล

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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การปนเปื้อนของตะกั่วในแม่น้ำปัตตานีได้รับความสนใจจากหลายหน่วยงานในช่วงระยะเวลา 10 ปีที่ผ่านมา แหล่งที่มาของการปนเปื้อนได้แก่ กลุ่มเหมืองร้างในอำเภอบันนังสตา จังหวัดยะลา ในช่วงหน้าฝนของทุกปี ตะกั่วซึ่งสะสมอยู่ในกากแร่และ บ่อน้ำทิ้งอันมีองค์ประกอบเป็นแร่กาลีนา (PbS) จะถูกชะลงสู่ต้นน้ำของแม่น้ำปัตตานี ในการนี้โปรแกรมแบบจำลองทางคณิตศาสตร์เพื่อการจำลองคุณภาพน้ำ (WASP 6.2) ได้ถูกเลือกเพื่อใช้ศึกษาการกระจายตัวในระยะยาวของการปนเปื้อนดังกล่าวตามรูปแบบ และขอบเขตในการคำนวณที่ได้ถูกออกแบบไว้ ในขั้นต้นมีการสร้างโจทย์ปัญหาอย่างง่ายเพื่อให้แบบจำลองทำการคำนวณ พบว่าแบบจำลองสามารถคำนวณได้อย่างถูกต้องแม่นยำ จากนั้นแบบจำลองได้ถูกนำไปใช้คาดการณ์การปนเปื้อนในพื้นที่จริง โดยผลของการคาดการณ์จะได้รับการตรวจสอบเทียบเคียงกับข้อมูลการปนเปื้อนจริงที่วัดโดยกรมอนามัย ในช่วงปีพ.ศ. 2533 – 2543 และกรมควบคุมมลพิษ ในปีพ.ศ. 2545 ผลการทดสอบทางสถิติพบว่าแบบจำลองให้ผลการคำนวณใกล้เคียงกับค่าที่ตรวจวัดจริง โดยมีความแตกต่างอยู่ที่ 0.014 มิลลิกรัม/ลิตร โดยประมาณ นอกจากนั้นยังพบความสัมพันธ์ของค่าที่ได้จากการคำนวณกับค่าที่ตรวจวัดจริงที่จุดตรวจวัด บริเวณอำเภอบันนังสตา จังหวัดยะลา อำเภอเมือง จังหวัดยะลา และอำเภอเมือง จังหวัดปัตตานี จากการวิเคราะห์พบว่าการไหลในแนวราบเป็นกระบวนการหลักที่ส่งผลต่อการกระจายตัวของตะกั่วในแม่น้ำ ในการนำแบบจำลองไปประยุกต์ใช้พบว่าจำเป็นต้องลดปริมาณของตะกั่วที่จะลงสู่แม่น้ำลง 10-30 % เพื่อให้ปริมาณตะกั่วในแม่น้ำอยู่ในระดับพื้นฐาน นอกจากนั้นยังพบว่าอัตราการไหลของน้ำในแม่น้ำที่ลดลงจะส่งผลให้ระดับของการปนเปื้อนของตะกั่วในแม่น้ำสูงขึ้น ดังนั้นอัตราการไหลของน้ำในแม่น้ำปัตตานีจึงเป็นอีกตัวแปรหนึ่งที่ควรได้รับความสนใจ และเฝ้าระวัง โดยเฉพาะในฤดูน้ำน้อย หรือ ฤดูแล้ง

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Lead contamination in Pattani River has been a topic of discussion over the past ten years. The source of lead in upstream section of the river is a group of abandoned tin mines in Bannangsta district, Yala Province. During the rainy season of every year, lead in the form of galena (PbS) is washed off from waste rock and sludge in the lagoon and into the upstream portion of Pattani River. The Water Quality Analysis Simulation Program (WASP 6.2) was selected to predict long-term distributions of the contaminant. A conceptual model of the lead contamination in the river was created. A simple scenario study demonstrated the high accuracy of the model. In the real contamination scenario, the predicted concentration was calibrated with the observed concentrations that were taken by the Department of Health from 1990–2000 and the Pollution Control Department in 2002. Statistical measures indicated a good fit between the predicted and observed concentration with the root mean square errors (RMSE) at about 0.014 mg/l. A strong correlation was found at three of the segments: in Bannangsta district and Muang district of Yala province, and Muang district of Pattani province. Advection, as determined by total stream flow, was identified as the major process that affects the distribution of total lead in the river. In application studies, it was found that waste loading should be reduced by about 10-30 % in order to keep the total lead concentration at background levels normally found in the river. In addition, reducing the upstream flow was found to increase the total lead concentration. Thus, the level of upstream flow in the river is of concern and must be monitored, especially during the low-flow season.

Field of study Environmental Management Student's signature ……..
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GLOSSARY

AMD. Acid Mine Drainage

CASRN. Chemical Abstracts Service Registry Number

IARC. International Agency for Research on Cancer

MCMs. Million Cubic Meters

Pb. Lead

PbS. Galena

PCD. Pollution Control Department

RID. Royal Irrigation Department

RMSE. Root Mean Square Error

US EPA. United States Environmental Protection Agency

WASP. Water Quality Analysis Simulation Program

WHO. World Health Organization

CHAPTER I

INTRODUCTION

The Pattani River is one of the main tributaries in the south of Thailand (Figure 1.1). With a length of 210 kilometers, it covers an area that includes the Yala and Pattani provinces. The flow direction is from the Thailand-Malaysia border to the Gulf of Thailand at Pattani Bay, Pattani province. The upstream part of the river is in Bannangsta district, Yala province. With regard to land utilization, land along the river consists of agricultural, forestry, community and mining activities.

Lead contamination in the Pattani River has been a topic of discussion over the past ten years. There are two principal sources of the contamination. The source of lead in the upstream section of the river is a group of abandoned tin mines in the Bannangsta district while the source of lead in the downstream section, especially in Pattani Bay, is a dockyard area where boats are repaired (Pollution Control Department, 2002 a).

Although the tin mines in the Bannangsta district ceased production in 1985 as a result of the collapse of tin prices, tailing piles, waste rock and sludge lagoons were left behind at the site. During the rainy season of every year, both dissolved and suspended lead in the form of galena (PbS) is washed off into the stream and flows into the upstream area of the Pattani River (Pollution Control Department, 2002 a).

In 2002, the Pollution Control Department monitored the water quality of the Pattani River Basin. An increasing tendency for lead contamination in water, sediments, and human bodies was found. At the upstream part of the river, especially in the Bannangsta district, the concentration of lead in water was found to be five times higher than that of the guideline value for surface water. Lead in sediments was found at the higher level of 1,000-15,000 mg/kg. Furthermore, the lead level in the blood of people who live near the river was found at a high concentration level, 40 µg/dL (Pollution Control Department, 2002 b).

The contamination of lead in the Pattani River affects not only to the ecological system and natural environment but also the people who live nearby and consume water from the river. Therefore, a strategic plan for the control, remediation and rehabilitation of water quality and other related resources of the Pattani River is

urgently required. A high level of physical information on the contamination and high quality instruments for predicting the long-term distributions of the contamination are required. Therefore, the aims of this study are to investigate the ability of the Water Quality Analysis Simulation Program (WASP) version 6.2 for predicting the concentration of total lead in the Pattani River and to simulate a scenario for reducing the amount of total lead concentration in the river in order to develop a proper strategy for the future.

1.1 OBJECTIVES OF THE STUDY

The objectives of the study can be summarized as follows:

1. To investigate the ability of the Water Quality Analysis Simulation Program (WASP) version 6.2 for prediction of the concentration of total lead in the Pattani River;
2. To simulate a scenario for reduction of the total lead concentration in the river.

1.2 HYPOTHESES

1. The WASP 6.2 can be used to simulate the distribution of total lead in the Pattani River;
2. The WASP 6.2 can be used to simulate a scenario of reduction the total lead concentration in the river.

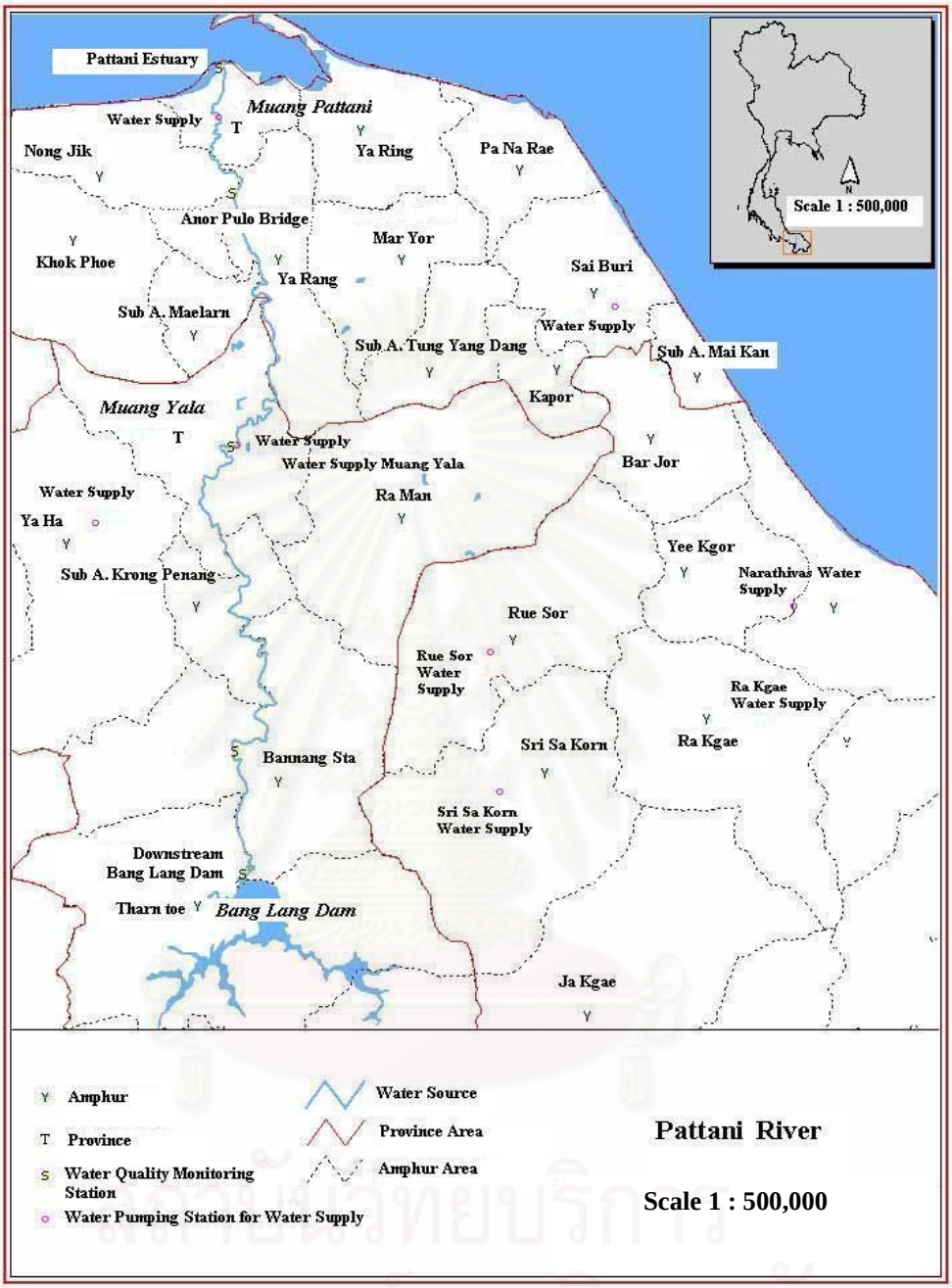

Figure 1.1 Pattani River Map (Water Quality Management Bureau, Pollution Control Department, 2001)

CHAPTER II

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 LEAD

2.1.1 Introduction

Lead is a silvery-grey soft metal. With the exception of nitrate, chlorate and chloride, the salts of lead have poor solubility in water. Lead can form stable organic compounds. Tetraethyllead and Tetramethyllead are used extensively as fuel additives. Both of them are poorly soluble and volatile in water. Lead is a by-product of mining. The most common form is sulfide, “galena”. Environmental pollution occurs through smelting and refining of lead, burning of petroleum fuels containing lead additives, and burning of coal and oil. Lead in the environment is strongly adsorbed onto sediment and soil particles. Due to the low solubility of most of the salts of lead, lead tends to precipitate out of complex solutions.

2.1.2 Chemical and Physical Properties

The chemical and physical properties of lead are shown in Table 2.1.

Although lead has four valence shell electrons, there are only two ready for ionizing. The +2 oxidation state of lead in inorganic compounds is more common than +4. The inorganic compounds of lead are generally poorly soluble. Some of the salts forms with organic acids, e.g., lead oxalate, which is also insoluble.

Table 2.1 Chemical and physical properties of lead

CASRN (Chemical Abstracts Service Registry Number)	7439-92-1
Chemical formula	Pb
Atomic number	82
Molecular weight	207.19 g/mol
Specific gravity	Lead, 11.34; Lead ore, galena, 7.3 – 7.6; Lead oxide (yellow), 9.5 – 9.9
Vapor pressure	10 mmHg. at 1,160 °C
Color	Bluish or silvery-grey soft metal
Melting point	327.5 °C
Boiling point	1,740 °C at atmospheric pressure
Natural isotopes (in order of abundance)	208, 206, 207 and 204

2.1.3 Toxicology Information

2.1.3.1 Exposure

The general routes of exposure of lead for people are food and controllable sources, which produce excess exposure and toxic effects. The examples of these sources are indoor paint, lead in contaminated drinking water, lead in dust from environmental sources, lead in air from the combustion of lead containing industrial emissions, and hand-to-mouth activities of young children who are living in the contaminated environments.

Most municipal water supplies measured at the tap contain less than 0.05 ug/l. Corrosive water (at pH lower than 6.4) will leach lead from soldered joints and lead-containing brass fittings. The introduction of lead-free gasoline and an increased awareness of the hazards of indoor leaded paint in the United State have been credited with decreasing lead levels in the blood for persons from ages 1 to 74, from 12.8 to 2.8 ug/day over the period 1988 to 1991. However, the mean blood lead level of African-American children living in central portions of cities with more than 1 million

people is 13.9 ug/dl, and about 35 percent of these children have blood lead levels higher than 10 ug/dl, which is above the guideline that is recommended by the U.S. Centers for Disease Control (Casarett et al., 2001).

The major risks of lead in children are houses containing lead-based paint and the exposure to urban dust. For infants and toddlers up to 4 years of age, the major cause of lead exposure is hand-to-mouth behavior. The lead is derived from dust sills and exterior surfaces and transferred to the children. There are also seasonal influences on children's lead exposure, as the seasonal variation of blood lead levels in children are related to the dust lead levels in the home.

In addition, several nutritional and dietary factors also influence lead toxicity. For example, alcohol consumption has been shown to account for a large proportion of variability in blood lead levels, followed by age and smoking. Wine had a greater effect on blood lead levels than beer. Moreover, there are many contributing factors that are related to lead toxicity after exposure such as gender, hematocrit, calcium intake, and consumption of milk products.

2.1.3.2 Toxicokinetics

Adults absorb 5 to 15 percent of ingested lead and usually retain less than 5 percent of what is absorbed. Children have a higher absorption of lead than adults. An average net absorption of 41.5 percent and 31.8 percent net retention was found in infants on regular diet. Lead absorption in children is related to their age and the development of their gastrointestinal tract. In addition, nutritional problems such as low dietary iron and calcium enhance lead absorption. Moreover, lead in water and beverages was proved to be absorbed to a greater degree than lead in food. Lead ingested between meals is absorbed more than lead with meals, and increasing the frequency of food intake minimizes lead absorption.

The major route of the excretion of lead from the body is the kidney. The renal excretion of lead is usually with glomerular filtrate and some renal tubular absorption. With elevated blood lead levels, excretion may be augmented by transtubular transport. Lead is also excreted to a lesser degree with other body fluids including milk during lactation. Lead crosses the placenta, so that cord blood levels generally correlate with maternal blood lead levels but are slightly lower. Maternal blood lead decreases slightly during pregnancy. However, during pregnancy, lead can

accumulate in fetal tissues, including the brain in the proportion to maternal blood lead levels (Casarett et al., 2001).

2.1.3.3 Toxicity

The toxic effects from exposures to inorganic lead form a continuum of biochemical effects to clinical effects. These effects involve several organ systems and biochemical activities. The most sensitive effects in infants and children involve the nervous system. For adults with excess exposure, the concerns are peripheral neuropathy (neurotoxicity) and/or chronic nephropathy (kidney toxicity). However, the critical effect of lead in the general population of adults is hypertension. Effects on the heme system provide biochemical indicators of lead exposure in the absence of chemically detectable effects. Other target organs are located in the gastrointestinal, reproductive and skeletal systems.

Neurologic, Neurobehavioral, and Developmental Effects in Children

The clinical effects of lead encephalopathy may occur in children with high exposure to lead, probably at blood lead levels of 80 ug/dl or higher. The symptoms begin with lethargy, vomiting, irritability, loss of appetite, and dizziness progressing to obvious ataxia and a reduced level of consciousness, which may progress to a coma and death.

Effects on the Developing Nervous System

The effects of lead on the developing nervous system are described in Table 2.2.

Table 2.2 Mechanisms for lead effects on the Nervous System (Casarett et al., 2001)

Morphologic effects (neurodevelopment)	-Impairment of timed programming of cell-cell connections -Interference with neural cell adhesion molecules -Altered migration of neurons during development
Pharmacologic effects (functional)	-Interference with neurotransmitter function
Disrupts calcium metabolism	-Blockage of voltage-dependent calcium membrane channels -The substitution of itself for calcium in calcium-sodium ATP pump -It competes for uptake by mitochondria -It binds itself to second messenger calcium receptors

Peripheral Neuropathy

Peripheral neuropathy is a classic effect of lead toxicity, particularly the footdrop and wristdrop of house painters and other workers with excessive occupational exposure. Motor nerve dysfunction, assessed clinically by electrophysiologic measurements of nerve conduction velocities, has been shown to occur with blood lead level as low as 40 ug/dl.

Hematologic Effects

The hematologic effects of lead are induced anemia; the red blood cells are microcystic and hypochromic, as in iron deficiency, and there are usually increased numbers of reticulocytes with basophilic stippling. Although the biochemical basis for anemia is not known, the effects are related to the inhibition of sodium and potassium dependent ATPases.

Bone Effects

Lead toxicity directly and indirectly alters many aspects of bone cell function. Retention and mobilization of lead in bone occur by the same mechanisms involved in regulating calcium influx and efflux; namely parathyroid hormone, calcitonin, vitamin D, and other hormones that influence calcium metabolism.

Reproductive Effects

The clinical effects of lead have been associated with sterility and neonatal deaths in humans. The gametotoxic effects of lead have been present in both male and female animals. The reduction in sperm counts and abnormal sperm motility are found in lead battery workers with blood lead levels as low as 40 ug/l.

Carcinogenicity

From a classification by the International Agency for Research on Cancer (IARC), lead is a class 2B carcinogen, possibly carcinogenic to humans. A study in England many years ago did not show an increased incidence of cancer. The most common tumors were found in the respiratory and digestive systems but not found in the kidney. In addition, epidemiologic studies suggest a relationship between occupational lead exposure and cancer of the lung and brain.

Other Effects

The purple-blue discoloration of gingival or lead lines is a former sign of lead poisoning in children. However this type of lead lines and the lead lines at the epiphyses margins of long bones is uncommon today.

2.1.3.4 Dose Response

The toxic effects of lead and the minimum blood lead level for each of the common observed effects are described in Table 2.3.

Table 2.3 Summary of Lowest Observed Effect Levels for Lead-Related Health Problems (Casarett et al., 2001)

Effect	**Blood lead level, ug/dl Adults**	**Blood lead level, ug/dl Children**
Neurologic		
-Encephalopathy	80-100	100-120
-Hearing deficits	20	-
-IQ deficits	10-15	-
-In-utero effects	10-15	-
-Reduced nerve conduction velocity	40	40
Hematologic		
-Anemia	80-100	80-100
-Increase U-ALA	40	40
-Increase B-EP	15	15
-ALA-D inhibition	10	10
Renal		
-Nephropathy	40	40-60
-Vitamin D metabolism	<30	-
Blood pressure	-	30
Reproduction		
-Males	-	40
-Females	-	-

2.1.4 Regulations

There are many regulations in Thailand that control the level of total lead concentrations in many forms of water resources. However, all standards allow the same maximum acceptable concentration of total lead in water resources; 0.05 mg/l. The following is a list of the standards and their sources.

1) The standard of water quality for consuming, Ministry of Health (1991)
2) Surface water quality standard, Water Quality Management Bureau, Pollution Control Department (1994)
3) Water quality standard for coastal area, Water Quality Management Bureau, Pollution Control Department (1994)
4) Water quality standard for marine animal protection, Department of Fisheries, Ministry of Agriculture and Co-operatives (1987)

2.1.5 Lead-Environmental Aspects

Due to the strong adsorption of lead on sediment and soil particles, the availability of lead to organisms is reduced. In addition, because of the low solubility of most of lead salts, lead tends to precipitate out of complex solutions.

In aquatic and terrestrial ecosystems, the uptake of lead by primary producers and consumers seems to be determined by the bioavailability of the lead, but the bioavailability of lead is generally low. It is unclear whether lead is adsorbed onto the organisms or actually taken up. Normally, the consumers take up lead from their contaminated environment, especially food with high concentrations, but without biomagnification.

The uptake and accumulation of lead by aquatic organisms from the water and sediment are influenced by many environmental factors, such as pH, temperature, salinity and humic acid. Almost all of the lead presents in aquatic systems is bound to the sediment. The dissolved form of lead in the water presents only a small fraction, even in the interstitial water between the sediment particles. After a number of weeks of exposure, the lead that was taken up by fish will reach equilibrium. Lead is accumulated mostly in the gills, livers, bones and kidneys. Fish eggs show an increase of lead levels with increased exposure concentrations, and there are indications that lead is present on the egg surface but not accumulated in the embryo (WHO, 1989).

Lead is unlikely to affect aquatic plants at a level that might be found in the general environment. Lead in the form of simple salts has an acute toxicity to aquatic invertebrates at a concentration between 0.1 to over 40 mg/l for fresh water organisms and between 2.5 to over 500 mg/l for marine organisms. The LC50 (the chemical concentration in the media that cause 50 % die of experimental animals) in 96 hours for fish varies between 1 and 27 mg/l in soft water and between 440 and 550 mg/l in hard water. The higher values for hard water represent nominal concentrations. Available lead measurements suggest that little of the total lead is in the solution in hard water. Because of low solubility in water, the availability of lead to the aquatic organisms is reduced.

With regard to the uptake and accumulation of lead by terrestrial organisms, the majority of lead is associated with the cell wall. In the higher plants, a similar phenomenon is noted. Lead that passes into the plant root cell can be combined with new cell wall material and subsequently removed from the cytoplasm to the cell wall. In addition, there is evidence of lead remaining in the root cell that translocates to the other parts of the plant because the concentration of lead in shoot and leaf tissue is usually much lower than in the roots. However, the tight binding to soils and the tendency of inorganic lead to form highly insoluble salts and complexes with various anions, strongly reduces its availability to terrestrial plants via the roots.

From the experimental studies on lead toxicity, high lead concentrations in the range of 100 to 1,000 mg/kg soil are needed to cause visible toxic effects on the photosynthesis, growth and other functions in plants. Thus, lead is only likely to affect plants at the sites of very high environmental concentrations.

In animals, a positive correlation between tissue and dietary lead concentrations was found, even though tissue concentrations are almost always lower. The distribution of lead within the animals is closely associated with the calcium metabolism.

With regard to the toxicity of lead to birds, lead salts are only toxic to birds at a high dietary dosage of 100 mg/kg or more. Almost all of the experiments on its toxicity to birds have been on chickens and other gallinaceous birds. Exposure of quail from hatching and up to the reproductive age resulted in effects on egg production at dietary lead levels of 10 mg/kg. Although a variety of effects at high dosages have been reported, most can be explained as primary effects on food

consumption. The primary effects of lead salts are diarrhea and a lack of appetite, leading to anoxia and weight loss. Although there is no experimental evidence of the effects on other bird species, a comparable sensitivity can be assumed. If these are correct, then it is highly improbable that environmental exposure would cause adverse effects.

Although there are many reports of lead levels in wild animals, there have only been a few reports of the toxic effects of the metal in wild or non-laboratory species. Wild rats that were captured from the area of a dump, which contained heavy metals, showed intranuclear inclusion bodies in their kidneys. These inclusions were identical in staining and electron-microscopic characteristics to the bodies induced by lead in the laboratory. Renal tumors were found in some of the rats associated with the inclusion bodies. Moreover, lead was also found in the liver of the trapped animals (WHO, 1989).

In the field, organisms have been found to intake lead from the environment, normally in proportion to the degree of contamination. Lead concentrations in shellfish are higher in the calcium-rich shell than in the soft tissue. In addition, the concentrations in the shell relate to the concentrations in the sediment. Lead concentrations in some marine fish are higher in the gills and skin than in other tissues due to adsorption. Lead concentrations in the liver increase significantly with age. In dolphins, lead is transferred from mothers to offspring during fetal development and lactation. This might be related to the calcium metabolism.

2.2 MINE WATER

2.2.1 Introduction

In mining activity, water is needed for many purposes such as mineral processing, washing, dust suppression and hydrometallurgical extraction. The unwanted or used water needs to be disposed of constantly during those mining activities. Modern mine sites usually have settling ponds and tailings dams to collect water. In contrast, the historic mine sites will release uncontrolled discharge of mine water into the environment. Normally, the volume of mine water produced, used, and disposed of at mine sites is much larger than the volume of solid waste generated. At mine site, water will contact with minerals and dissolve them. Thus, water at mine site usually consists of many dissolved and particulate matter. When water reaches

receiving water bodies, lake, stream or aquifers, the water can cause turbidity, sedimentation and toxic effects on plants, animals and human health.

2.2.2 Acid Waters

Oxidation of pyrite and other sulfides is the major contributor of hydrogen ions in mine waters, but a low pH is only one of the characteristics of Acid Mine Drainage (AMD) waters (Lottermoser, 2003). The oxidation of sulfide minerals does not only create acid, but it also liberates metals and sulfate into waters and accelerates the leaching of other elements from minerals. In fact, AMD is associated with the release of sulfate, heavy metals (Fe, Cu, Pb, Zn, Cd, Co, Cr, Ni, Hg), metalloids (As, Sb), and other elements (Al, Mn, Si, Ca, Na, K, Mg, Ba). In addition, the presence of acid conditions in surface waters should not always be attributed to anthropogenic processes such as mine activities. Acidity of streams may also be caused by naturally occurring organic acids that are flushed from soils into surface waters. Therefore, acidic drainage waters are not exclusive to sulfidic wastes. Most of the acidity of mine waters is the result of sulfide oxidation.

2.2.3 Adsorption and Desorption

In environment, trace elements move between dissolved and particulate phases. Adsorption is the term which refers to the removal of ions from solution to the surfaces of solids. The attachment of the solutes onto the solid phases does not represent a permanent bond. Adsorption is based on ionic attraction of the solutes and the solid phases. The solid phases can be organic or inorganic composition. Adsorption is an important process that controls the transport, concentration and fate of many elements in AMD waters.

The kind of metal adsorbed and the extent of metal adsorption is a function of: (a) the solution pH; (b) the presence of complexing ligands; and (c) the metal concentration of the AMD (Lottermoser, 2003). In addition, arsenic and lead are the effectively adsorbed metals at acid pH values, while zinc, cadmium and nickel are adsorbed at near-neutral pH values. Thus, when AMD waters are neutralized, various mineral precipitate and adsorb metals. Adsorption is selective. Then, the chemical composition of the water changes as the pH increases. Ions are removed from solution by adsorption process. Finally, the metal-rich sediment will accumulate.

2.2.4 Non-acid producing sulfide minerals

Sphalerite (ZnS) and galena (PbS) are the most important base metal bearing minerals. Though zinc (Zn) is toxic only at very high concentrations, sphalerite may contain environmentally dangerous amounts of cadmium (Cd) and Thallium (Tl). Galena is the main source of lead (Pb) contamination in mine areas and AMD. The common result of the wet oxidation of sphalerite is a leach rich in dissolved Zn, and sulfate, with variable Cd amounts, while that of galena is secondary anglesite ($PbSO_4$) in equilibrium with Pb^{2+} and SO_4^{2-} (Dold, 2004) solution according to the following equation:

$$PbS + 2O_2 \longrightarrow Pb^{2+} + SO_4^{2-} \quad \text{…….(2.1)}$$

Secondary anglesite coating on galena may increase the apparent resistance because anglesite has a low solubility and protects the sulfides from direct contact with oxidizing reagents.

2.2.5 AMD Management Strategies

At mine sites, containment of all contaminated water is to be ensured using water management strategies. These strategies aim to protect aquatic environments and to reduce the water volume requiring treatment. The different strategies are applied depend on the location and the climate of mine areas. Various techniques can reduce mine water volumes (Lottermoser, 2003):

(a) interception and diversion of surface waters through construction of upstream dams;
(b) diversion of runoff from undisturbed catchments;
(c) maximization of recycling and reuse of water;
(d) segregation of water types of different quality;
(e) controlled release into nearby waters;
(f) sprinkling of water over dedicated parts of the mine site area;
(g) use of evaporative ponds;
(h) installation of dry covers over sulfidic wastes in order to prevent infiltration of meteoric water

These water management strategies will reduce the potential AMD water volume.

2.2.6 Treatment of AMD

AMD is a persistent and potential severe source of pollution from mine sites that can continue long after mining has ceased. The cost of treatment of AMD is extremely high. Thus, prevention or minimization of sulfide oxidation at the source is better than the treatment of AMD waters. A greater control of sulfide oxidation creates a smaller volume of AMD water requiring treatment.

Like the techniques to reduce the potential AMD water volume, AMD treatment technologies are site specific, and multiple remediation strategies are commonly needed to achieve successful treatment of AMD waters. Many of the treatment techniques are not standard industry practices, are used only at some individual mine sites, or are still at the exploratory stage. Both established and innovative AMD treatment techniques are generally designed (Lottermoser, 2003):

(a) to reduce volume;
(b) to raise pH;
(c) to lower dissolved metal and sulfate concentrations;
(d) to lower the bioavailability of metals in solution;
(e) to oxidize or reduce the solution; or
(f) to collect, dispose or isolate the mine water or any metal-rich sludge generated.

AMD treatment techniques can also be classified as active or passive:

(a) *Active treatment*. Active treatment systems such as neutralization require continued addition of chemical reagents, active maintenance and monitoring, and mechanical devices to mix the reagent with the water.
(b) *Passive treatment*. Passive methods like wetlands use chemical and biological processes to reduce dissolved metal concentrations and to neutralize acidity. Such methods require little or no reagents, active maintenance and monitoring, or mechanical devices.

2.2.7 Neutralization

Neutralization is an effective technique for treatment of AMD water. Neutralization involves collecting the leachate, selecting an appropriate chemical, and mixing the chemical with the AMD water. In the process, acid is neutralized, and metals and sulfate are removed from solution and precipitated as sludge.

A large variety of natural, by-product or manufactured chemical are used for AMD treatment including local waste rock. Each of neutralizing agents has different advantages and disadvantages. Both limestone (largely $CaCO_3$) and hydrated lime ($Ca(OH)_2$) are the famous neutralizing agents. The advantages of using limestone include low cost, ease of use, and formation of a dense, easily handled sludge. Disadvantages include slow reaction times and coating of the limestone particles with iron precipitates. In the reaction of limestone with AMD waters, hydrogen ions are consumed, bicarbonate ion generated, and dissolved metals are converted into sparingly soluble minerals such as sulfates, carbonates, and hydroxides (Lottermoser, 2003):

$$CaCO_{3(s)} + H^{+}_{(aq)} + SO_4^{2-}{}_{(aq)} + Pb^{2+}_{(aq)} \rightarrow PbSO_{4(s)} + HCO_3^{-}{}_{(aq)} \quad \text{.....(2.2)}$$

$$CaCO_{3(s)} + Pb^{2+}_{(aq)} \rightarrow PbCO_{3(s)} + Ca^{2+}_{(aq)} \quad \text{.....(2.3)}$$

$$CaCO_{3(s)} + Zn^{2+}_{(aq)} + 2H_2O_{(l)} \rightarrow Zn(OH)_{2(s)} + Ca^{2+}_{(aq)} + H_2CO_{3\ (aq)} \quad \text{....(2.4)}$$

Hydrated lime ($Ca(OH)_2$) is easy and safe to use, effective, and relatively inexpensive. However, the major disadvantages are the voluminous sludge produced and high initial costs for the establishment of the active treatment plant. In this process, acid is neutralized, metals (Me^{2+}/Me^{3+}) are precipitated in the form of metal hydroxides, and gypsum is formed, if sufficient sulfate is in solution:

$$Ca(OH)_{2(s)} + 2H^{+}_{(aq)} \rightarrow Ca^{2+}_{(aq)} + 2H_2O_{(l)} \quad \text{.....(2.5)}$$

$$Ca(OH)_{2(s)} + Me^{2+}/Me^{3+}{}_{(aq)} \rightarrow Me(OH)_{2(s)} \,/\, Me(OH)_{3(s)} + Ca^{2+}_{(aq)} \quad \text{.....(2.6)}$$

$$Ca^{2+}_{(aq)} + SO_4^{2-}{}_{(aq)} + 2H_2O_{(l)} \rightarrow CaSO_4 \,.\, 2H_2O_{(s)} \quad \text{.....(2.7)}$$

Lime neutralization is efficient for removing metals such as cadmium, copper, iron, lead, nickel and zinc from solution. However, the solubility of metals varies with pH, and the lowest dissolved metal concentration is not achieved at the same pH. Not all metal can be precipitated at the same pH, and a combination of neutralizing agents e.g. lime plus limestone and other chemical additives may be needed to achieve acceptable water quality.

In worst case scenario, if excessive neutralization is used to treat AMD effected streams, sulfate, metals, and metalloids previously fixed in the stream sediments may then be redissolved by the treated water. Thus, remediation of AMD waters should raise pH only to values necessary to precipitate and adsorb metals.

Lead and other heavy metals precipitation as the hydroxide and the sulfide diagram was presented in Figure 2.1 (Eckenfelder, 2000).

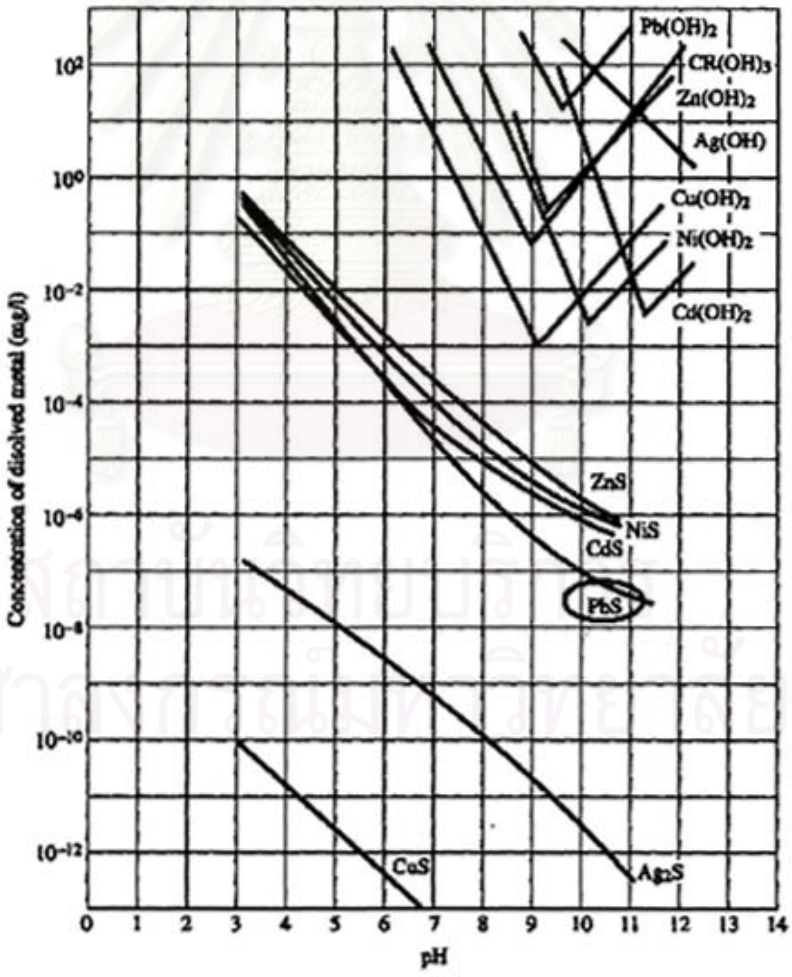

Figure 2.1 Heavy metals precipitation as the hydroxide and the sulfide

2.3 MODEL SELECTION

2.3.1 Criteria for Model Selection

According to U.S. EPA information, there are six criteria for water quality model selection:

1) availability of pertinent documentation,
2) ease of application,
3) available time and resources,
4) applicability of model processes and variables,
5) hydrodynamic model capabilities, and
6) evidence of demonstrated applicability to size and type of project.

2.3.2 Decision for Model Selection

Based on the criteria of U.S. EPA, the Water Analysis Simulation Program (WASP) Version 6.2 was selected for this research. The supporting reasons for this model selection are described as follows:

1) The WASP 6.2 can simulate both dynamic and steady state conditions. It can simulate the water quality variables of almost any water bodies.
2) The WASP 6.2 has high flexibility in both temporal and spatial options. It can simulate as one, two or three dimensional systems.
3) The WASP 6.2 has a submodel “TOXI” that can simulate the scenario of contamination of inorganic and organic chemicals in a surface water system. In this study, the submodel TOXI will be used to simulate the contamination of lead in a river.
4) The WASP 6.2 added a graphical interface to the original WASP model which can be operated on Windows system.
5) The WASP 6.2 is a free-ware model. A user can download the model from the U.S. EPA web site.
6) The WASP 6.2 is used by many modelers around the world, For example, WASP has been used to study the Scheldt Estuary (Vuksanovic et al., 1995), Ta-chi reservoir in Taiwan (Wu et al., 1996), Tampa Bay (Wang et al., 1999), Venice Lagoon (Umgiesser et al., 2003), Pong River in Thailand (Chanchai et al., 2004), and Onondaga lake (Kim et al., 2004).

2.4 MODEL WASP VERSION 6.2

2.4.1 Introduction

The Water Quality Analysis Simulation Program (WASP 6.2) is an enhanced version of the original WASP, developed by Di Toro in 1983. The model helps users to interpret and predict water quality responses to natural phenomena and man-made pollution. The WASP 6.2 is a dynamic compartment-modeling program for aquatic systems, including both the water column and the underlying benthos. The time-varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the basic program (Wool et al., 2003).

The WASP consists of two sub models, which are the EUTRO and TOXI. The EUTRO is used to analyze conventional pollution; for example, dissolved oxygen, biochemical oxygen demand, nutrients and eutrophication. The TOXI, which is mentioned in this study, is used to simulate toxic pollution involving organic chemicals, metals and other simple toxicants.

2.4.2 Relevant Equations

General Mass Balance Equation

The mass balance equation for dissolved constituents in a water body concerns all materials which enter and leave the system through direct and diffuse loading; advective and dispersive transport; and physical, chemical and biological transformation. The general mass balance equation is shown in Equation 1, where the x-, y- and z-coordinates are in the longitudinal, lateral, and vertical direction respectively.

$$\frac{\partial C}{\partial t} = -\frac{\partial (U_X C)}{\partial X} - \frac{\partial (U_Y C)}{\partial Y} - \frac{\partial (U_Z C)}{\partial Z} + \frac{\partial (E_X . \partial C / \partial X)}{\partial X} + \frac{\partial (E_Y . \partial C / \partial Y)}{\partial Y} + \frac{\partial (E_Z . \partial C / \partial Z)}{\partial Z} + S_L + S_B + S_K$$

…… (2.8)

where:

C = concentration of the water quality constituent, mg/l

t = time, days

U_x, U_y, U_z = longitudinal, lateral and vertical advective velocities, m/day

E_x, E_y, E_z = longitudinal, lateral and vertical diffusion coefficients, m^2/day

S_L = direct and diffuse loading rate, g/m^3_day

S_B = boundary loading rate (including upstream, downstream, benthic, and atmospheric), g/m^3_day

S_K = total kinetic transformation rate; positive is source, negative is sink, g/m^3_day

The WASP implements a finite difference form of equation by expanding the infinitesimally small control volumes into larger adjoining "segments" and by specifying the appropriate transport, loading and transformation parameters. However, the derivation of the finite difference form of the mass balance equation will be for one dimension. By assuming vertical and lateral homogeneity, Equation 2.1 can be integrated over Y and Z to obtain Equation 2.2.

$$\frac{\partial (A.C)}{\partial t} = \frac{\partial (-U_X.A.C + E_X.A.(\partial C / \partial X))}{\partial X} + A.(S_L + S_B) + A.S_K \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.9)$$

where:

A = cross-sectional area, m^2

Equation 2.9 presents the three major classes of water quality processes which are transport (term 1), loading (term 2), and transformation (term 3).

Loading Process

WASP 6 allows the user to specify the loading rate for each variable. The user inputs the dataset to specify point source loads. Loads, in kg/day will be added to the designated segments at the following rates:

$$V_i S_{Lik} = 1000 \times L_{ik}(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.10)$$

where:

V_i = volume of boundary segment "i" (m^3)

S_{Lik} = loading rate response of chemical "k" in segment "i" (g/m^3-day)

$L_{ik}(t)$ = loading rate of chemical "k" into segment "i" (kg/day)

Manning's Equation

In this study, Manning's equation will be used to calculate stream velocities. It provides reasonably accurate results for a large range of natural and artificial channels under the assumption of uniform flow conditions. It has been widely adopted for use by engineers throughout the world (Chadwick et al., 1993).

$$v = (1/n) \times R^{2/3} \times S^{1/2} \quad \text{.....(2.11)}$$

where:

v = Stream velocity (m/sec)

n = Manning's n

R = The ratio between the cross-section area and perimeter (m)

S = Slope of river (m/m)

Sorption

Sorption is the bonding of dissolved chemicals onto solid phases, such as benthic and suspended sediment. Sorption is important in controlling the environmental fate and the toxicity of heavy metals in the water. Sorption may cause the accumulation of heavy metals in the bed sediment. Sorption may retard some reactions, such as volatilization, or enhance some reactions such as acid-catalyzed hydrolysis. Sorption reactions are fast relative to other processes, and local equilibrium may be assumed. For environmentally relevant concentrations (less than 10^{-5} M or one-half water solubility), equilibrium sorption is linear with dissolved chemical concentration (Wool et al., 2003) as follows:

$$C_s = K_{ps} \times C_w \quad \text{..... (2.12)}$$

where:

K_{ps} = Partition coefficient

C_s = Concentration in sediment (solid phase), mg/kg

C_w = Concentration in dissolved form (liquid phase), ug/l

At equilibrium, the distribution among the phases is controlled by the partition coefficients K_{ps}. The total mass of the chemical in each phase is also controlled by K_{ps} and the amount of solid phase present, so that

$$f_D = n /(n + \Sigma_s K_{ps} \times M_s) \quad \text{……. (2.13)}$$

$$f_S = K_{ps} \times M_s / (n + \Sigma_s K_{ps} \times M_s) \quad \text{……. (2.14)}$$

where:

f_D = Dissolved fraction

f_S = Solid fraction

M_s = Total mass of chemical in each phase

n = Amount of solid phase present

These fractions are determined in time and space throughout a simulation from the partition coefficients. Given the total concentration and the phase fraction of chemical “i” in segment “j,” the dissolved and sorbed concentrations are uniquely determined as follows:

$$C_{wij} = C_{ij} \times f_{Dij} \quad \text{……. (2.15)}$$

$$C_{sij} = C_{ij} \times f_{sij} \quad \text{……. (2.16)}$$

where:

F_{ij} = Fraction of chemical i in segment j

C_{ij} = Concentration of chemical i in segment j

Sediment Transport

Sediment transport influences chemical transport and fate. Many chemicals, which sorb strongly to the sediment, undergo settling, scour and sedimentation. Sediment size fraction or solid type is simulated using the TOXI program. Simulations may incorporate total solids as a single variable, or represent from one to three solid types. The character of the three solid types may represent sand, silt and clay, or organic and inorganic solids. A simple mass balance on each solid variable in each compartment is performed by WASP 6.2. The computation of mass balance is performed in the benthic compartment as well as the water column compartment. The user can vary all solid transport rates in space and time. However, there are no special process descriptions for solids transport.

With regard to water column transport, the sediment and particulate chemicals may settle to the lower water segment. Velocities and the surface area in transport fields describe settling, deposition and scour rates in the WASP 6.2. Settling velocities should be set within the range of Stokes velocities corresponding to the suspended particle size distribution (Wool et al., 2003) as follows:

$$V_s = 8.64\ g\ (\rho_p - \rho_w)\ d^2_p / 18\ \mu \qquad \text{..... (2.17)}$$

where:

V_s = Stokes velocity for a particle with diameter d_p and density ρ_p m/day

g = acceleration of gravity = 981 cm/sec^2

μ = absolute viscosity of water = 0.01 poise (g/cm^3-sec) at 20 °C

ρ_p = density of the solid, g/cm^3

ρ_w = density of the water, 1.0 g/cm^3

d_p = particle diameter, mm

Estimation of the River Dispersion Coefficient

Fischer et al. (1979) suggested that the equation for estimating the dispersion coefficient in real streams is as follows:

$$E_x = 3.4 \times 10^{-5} U^2 B^2 / HU^* \quad \text{..... (2.18)}$$

Where:

E_x = Dispersion Coefficient, mi^2/day

U = mean river velocity, ft/sec

B = mean width, ft

H = mean depth, ft

U* = river shear velocity, ft/sec

The river's shear velocity is given by the following equation:

$$U^* = (gHS)^{1/2} \quad \text{..... (2.19)}$$

Where:

g = 32 ft/sec^2

S = river slope in ft/ft

2.5 LITERATURE REVIEW

2.5.1 Lead contamination situation in the Pattani River

From 1986 – 1997, the Office of Environmental Health of the Department of Health under the Ministry of Health monitored the contamination levels of total lead in the Pattani River. During 1986 – 1992, four of the ten water sampling stations showed lead concentrations that exceeded the permissible river and drinking water quality standard of 0.05 mg/l. One station, which is located in Bannangsta district, was found to exceed the standard from 1986 – 1992 and 1996 – 1997. This established the evidence that lead contamination in the Pattani River at Bannangsta district still exists.

Tutep (1994) studied the contamination of metals in stream sediments of the Pattani River in the Yala province. The metals As, Cd, Cu, Fe, Mn, Pb and Zn were adsorped onto clay particles in a similar manner to that of silt, but twice as much as on sand at the station near the mining area. Concentrations decreased with increasing distance in the downstream direction.

In 2002, the distribution of lead in the Pattani River Basin was reported by the Pollution Control Department under the Ministry of Natural Resources and the Environment. The level of total lead and the level of lead in sediments in the streams around the abandoned tin mining area and in the river were investigated. The first sampling was carried out in March, the early of dry season, while the second sampling was carried out in June, the early of rainy season.

With regard to the investigation of lead contamination in streams around the abandoned tin mine area, the lead in stream sediment was found in very high concentrations. In the first sampling, lead in clay particles (particle size < 53 μm) of sediment samples around the Tum Ta Lu abandoned mine was found in the range of 390 – 28,679 mg/kg dry weight. In the second sampling, lead in the particles of sediments in the stream from the Na Sua and Tum Ta Lu mine was also found at high concentrations: 510.6 – 23,720.2 mg/kg dry weight. The contamination level of lead in the stream sediments was found to be 100 – 1,000 times higher than that of the river sediments. Lead contamination in water samples in Na Sua Pond at the Na Sua abandoned mine was found to be highest at 264.38 and 777.52 μg/L in the first and second sampling, respectively. The concentration of lead at other stations was found to decrease in the second sampling when compared with the first sampling because the elution rate in the dry season is less than in the rainy season. Moreover, lead in a water sample from the village piped water system was found to be 4.8 + 0.2 μg/L, which is the same as the maximum guideline level for lead in the drinking water standards.

An investigation of lead contamination in the Pattani River in Yala and Pattani provinces found that, from 11 sampling stations, the amount of total lead was lower than 15 μg/L at every station, except for at the Cha Lerm Pra Kiat Bridge where the level of suspended solid was higher than that of other stations, which resulted in a higher level of lead. Lead in river sediment was mainly in the clay composition of the sediment. The results from both samplings showed a good agreement to the high concentration of lead that was found at the station in Bannangsta district, where the Pattani River originates and connects with the streams from abandoned tin mines. The concentration of lead in the sediment was found to decrease as the distance increased from the mining area. However, the concentration of lead was found to increase at the

Pattani River mouth. The increase in the lead concentration might have resulted from the use of lead oxide in boat repairing that occurs at the dock yard.

2.5.2 Example applications of the WASP model in water quality analysis and simulation

Vuksanovic et al. (1995) studied the transport of polychlorinated biphenyls (PCB) in the Scheldt Estuary using the Water Quality Simulation Program (WASP). WASP was applied to simulate the spatial distribution of 12 selected PCB isomers. The simulations were performed under average hydrodynamic and suspended sediment transport regimes. Calculated evolution profiles of the dissolved and sorbed concentration in the water column indicated a high accumulation of PCB in the turbidity maximum zone. The simulated distributions of the sorbed PCB, suspended sediment and salinity agreed with the observations but more measurements are needed in order to verify the predictability of the simulations.

Wu et al. (1996) investigated the effects of reservoir operations on water quality, which they simulated using the Water Quality Simulation Program. WASP was employed to predict the water quality under several sedimentation conditions and operation policies. Several reservoir operation rules were simulated to address the possibility of maintaining water quality through proper operation. The watershed of the Ta-chi reservoir in Taiwan was chosen as a case study. The simulation results show that an appropriate operation rule can improve outlet water quality by releasing water from a certain depth in the reservoir. This is because the flow field that influences the bio-chemical reactions is altered.

Wang et al. (1999) applied WASP to simulate and evaluate the relationships between external nutrient loading and the water quality of Tampa Bay, U.S.A. Tampa Bay was phosphorus enriched and nitrogen limited for algal growth. The model estimated the impact of the nutrient loads on water clarity, a pivotal water quality parameter for sea grass meadows. The model also estimated the impacts over long time periods and on a large scale. Model results were compared with monthly measurements and yearly averaged estimates for 1985 – 1994. A component analysis indicated that the internal nutrient cycling and transport exceeded external loadings (external inputs from the watershed are the ultimate source of nitrogen). Cycling of

nitrogen was governed primarily by phytoplankton, including growth, death and mineralization of organic-N.

Umgiesser et al. (2003) developed the Finite Element Ecological Model (FEEM) by fully coupling a primitive equation finite element hydrodynamic model (FEM) with an ecological model derived from EUTRO, the submodel contained in the Water Quality Simulation Program. The integrated model has been applied to the Venice Lagoon. Idealized forces, such as tides, have been used together with actual field data, river discharge and nutrient loadings to run simulations over a one-year period. Analysis of the results shows that the model is numerically stable, variations in the state variables are consistent, and nutrients, plankton and oxygen evolves in space and time in a ecologically coherent way.

Sangsurasak (2004) applied WASP to simulate the scenario of eutrophication that caused “Fish Kill” in the year of 1999 at Pong River Thailand. A dynamic water quality model was developed with a new method for estimating the unavailable runoff data and calibrating flow, using a combination of lignin and tannin as conservative trace. Results of correlation coefficients from the runoff calibration were reasonably high. Root mean square error from the calibration of the flow was comparable with the literature values, using salinity as conservative trace. The model predicted the bloom die-off which lowered DO and possibly caused fish kills on the same day in 1999. The accuracy of the dynamic model was on a time scale of days.

Kim et al. (2004) modified WASP to simulate the presence of mercury and evaluate the effects of remedial actions, such as dredging and capping of mercury speciation and transport in Onondaga lake. Model predictions for the water column generally agreed with the measured values reported in literature. Natural attenuation showed no positive impact from these remediation effects.

CHAPTER III

STUDY AREA, DATA COLLECTION AND CONCEPTUAL MODELING APPROACH

The details in this chapter describe the study area, which is the Pattani watershed, and the phases of the modeling procedures in this research, which include data collection, model creation, model verification, model calibration, model sensitivity analysis and model prediction. The existing data in this research was gathered from government agencies. The model creation phase includes all processes of model construction, such as segmentation, determination of the flow function, the development of initial conditions and a waste loading determination. The model validation describes the accuracy of the model's execution in the assumed conditions. The model calibration phase demonstrates how the constants and coefficients were adjusted to calibrate the model to a real data. This phase also includes the statistical analysis for determining the fit of the predicted data with the existing data. Model sensitivity analysis presents the sensitivity of the model's predicted results when the parameters are varied. Finally the calibrated model is used to simulate a scenario of reducing the total lead concentration in the river. The purpose is to set up a remediation target number for the initial concentration of lead that would be released into the upstream section of the river.

3.1 STUDY AREA, WATER USES, WATER QUALITY AND LAND UTILIZATION

This section describes the location of the Pattani River, water uses, water quality and land utilization in the area of the Pattani watershed.

Location

The Pattani River is the main tributary of the Pattani watershed. The area of the watershed is 3,896,587 km^2. The size of the water receiving area is 3,857 km^2. The watershed covers an area of the Yala and Pattani provinces. The length of the river is 210 km. The annual average rainfall is in the range of 1,500 – 2,200 mm (the average number: 1,630 mm). The annual average runoff is 2,738,000,000 m^3 or 23.24 l/sec/km^2.

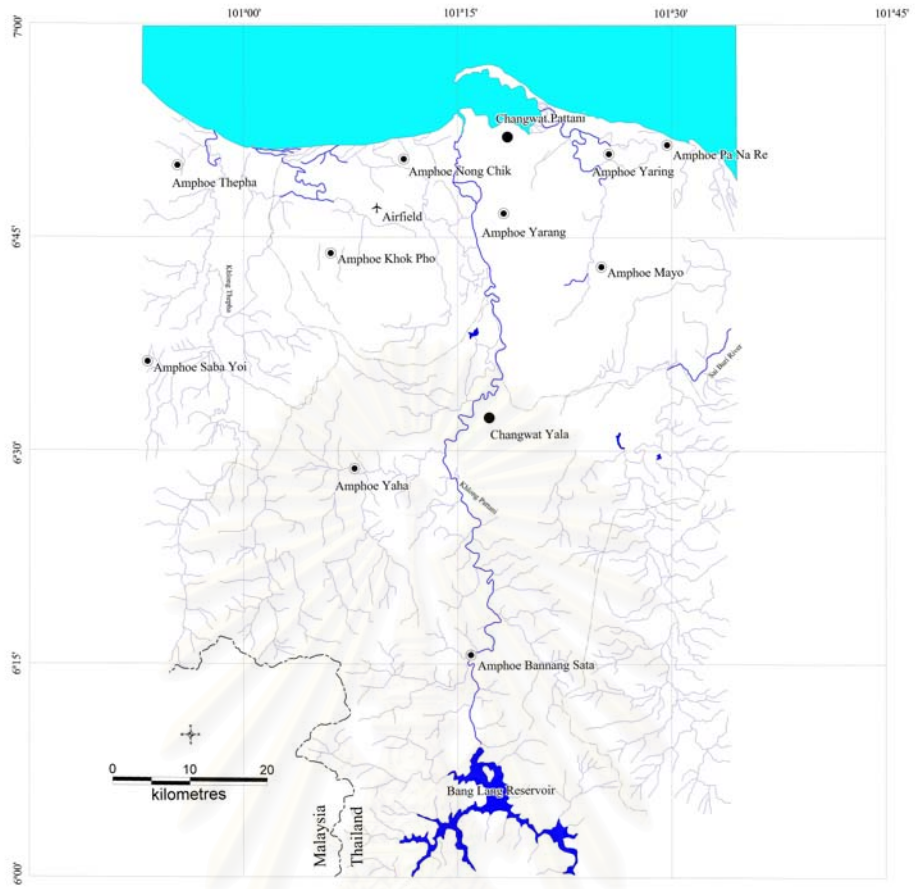

Figure 3.1 Pattani Watershed Map

Water uses

There are two major irrigation projects in the Pattani watershed. The first project is Bang Lang Dam, which belongs to the Electricity Generating Authority of Thailand. The other is the Pattani irrigation project, which covers an area of 482 km^2. The Pattani irrigation project has two water supply sections: the water supply station in Muang Yala and the water supply station of Muang Pattani. The volume of water that is produced from these two stations is 671,000,000 m^3/year. From an analysis by the Royal Irrigation Department, the Pattani watershed should not have a drought, but a flooding problem can occur during the months of November – December of every year.

Bang Lang Dam

Bang Lang Dam is located in Ban-Bang Lang, Bajor sub-district, Bannangsta district, Yala province. The objectives of the dam's construction were flood protection, irrigation and electrical generation. The dam is made of rock with clay in its core. The height, length and width of the dam are 85 m, 430 m and 10 m, respectively. With a volume of 1,420,000,000 m^3, the catchments upstream of the dam have an area of 2,080 km^2. The dam has three electrical generators that can produce electricity, about 200,000,000 kilowatt-hour, for the Yala province.

Pattani Dam

Pattani Dam was constructed across the Pattani River at the border of Muang Yala, Yala province and Yarang district in the Pattani province. It is the first concrete dam in Thailand that has a reservoir in the upstream area of the dam. The purposes of this dam's construction are flood protection and irrigation in Khokpoh district, Yarang district, Mayor district, Nong-Jik district, Muang Pattani, Yaring district and Panarae district of the Pattani province and an area about 53 km^2 in the Yala province.

The Banglang Dam is located in the upstream of the Pattani Dam, which is located in the middle of the river. These two dams affect the flow of the river. So, in this research, the river will be separated into two parts, which are upstream and downstream of the Pattani Dam, in order to control the flow function in the model's execution.

Water Quality

Although the objectives of this study focus on the lead contamination in the Pattani watershed, the existing data on the conventional pollutants (i.e., nitrogen, phosphorus and BOD) and pesticide contamination can provide information about the existing water quality in this watershed.

An investigation of Pollution Control Department in 2002 found that the amounts of nitrogen, phosphorus, BOD and pesticides that were produced by agricultural activities in the Pattani watershed were 7,300,169 kg/year, 1,126,665 kg/year, 3,862,009 kg/year and 13,895 kg/year, respectively. After comparing these numbers with the amount of pollutants from other watersheds in Thailand, it can be concluded that a majority of the conventional pollutants and pesticide contamination

from agricultural activities in the Pattani watershed is at a high level. However the area of contamination is concentrated in the lower part of the watershed, especially in Muang Yala, Yala province and Muang Pattani, Pattani province because these parts are residential areas, while the upper part of the watershed are forestry and mining areas.

Land Utilization

In the area of the Pattani watershed, which is 3,896,587 km^2, the land use can be grouped as shown in Figure 3.2. Most of the area in this watershed is used for agricultural activities. An investigation by the Pollution Control Department in 2002 found that the highest agricultural activities in the Pattani watershed are rubber tree and oil palm planting with an area of 2,014,238 km^2. The areas of fruit orchards and paddy fields are 191,910 km^2 and 160,975 km^2, respectively.

The Pattani watershed has a forest area of about 1,335,855 km^2. The people who live in this watershed reside in a suburban community with a living area of 33,387 km^2.

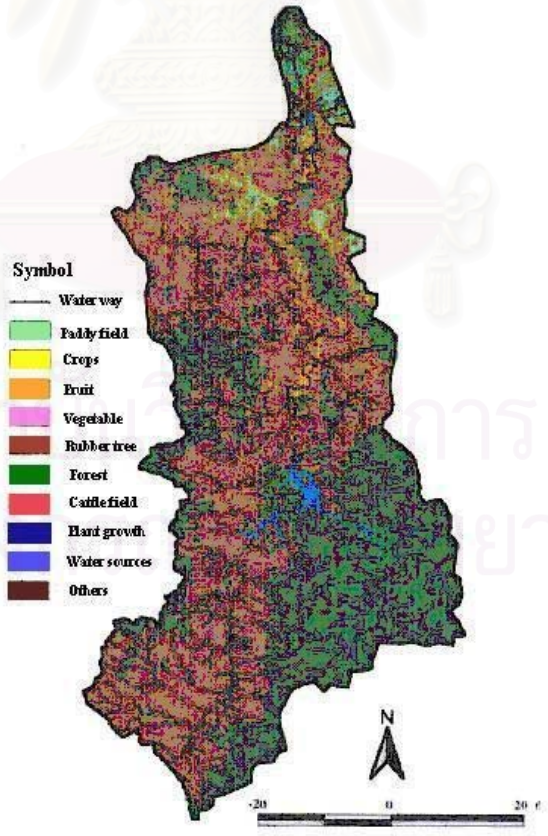

Figure 3.2 Land Utilization in Pattani Watershed (Pollution Control Department, 2002)

3.2 EXISTING DATA SURVEY AND DESCRIPTION

The existing data in this research was gathered from literature and various government agencies. Due to the crisis in the southern area of Thailand during the year 2004, the plan for collecting the field data was terminated. The existing data can be categorized into three groups: total lead concentration data, water transport data and river-cross sectional data.

3.2.1 Total Lead Concentration Data

The existing data of total lead concentration in the Pattani River were collected from two government agencies, the Department of Health, under the Ministry of Health, and the Pollution Control Department, under the Ministry of Natural Resources and Environment. From 1986–1997, the Office of Environmental Health of the Department of Health under the Ministry of Health monitored the contamination levels of total lead in the Pattani River. During 1986–1992, four of the ten water sampling stations showed high lead concentrations which exceeded the permissible river and drinking water quality standard of 0.05 mg/l. A station located in Bannangsta district was found to exceed the standard from 1986–1992 and 1996–1997.

In 2002, the level of total lead and the level of lead in sediments in the streams around the abandoned tin mining area and in the Pattani River were investigated by the Pollution Control Department under the Ministry of Natural Resources and the Environment. The first sampling was carried out in March, the early of dry season, while the second sampling was carried out in June, the early of rainy season.

The existing data of total lead concentration in the Pattani River at Bannangsta district, Muang Yala and Muang Patani that were collected by the Department of Health and Pollution Control Department from 1986 – 2002 are presented in Figure 3.3.

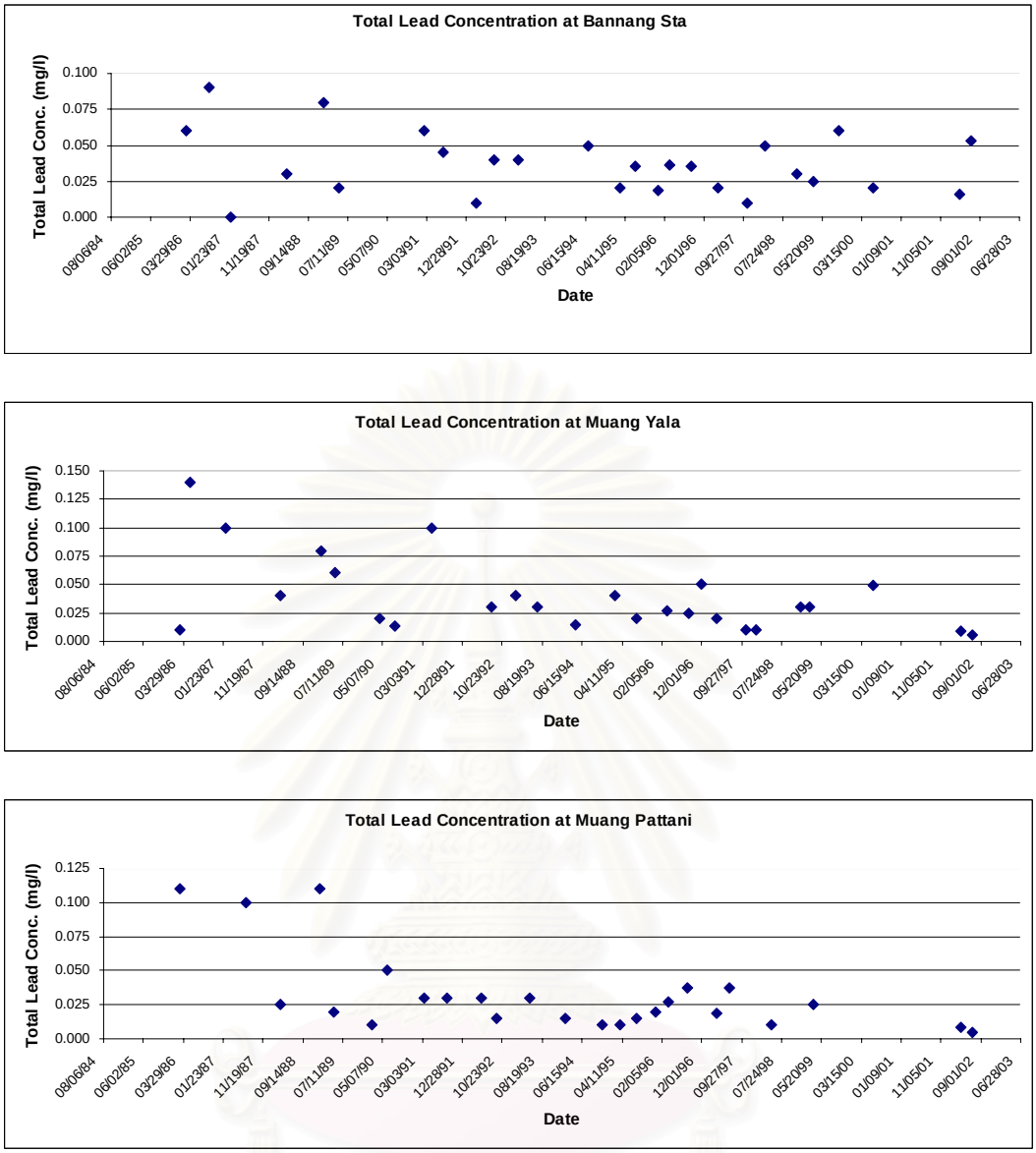

Figure 3.3 Total lead Concentration in the Pattani River from three Segments, Bannangsta district, Muang Yala and Muang Pattani (Department of Health, 1986-2000 and PCD, 2002)

3.2.2 Flow Data

The flow data in this study was collected from the Royal Irrigation Department, under the Ministry of Agriculture and Co-operatives. There are two parts to the flow data due to the hydrological characterization of the river. The first part of the flow was measured at Bannangsta district, which is the first segment of the model's execution. Due to the location of the Pattani Dam in the middle of the Pattani River, the second part of flow was used for the downstream part of the Pattani River, which

terminates with the last segment of model located at the Dechanuchit Bridge in Pattani province.

The original unit of the outflow from the dam is in MCMs (mega-cubic meters). The average daily flow was determined by multiplying the daily outflow by 1,000,000 in order to convert it to the appropriate units, and then dividing it by the total number of seconds in a day (86, 400).

The flow data of the Pattani River at Bannangsta district, Yala province and the outflow data from the Pattani Dam are shown in Figure 3.4 and Figure 3.5, respectively.

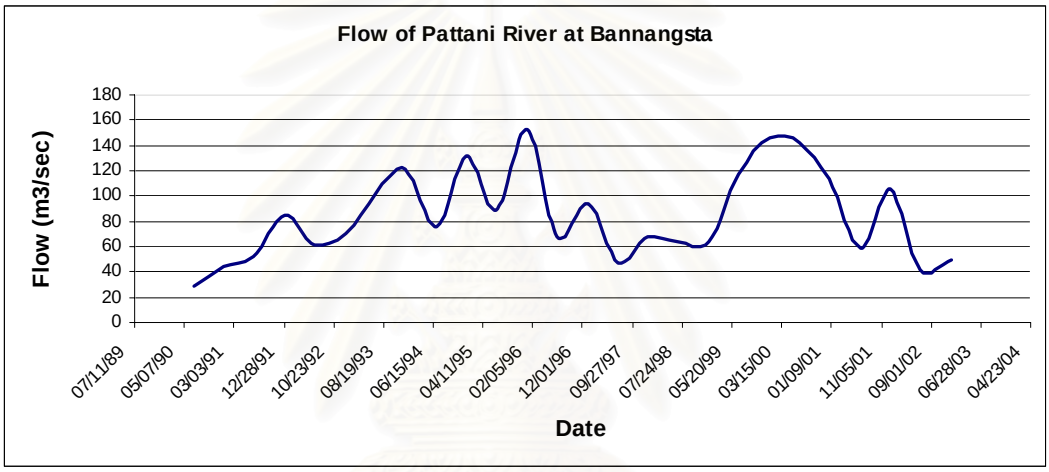

Figure 3.4 Flow data of the Pattani River at Bannangsta district, Yala province (Royal Irrigation Department, 1990-2002)

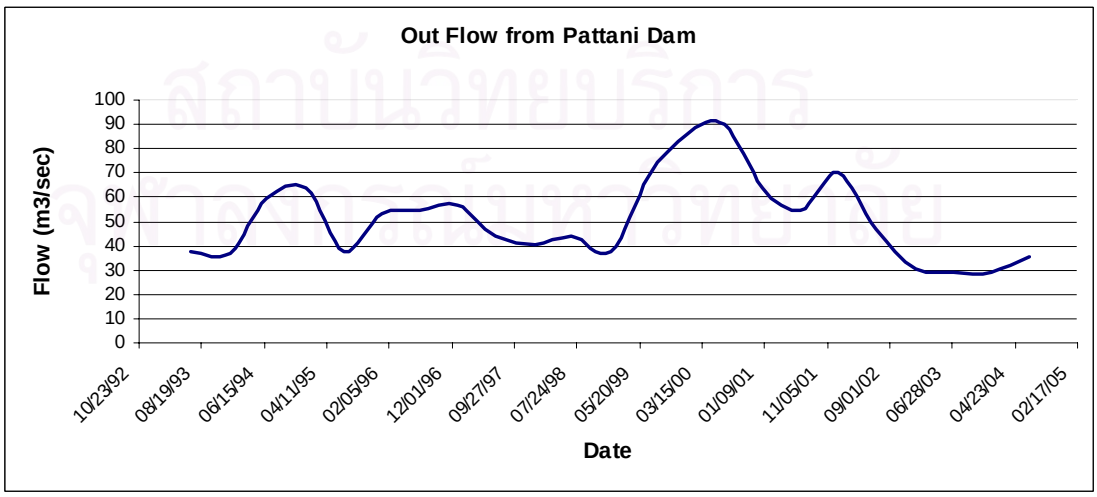

Figure 3.5 Outflow data of the Pattani Dam at Yarang district, Pattani province (Royal Irrigation Department, 1993-2004)

3.2.3 Cross section of the Pattani River

The cross section information of the river is important for this study in order to calculate the cross sectional area, mean depth, mean width, slope and perimeter, which is used in many equations by the model. The cross section of the Pattani River was also measured by the Royal Irrigation Department, Ministry of Agricultural and Co-operatives. There are four locations that were investigated by the Royal Irrigation Department, which are located in Bannangsta district, Yaha district and Muang Yala in Yala province and Muang Pattani in Pattani province. The cross sections of the Pattani River at each location are presented in Figures 3.6 to 3.9.

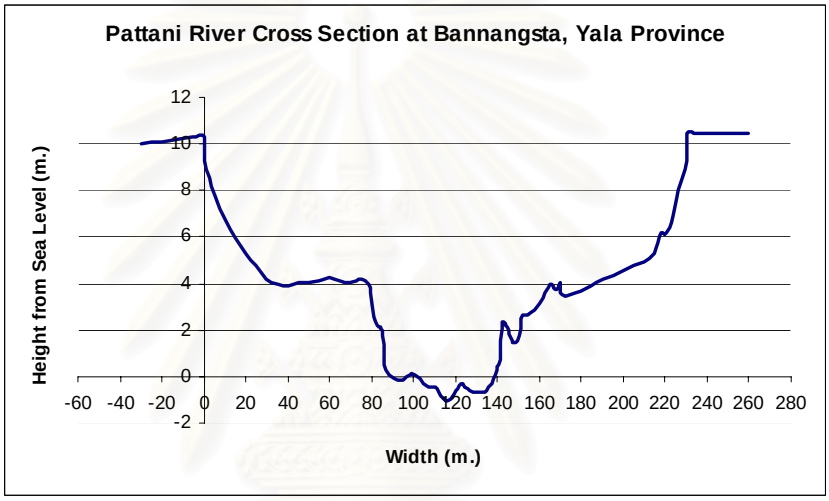

Figure 3.6 Cross Section of the Pattani River at Bannangsta district, Yala Province (Royal Irrigation Department, 2004)

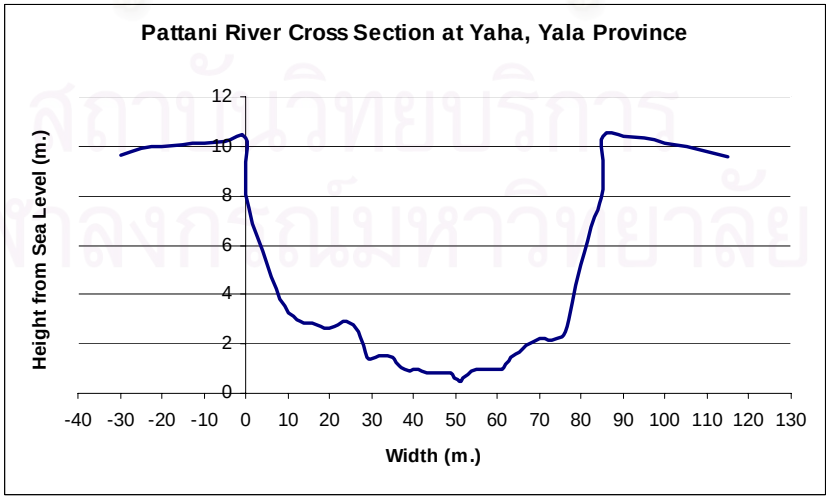

Figure 3.7 Cross Section of the Pattani River at Yaha district, Yala Province (Royal Irrigation Department, 2004)

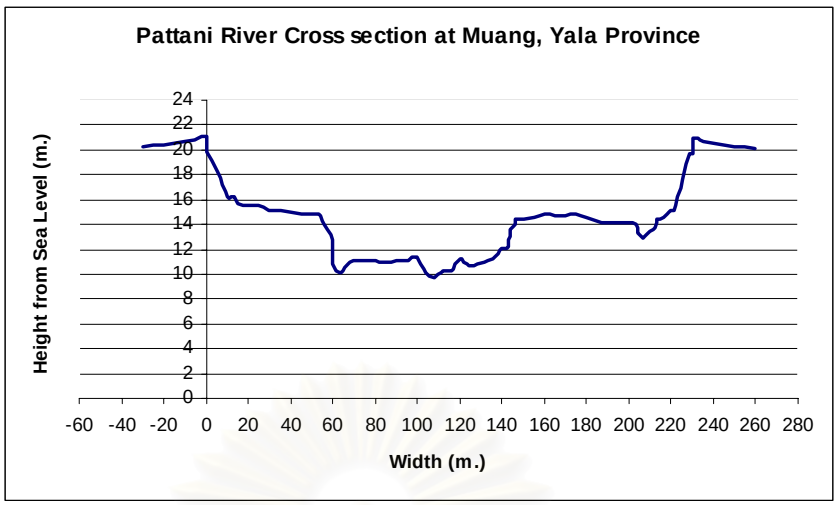

Figure 3.8 Cross Section of the Pattani River at Muang Yala, Yala Province (Royal Irrigation Department, 2004)

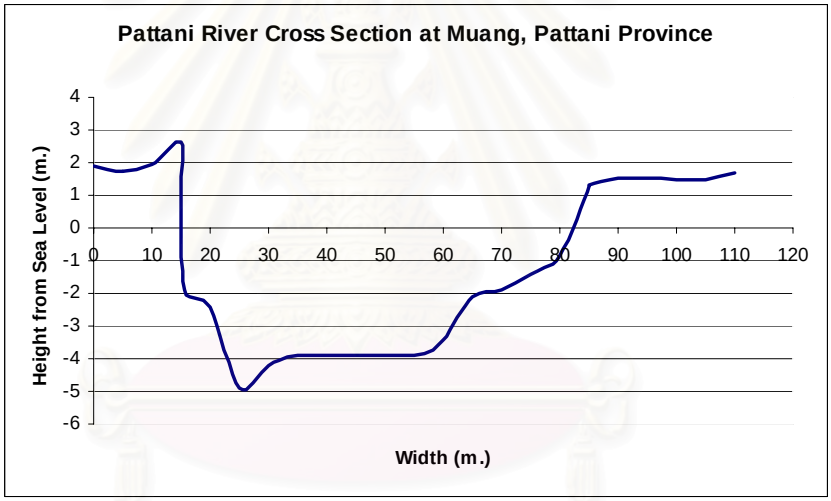

Figure 3.9 Cross Section of the Pattani River at Muang Pattani, Pattani Province (Royal Irrigation Department, 2004)

3.3 CONCEPTUAL MODELING APPROACH

In water quality modeling, waste loading which in this study is the total lead load is put into the river at Yelapun, Bannangsta segment. The observed response is the water quality, or in the other words, the level of total lead concentration in each segment of the river. The relationship between the waste loading and the water quality is investigated by inputting the water column transport variables and the transformation coefficients of the waste. Then, all of the variables and the coefficients will be adjusted until the predicted concentration and observed concentration are in

agreement. The Water Quality Analysis Simulation Program (WASP) Version 6.2 was selected to develop the modeling scenarios in this study. This thesis section will present the temporal condition, factors that affect the modeling, model creation steps, model verification, model calibration and other applicable studies in developing a model.

3.3.1 Temporal Condition

The WASP model can simulate three different temporal conditions; the steady state condition, dynamic condition and quasi-dynamic or quasi steady-state condition.

Steady-state condition

In the steady-state scenario, the concentration of the water quality parameter is constant as a function of time in the system under study.

Dynamic condition

In the dynamic scenario, the time-dependent flows are input. The dynamic model can simulate the flows and loads and predict the water quality. In order to develop a dynamic scenario, the coupling of hydrodynamic and water quality models is required.

A typical study uses the hydrodynamic model first to simulate the hydrological characteristics and save the output for use by the quality model later. However, WASP 6.2 solves that complicated problem by combining two stand-alone computer programs, DYNHYD5 for hydrodynamic simulations and WASP6 for water quality simulation, together. The two models can be run in conjunction or separately. The hydrodynamic program, DYNHYD5, simulates the movement of water while the water quality program, WASP6, simulates the movement and interaction of pollutants within the water column.

Quasi-steady-state condition

In the quasi-steady-state scenario, a dynamic condition of the water quality parameter is simulated with steady-state flows, or the steady-state condition of water quality parameter is simulated with the time-variable flows.

In this study, both the steady state condition and quasi steady state condition were developed. The steady state simulations were used in the model validation step. Simple scenarios were designed with constant flow and water quality parameters to study the model results and to verify the accuracy of the model. Then, the quasi steady state condition was developed with time-variable flows and the constant water quality parameters, such as the sorption and diffusion coefficients, to simulate the lead contamination in the river. Due to the existing information, the daily outflows from the dam and runoff flows were inputted to create the model scenario.

The three categories of temporal conditions are summarized in Table 3.1.

Table 3.1 Summary of Temporal Conditions (Sangsurasak, 2004)

Condition	**Flows**	**Water Quality Parameters**
Steady-State	Constant	Constant
Quasi-Steady State	Constant	Dynamic (Time-variable)
Quasi-Steady State	Time-variable inflows but uniform flows through area	Constant or dynamic
Dynamic State	Time-variable	Time-variable

3.3.2 Principle of Physico-chemical Components on Lead Contamination Analysis

Before developing any of the model scenarios, a conceptual model has to be determined first to identify the reactions involved and parameters used in the model. With regard to the creation of a lead contamination scenario in this study, this section will show how the conceptual model in this research was identified.

Normally, there are three features that separate toxic substances such as lead and other heavy metals, from more conventional pollutants (Thomann, 1987).

1. The tendency for certain chemicals to sorb to particulates in the water body.
2. The tendency for certain chemicals to be concentrated by aquatic organisms and transferred up the food chain.
3. The tendency for certain chemicals to be toxic at relatively low concentrations in water (ug/l or ng/l level).

Due to the general features of the physico-chemical phases of the transport of a toxic substance in the water body, the specification of the inputs of the toxic substance is very important. The inputs include all sources such as municipal and industrial discharges, urban and agricultural runoff, and atmospheric deposition. The physical and chemical phenomena that can be included in the water column and sediment are as follows (Thomann, 1987).

1. Sorption and desorption between dissolved and particulate forms in the water column and sediment.
2. Settling and resuspension of particulates between the sediment and the water column.
3. Diffusive exchange between the sediment and the water column.
4. Loss of the chemical due to biodegradation, volatilization, photolysis, and other chemical and biochemical reactions.
5. Gain of the chemical due to chemical and biochemical reactions.
6. Transport of the toxicant due to advective flow transport and dispersive mixing.

The conceptual model in this study which is shown in Figure 3.10 is based on the properties of lead in the water column. Biodegradation and photolysis are neglected because the degradation and transformation of lead by microbial and photolysis in nature occur at a very low level. Moreover, the vapor pressure that affects the volatilization of lead is very low. So, the volatilization of lead in this scenario is also ignored.

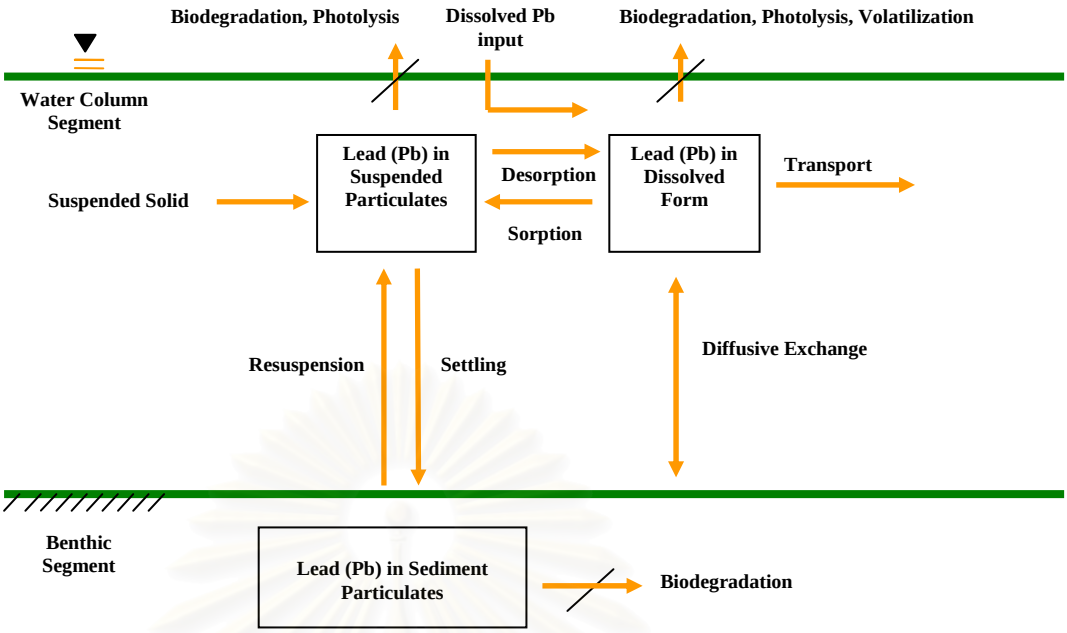

Figure 3.10 The conceptual model of lead contamination in the river (Thomann, 1987)

3.3.3 Model Scenarios

After the conceptual model was created, scenarios can be created by inputting data into the model. Regarding WASP 6.2 requirements, there are twelve sets of data that have to be defined through their menu screens. They are 1) input parameterization, which includes the model type, time range and hydrodynamic type, 2) time step for model execution, 3) print interval time range and scale, 4) segmentation and segment parameters, such as volume, velocity multiplier, velocity exponent, depth multiplier and depth exponent, 5) system data, i.e., the number of chemical and solid types in the system, 6) physical parameter data, 7) constant parameter data such as sorption, biodegradation and volatilization, 8) input waste loading, 9) time functions, 10) exchange fields, which included dispersion and diffusion, 11) flow function setting and 12) input boundary concentration. In this study, the model type that was selected in the input parameterization menu was the sub-model TOXI. The type of sub-model defines the required input parameters and the systems needed for the simulation.

To simulate the scenario of a simple toxicant contamination, such as lead with WASP 6.2, the data of the water column segments, benthic segments, solid transport rates, flow function and transformation parameters have to be input in to the model.

During the simulation, solids and toxicants will be transported both by the water column advection rates and by these solids transport rates.

The model input parameters in the sub-model TOXI can be categorized in four major sections of the preprocessor, which are environmental parameters, transport parameters, boundaries parameters and transformation parameters.

The environmental parameters include segmentation, segment parameters and systems data. These parameters define the basic model identity and control the simulation.

The transport parameters include water column flows, sediment transport velocities, such as settling and resuspension, cross-sectional area, which is the interfacial surface area for adjoining segments where the sediment transport occurs, water column dispersion, and water diffusion coefficients.

The boundary parameters include waste loading, which is used for inputting the total lead loading from the mining area to the first segment of the model and the boundary concentrations, which are used in this study for inputting the total lead concentration from the upstream part of the Pattani dam to simulate the effects in the downstream part of the Pattani dam.

The transformation parameters include all parameters that are involved in the transformation of the chemical during the model's execution. However, because lead is a heavy metal that is quite inert in the environment, most of the reactions can be ignored, so the required transformation parameter in the real scenario of this study is only the sorption coefficient.

3.3.4 Model Validation

The purposes of this section are to study the calculation step of WASP 6.2 and to verify the accuracy of the model execution. The results of the model verification step can be a guideline to developing a real model scenario later.

For verification of the model, the scenarios were constructed with ten segments. The volume of the toxicant was inputted with its decay rate and the conditions that were varied are as follows:

1. Set up the constant steady state flow with an upstream concentration, but no point loading (Figure 3.11).

The objective of this condition is to observe how the WASP 6.2 calculates the distribution of the toxicant from the boundary input of the system without any concern of waste loading.

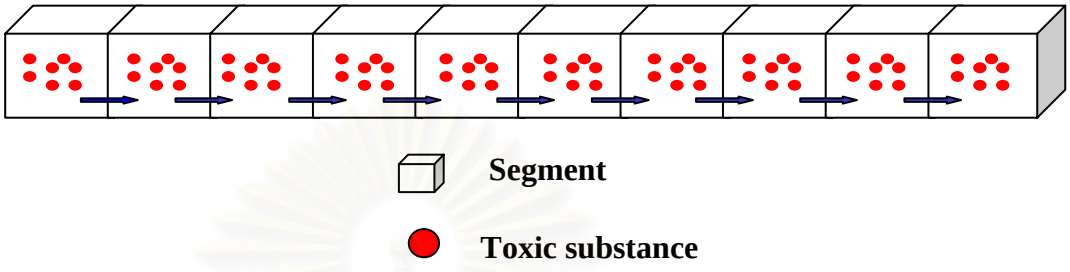

Figure 3.11 Simple Scenario Study Condition 1

2. Input point loading of the chemical with a constant steady-state flow and upstream concentration (Figure 3.12).

The objective of this condition is to observe how the model calculates the distribution of the toxicant when the waste loading was input at some mid-stream segment of the system.

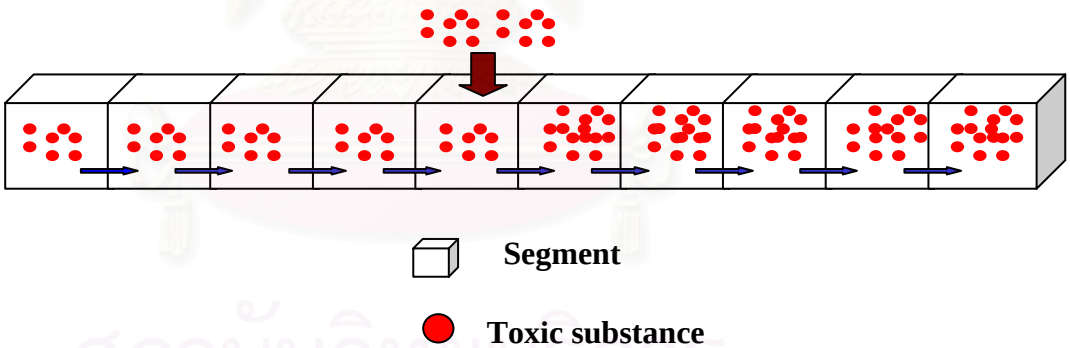

Figure 3.12 Simple Scenario Study Condition 2

3. Set up the constant steady state in the main stream flow with an upstream concentration combined with an additional small tributary flow into segment five (Figure 3.13).

The objective of this condition is to observe how the model calculates the distribution of the toxicant when the waste loading was input from a tributary of a small segment that connects with the main stream.

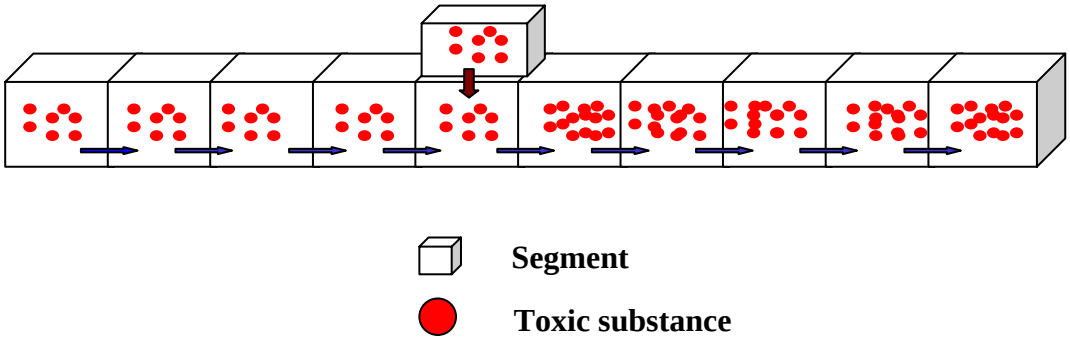

Figure 3.13 Simple Scenario Study Condition 3

4. Set up a constant steady state flow and input the solid into the system (Figure 3.14).

The objective of this condition is to observe how the model calculates the distribution of the solid in the system without any input of the toxicant.

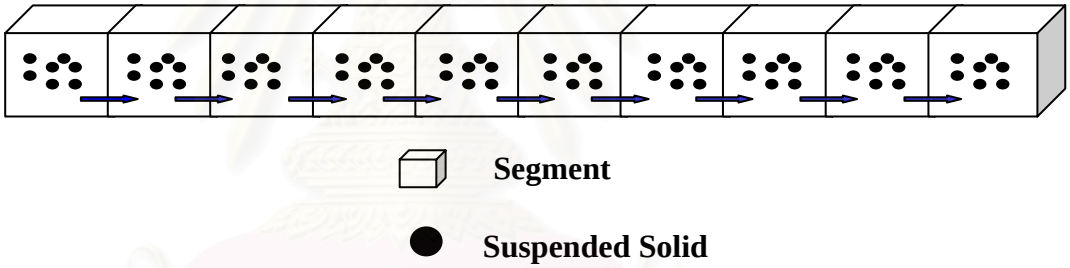

Figure 3.14 Simple Scenario Study Condition 4

For these simple scenarios, an analytical solution is available, which can be compared against the numerical (model execution) results to observe the formation of the model's calculations and the accuracy of the results. The basically analytical equation that was used is shown in equation 3.1 below,

$$C(x) = C_0 e^{-(k.x)/v} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

So,

$$\ln C(x) = \ln C_0 - (k.x)/v \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

Where:

C(x) = Chemical Concentration (mg/l) at distance "x"

C_0 = Initial Chemical Concentration (mg/l)

x = Distance (m)

v = Stream Velocity (m/day)

k = Decay Rate (day^{-1})

3.3.5 Real Scenario Study

After creating the conceptual model and verifying the model's execution, the model is ready to receive the existing data to create a real scenario of lead contamination in the river.

Segmentation and Segment Parameters

With regard to the model's execution, the Pattani River was separated into segments. This process is called segmentation. Figure 3.15 shows the diagram of segmentation of the Pattani River in this study. The required parameters and information of each of the segments were input to the model to create the condition needed to execute the model. There are two types of segments, water segment and benthic segment, which have to be input to the model. The basic information and parameters of each segment in this study are presented in Tables 3.2 and 3.3. Table 3.2 shows the water segment information, while Table 3.3 shows the benthic segment information.

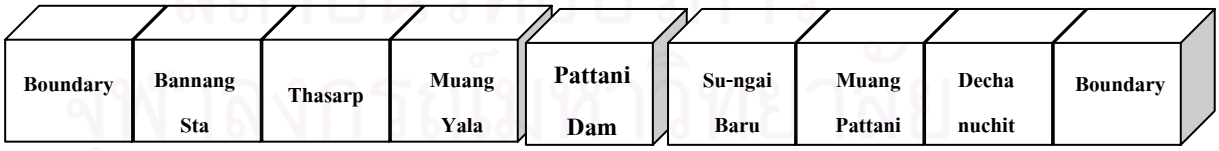

Figure 3.15 Segmentation of the Pattani River

Table 3.2 Water Segment Information

No.	Segment Name	Latitude	Longitude	Cross Sectional area (m^2)	Depth (m)	Volume (m^3)
1	Yelapun Bridge, Bannangsta	6 16' 60.3"	101 17' 52.7"	1435	7	68,880,000
2	Thasarp Bridge	6 33' 15.2"	101 15' 48.9"	1680	8	11,340,000
3	Yala Train Bridge, Muang Yala	6 33' 80.4"	101 17' 55.4"	1680	8	43,680,000
4	Su-ngai baru mosque Bridge	6 44' 13.0"	101 16' 57.6"	590	10	10,325,000
5	Talubo Bridge, Muang Pattani	6 50' 62.5"	101 15' 8.1"	318.5	6.5	1,353,625
6	Dechanuchit Bridge	6 50' 97.8"	101 15' 19.0"	318.5	6.5	1,353,625

Table 3.3 Benthic Segment Information

No.	Segment Name	Top Segment	Distance (m)	Assumed Depth (m)	Top-view Cross Sectional area (m^2)	Volume (m^3)
1	Benthic 1	Yelapun Bridge, Bannangsta	48,000	1	8,640,000	8,640,000
2	Benthic 2	Thasarp Bridge	6,750	1	1,282,500	1,282,500
3	Benthic 3	Yala Train Bridge, Muang Yala	26,000	1	4,940,000	4,940,000
4	Benthic 4	Su-ngai baru mosque Bridge	17,500	1	437,500	437,500
5	Benthic 5	Talubo Bridge, Muang Pattani	4,250	1	119,000	119,000
6	Benthic 6	Dechanuchit Bridge	4,250	1	119,000	119,000

There are two flow functions in this study, which are shown in Table 3.4. Due to the hydrological characteristic of the Pattani River, there are two dams that are located on the river. Banglang Dam is located in the upstream, while the Pattani Dam is located in the middle of the river. These two dams affect the flow of the river. So, the river is separated into two sections, as show in Figure 3.16, which are the upstream and downstream sections of Pattani Dam. The first flow function was used for the upstream segments of the Pattani River, while the second flow function was used for the downstream segments of the Pattani River.

Table 3.4 Flow functions in this model

Flow Function	The order in which the segments were linked to each other
1	Boundary → Bannangsta → Thasarp → Muang Yala → Boundary
2	Boundary → Su-ngai Baru → Muang Pattani → Dechanuchit → Boundary

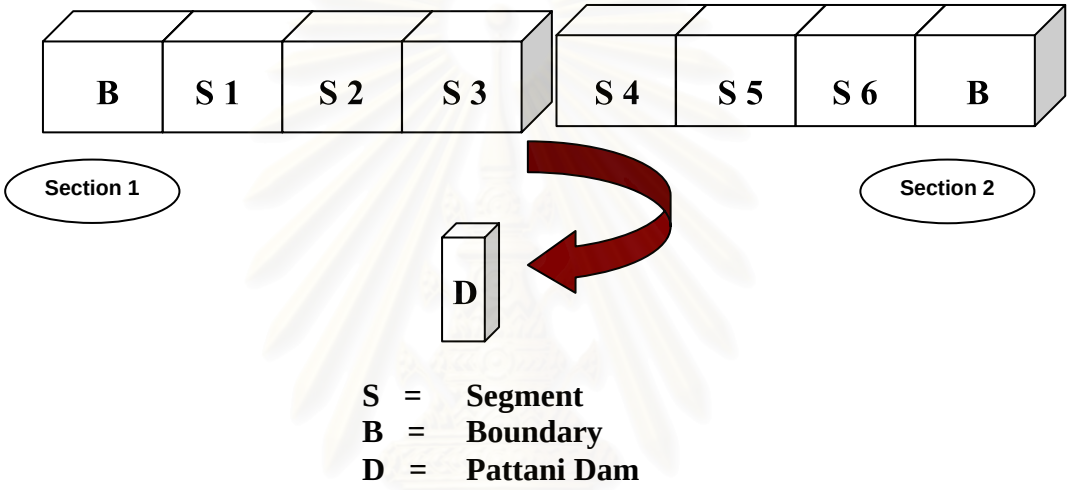

Figure 3.16 Segmentation and Section design of the Pattani River under the model execution of this study

In the first section of the river, three segments were designed, namely S1, S2 and S3. Each segment consists of two parts, which are the water and benthic segments. The loading of lead was inputted at the first segment of this section. The stream flows from the boundary, which is the downstream area of the Banglang Dam, to segments S1, S2, S3 and the end-boundary, which is in the upstream area of the Pattani Dam. Figure 3.17 shows the component, pollutant input and flow diagram of the first section of the Pattani River in this study.

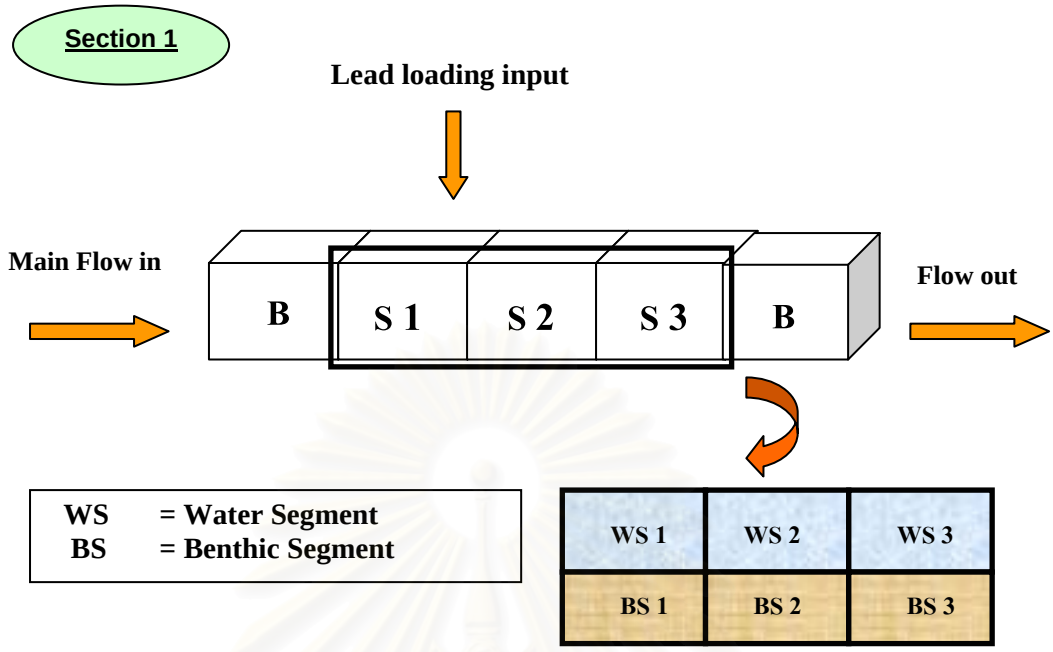

Figure 3.17 Pollutant input and flow diagram of the upstream part of the Pattani Dam

In the second section of the river, three segments were also constructed, S4, S5 and S6. Each of these segments also consists of two parts, the water segment and benthic segment. The boundary concentration of lead, which is the total lead concentration from the calibrated model of section 1, was input into the first segment of this section. The stream flows from the boundary, which is the Pattani Dam, through segments S4, S5, S6 to the end-boundary, which is the estuary of the Pattani River. Figure 3.18 shows the component, pollutant input and flow diagram of the second section of the Pattani River in this study.

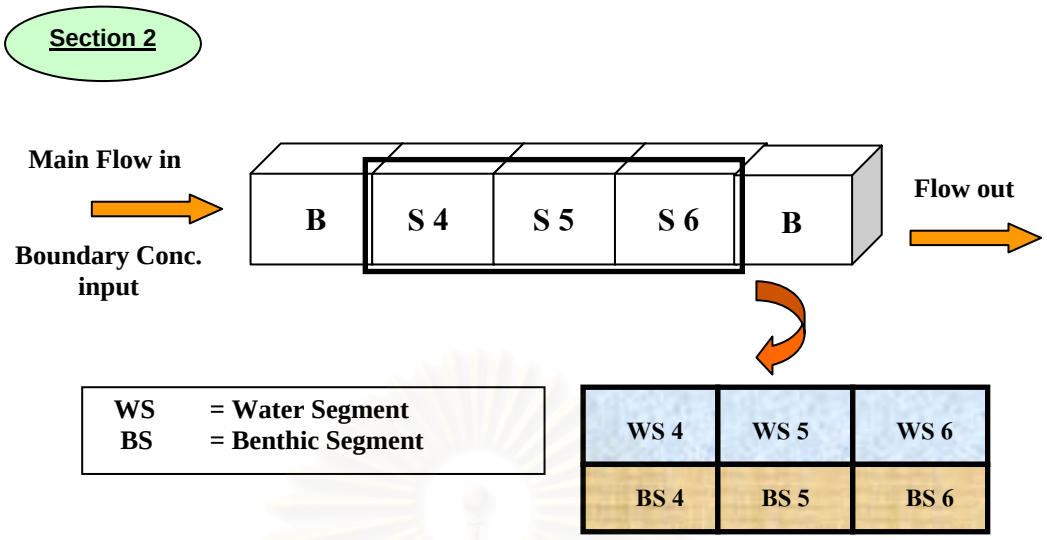

Figure 3.18 Pollutant input and flow diagram of the downstream part of the Pattani Dam

Velocity Multiplier and Velocity Exponent Identification

The velocity multiplier and exponent are also required to be input to the model. From the relation between the velocity and flow, shown in equation 3.3, the velocity multiplier can be identified by plotting the graph between the natural log of the velocity and the natural log of the flow. In this study, the software named FlowMaster, made by Haested Methods, was selected to calculate the velocity and flow; it solves Manning's equation that was presented earlier. The relation between ln V and ln Q of the Pattani River, calculated by the FlowMaster Program, is shown in Figure 3.19. From the graph, the velocity multiplier is 0.1655 and the velocity exponent is 0.2827.

$$V = a Q^{b} \quad \text{..... (3.3)}$$

So,

$$\ln V = \ln a + b \ln Q \quad \text{..... (3.4)}$$

Where:

V = Stream Velocity

Q = Flow

a = Velocity multiplier

b = Velocity exponent

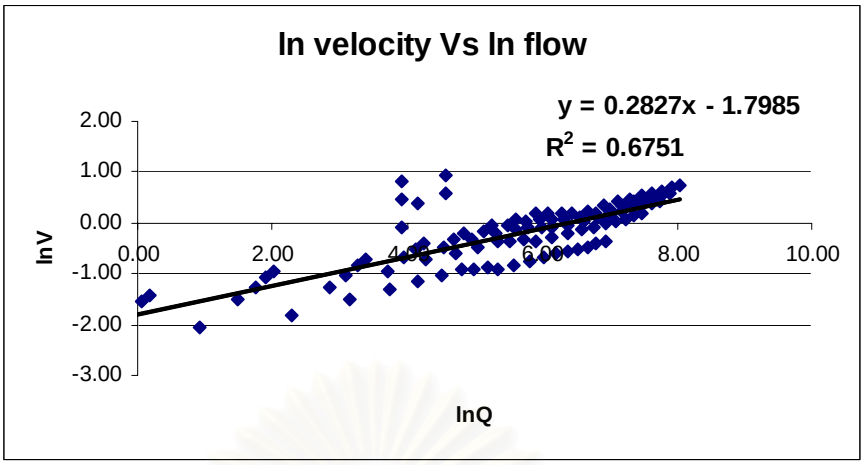

Figure 3.19 The relation between ln V and ln Q of Pattani River calculated by FlowMaster Program

Waste Loading Identification

The loading of total lead that was input into the first segment of the model is important. However, the amount of waste loading can be calculated by a simple mass balance equation. Due to the fact that the flow and total lead concentration in the Bannangsta district, which is located in the first segment of model execution, comes from the downstream area of the Banglang Dam and Klong Namkhun that is connected to a mining area, the waste loading can be calculated by using equations 3.5 and 3.6.

$$Q_t C_t = Q_1C_1 + Q_2C_2 \quad \text{..... (3.5)}$$

So,

$$\text{Waste Loading} = Q_2 \times C_2 \quad \text{..... (3.6)}$$

Where:

Q_t = Flow at Bannangsta segment

C_t = Total lead concentration at Bannangsta segment

Q_1 = Flow at the downstream of Banglang Dam

C_1 = Total lead concentration at the upstream of Bannangsta segment

Q_2 = Flow at Klongnamkhun

C_2 = Total lead concentration at Klongnamkhun

From the calculation, the total lead concentration at Klongnamkhun is 0.0369 mg/l, which close to the number that was found by the Pollution Control Department in 2002. By multiplying the total lead concentration with the flow, the loading of total lead that is input to the Pattani River at Bannangsta district is 142.1676 kg/day.

Partition Coefficient Identification

Due to the transformation of lead in the modeling system, sorption is the only process that was concerned in this study; the partition coefficient is the sorption parameter that is required. The coefficient is the slope of the graph that can be identified by plotting the graph between the total lead concentration in suspended matter and the total lead concentration in water. In this study, the total lead concentration in the Pattani River that was found in 2002 was used to plot the graph. From Figure 3.20, the partition coefficient of lead in Pattani River is 0.1546 l/kg.

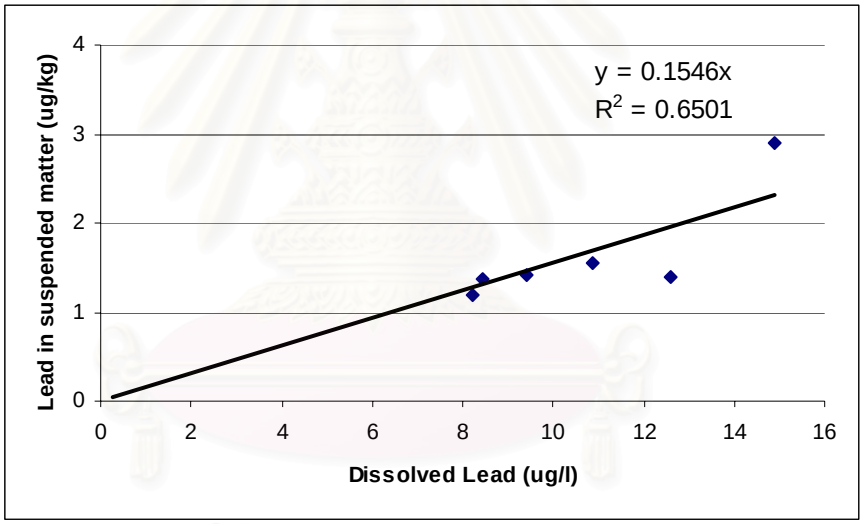

Figure 3.20 The relation between total lead concentration in suspended matter and total lead concentration in water (Pollution Control Department, 2002)

Pore Water Diffusion Coefficient Identification

The pore water diffusion coefficient is the parameter that represents the diffusive exchange between the lead in its dissolved form and the lead in the sediment particulate. In this study, the exact pore water diffusion coefficient of Pattani River was not investigated because of the limited onsite information; instead the coefficient can be identified using Figure 3.21 that shows the relation between the pore water

diffusion coefficients for each percentage of volumetric water content (UFA Ventures Inc., 2004).

By assuming that the porosity is equal to the water content, the porosity can be calculated by equation 3.7. The calculated porosity was multiplied by 100 and assumed as the percentage of water content. After that, the percentage of water content was observed in Figure 3.21 to identify the pore water diffusion coefficient later.

$$n = e / (1+e) \quad \text{..... (3.7)}$$

Where:

n = Porosity

e = Voids ratio

Tables 3.5 and 3.6 show the identification of the pore water coefficient and the value of the pore water diffusion coefficient for each of the segments of this study.

Table 3.5 The identification of the Pore Water Diffusion Coefficient in this study

Sediment Type	**Assumed Void ratio**	**Porosity**	**Water content (%)**	**d (m^2/s) From UFA Ventures**
Coarse Sand	0.4	0.286	28.571	3.36E-10
Sand	0.5	0.333	33.333	4.83E-10
Fine Sand	0.6	0.375	37.500	6.43E-10
Silt	0.7	0.412	41.176	8.09E-10
Clay	1	0.500	50.000	1.31E-09

Table 3.6 Pore Water Diffusion Coefficient for each segment

No.	**Segment Name**	**Assumed Sediment Type**	**d (m^2/s)**
1	Yelapun Bridge, Bannangsta	Sand	4.83E-10
2	Thasarp Bridge	Fine Sand	6.43E-10
3	Yala Train Bridge, Muang Yala	Fine Sand	6.43E-10
4	Su-ngai baru mosque Bridge	Fine Sand	6.43E-10
5	Talubo Bridge, Muang Pattani	Silt	8.09E-10
6	Dechanuchit Bridge	Clay	1.31E-09

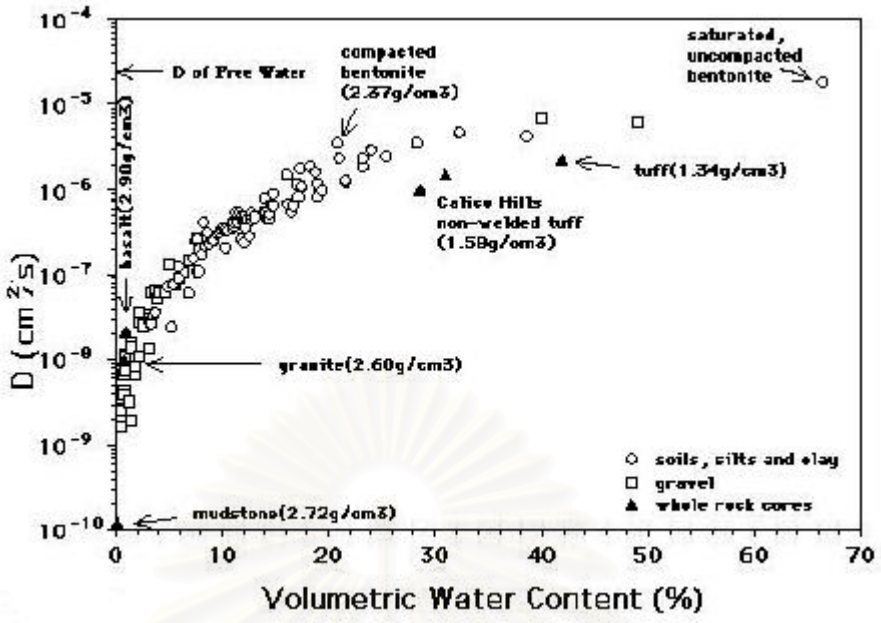

Figure 3.21 Pore Water Diffusion Coefficient for each percentage of Volumetric Water Content (UFA Ventures Inc., 2004)

Boundary Solid Concentration Identification

The solid concentration was input into the model as a boundary solid concentration at the Yelapun, Bannangsta segment and Su-ngaibaru segment, which are the first segment of each part of the model. Due to the investigation of the Pollution Control Department since 1996 to date, the total solid concentration in the Pattani River is varied in the range of 30 – 70 mg/l. Thus, in this study, the boundary solid concentration was assumed at 50 mg/l. The sensitivity of model with this assumption will be presented in the model sensitivity analysis part.

3.3.6 Model Calibration

Model calibration is the process in which the model is executed after inputting a set of data, such as waste loading, flows and transformation parameters. Then, the result of the model's execution, which in this study is the total concentration of lead, is compared with the measured total lead concentration in the Pattani River. If the predicted concentration does not fit reasonably well with the measured concentration, then some interrelated variables of the model will be adjusted within acceptable ranges.

In this study, the output of the model from three segments, which are the Bannangsta district, Muang Yala and Muang Pattani, was calibrated by comparing

model results with previous measurements taken by the Department of Health from 1990–2000 and the Pollution Control Department in 2002. Three statistical parameters, the Root Mean Square Error (RMSE) in equation 3.8, the correlation coefficient (R^2) and Paired Samples T-test, were used for observing the "goodness of fit" between the predicted total lead concentration and the measured concentration.

The RMSE is one of the most widely employed methods of evaluating the differences between the predicted and observed values in modeling. Ideally, the RMSE should be as small as possible.

$$RMSE = [\sum (C_0 - C_p)^2 / N]^{1/2} \quad \text{.....} (3.8)$$

Where:

C_0 = Observed Value

C_p = Predicted Value

N = Numbers of measurement

The correlation coefficient (R^2) is the statistical parameter that shows the correlation between the predicted and observed values in modeling. Normally, an acceptable correlation coefficient should be over 0.6.

A Paired Samples T-test is the statistical testing method that is used to observe the difference of two populations of data at any percentage of confidence. The 2-tailed significance of the Paired Samples T-test is the method that was used to identify whether the difference between the predicted and observed values in modeling have any significance. In this study, the 2-tailed significance was calculated by using the statistical package for the social science (SPSS) version 11.01. If the 2-tailed significance is over 0.05, it can be determined that the simulated and measured total of lead concentrations do not have a significant difference at the confidence of 95 %.

According to the hydrological characteristics of the Pattani River, there are two dams that are located on the river. The Banglang Dam is located upstream, while the Pattani Dam is located in the middle of the river. These two dams affect the flow of the river. So, the river is separated into two parts, which are upstream and downstream of the Pattani Dam. The calibrated output of the total lead concentration from the upstream part is calculated and used as the lead loading of the downstream

part. The lead loading of the downstream part of the Pattani dam is shown in Appendix H.

3.3.7 Model Sensitivity Analysis

The model sensitivity analysis follows model calibration; it is an important part of the process. The sensitivity of the modeling result, when the parameters are varied, gives insight into significant processes. Some parameter values need to be assumed due to limited data; sensitivity studies are particularly useful in assessing this uncertainty.

To observe model sensitivity, the parameters in the calibrated model were varied. Then, the model was re-executed. The predicted total lead concentration was detected and calculated to show the percentage of change. Finally, the percentage of the output change was plotted with the percentage of the parameters change to observe the sensitivity of the model.

In this study, four parameters, the partition coefficient, the boundary solid concentration, the pore water diffusion coefficient and the segment volume, were varied to observe the sensitivity of the predicted number of total lead concentration in the calibrated model.

3.3.8 Application Study: The Model Prediction

The last section of this study is the application study which describes the step when the calibrated model is used to predict the total lead concentration in the Pattani River after the simulation of some remediation scenarios, such as reducing the lead loading at the first segment of model. The objective is to identify the percentage of reduced lead concentration at the source of the contamination to control the level of the lead load that would be released into the upstream section of the river. The cost of each percentages of lead load reducing is also analyzed. The cost analysis information of acid mine drainage treatment with chemicals is based on the study of West Virginia University in 1996 (Skousen, 1996).

Moreover, the effects of the upstream flow and the outflow from the Pattani Dam change on the total lead concentration in the river were also predicted to estimate the percentage of flow increasing that can raise the total lead concentration in the river over the water quality standard.

CHAPTER IV

MODELING RESULTS

This chapter presents the modeling results, including the results of model validation or the simple scenario analysis, model calibration, sensitivity analysis and any application studies. The results of calibration are justified in terms of the goodness of fit by using statistical analysis. The sensitivity of the calibrated model was tested by varying some of the coefficients. Finally the calibrated model was used to predict the effects of waste loading reduction, varying the upstream flow and the changing of the outflow from the Pattani Dam.

4.1 MODELING RESULTS

This section begins with the modeling results of the model validation. With regard to the four simple scenarios, model results were compared to results from the theoretical calculation, i.e., the analytical value. The second part presents the results of model calibration for the real scenario. The goodness of fit is also shown in this part by using three statistical parameters, which are the Root Mean Square Error (RMSE), the Correlation Coefficient (R^2) and 2-tailed significance of Paired Samples T-test. The last part of this section presents the results of the model sensitivity analysis, which is the sensitivity of the model output to varying parameters.

4.1.1 Results of Model Validation

There are four simple conditions that were designed to verify and observe the model accuracy; they are as follows:

Condition 1: Set up the constant steady state flow with an upstream concentration, but no point loading

Condition 2: Point loading of the chemical with a constant steady-state flow and upstream concentration

Condition 3: Set up the constant steady state in the main stream flow with an upstream concentration combined with an additional small tributary flow into segment five

Condition 4: Set up the constant steady state flow and input a solid into the system

The objectives of each condition were already presented in chapter 3. The numerical result, which is the model output, was plotted against the analytical values and is shown in Figures 4.1 to 4.4. As can be seen, the model matches the analytical solution in each of the four scenarios.

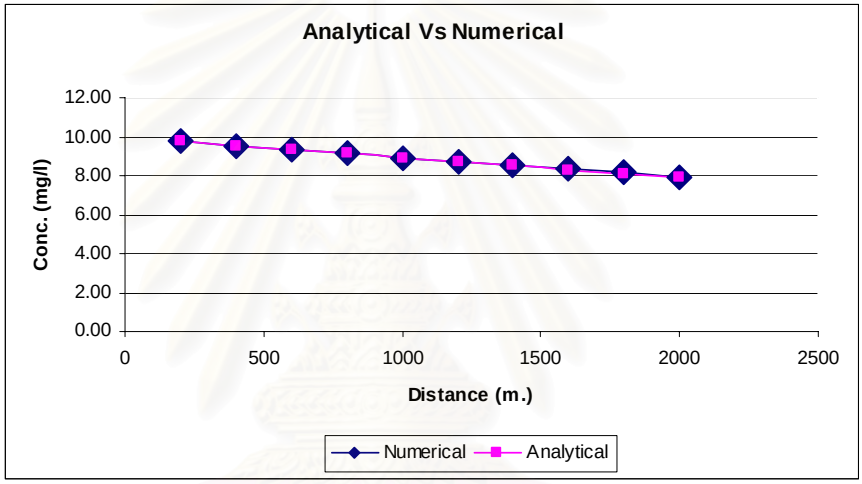

Figure 4.1 The result of model validation under condition 1

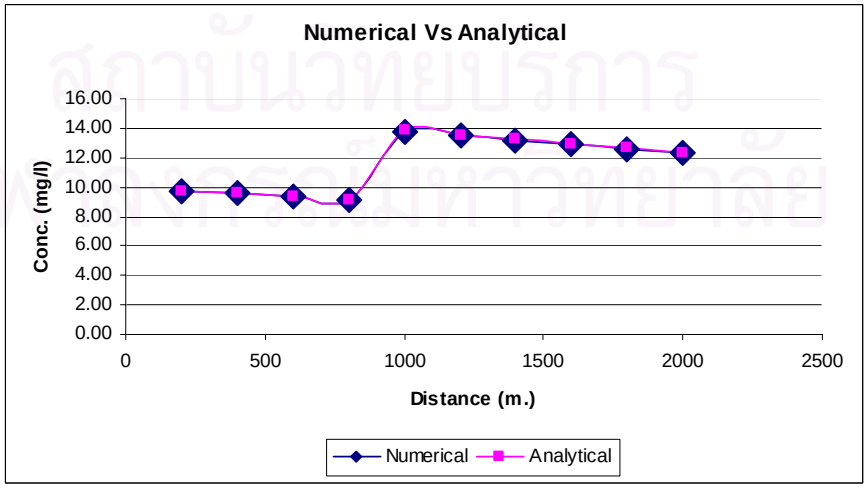

Figure 4.2 The result of model validation under condition 2

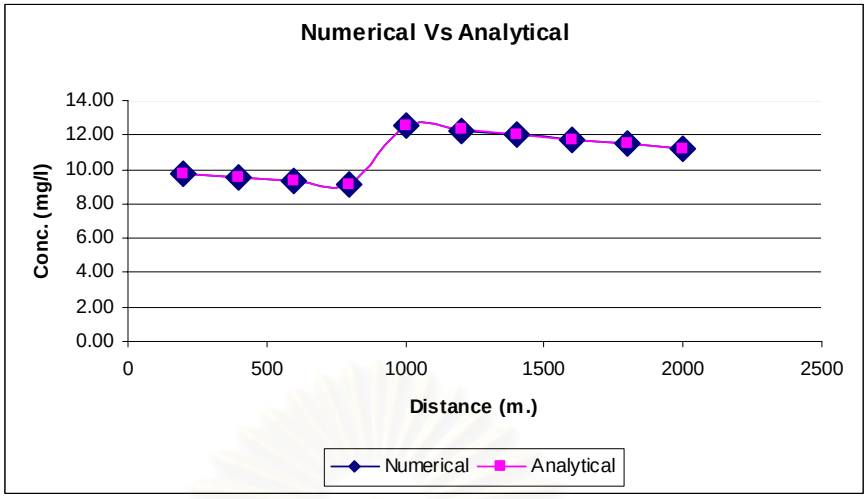

Figure 4.3 The result of model validation under condition 3

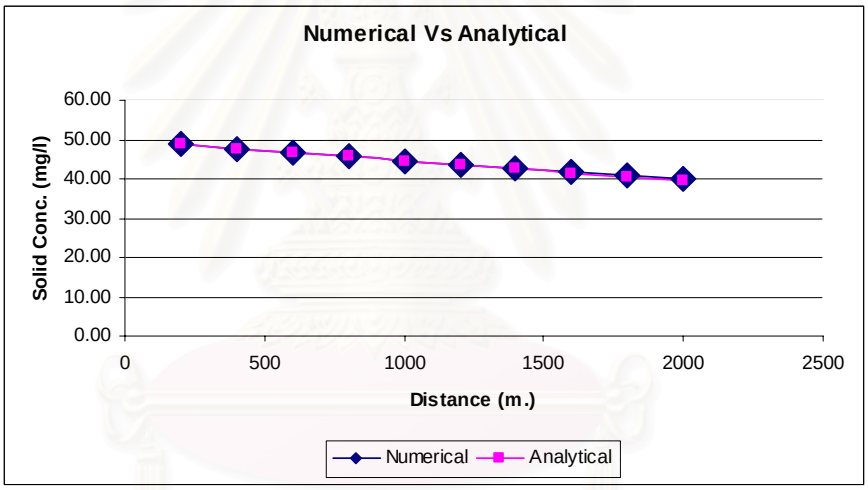

Figure 4.4 The result of model validation under condition 4

4.1.2 Results of Calibration of Total Lead Concentration

After setting up the real scenario, the predicted total lead concentration was calibrated by comparing it with the previous measurements taken by the Department of Health from 1990–2000 and the Pollution Control Department in 2002.

The calibrated results of three of the segments, Bannangsta district and Muang district in Yala province and Muang district in Pattani Province, are shown in Figures 4.5 to 4.7.

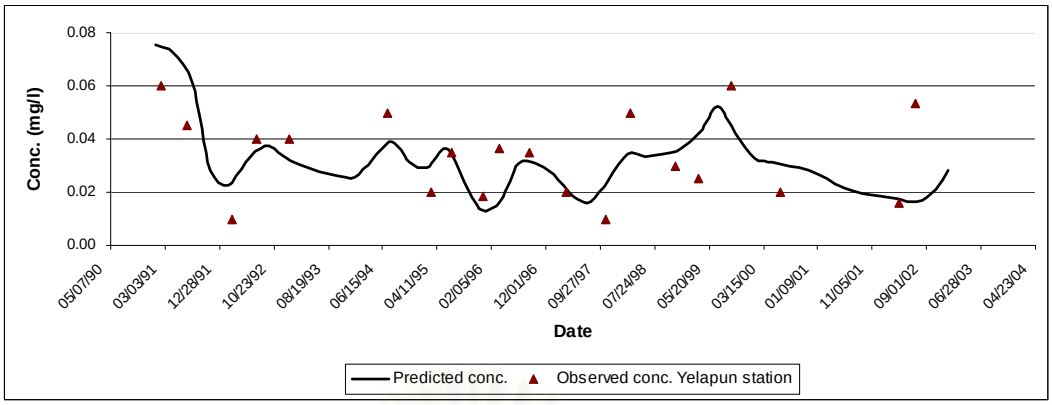

Figure 4.5 Comparison between simulated and measured amounts of total lead concentration in the Pattani River at Bannangsta district, Yala Province

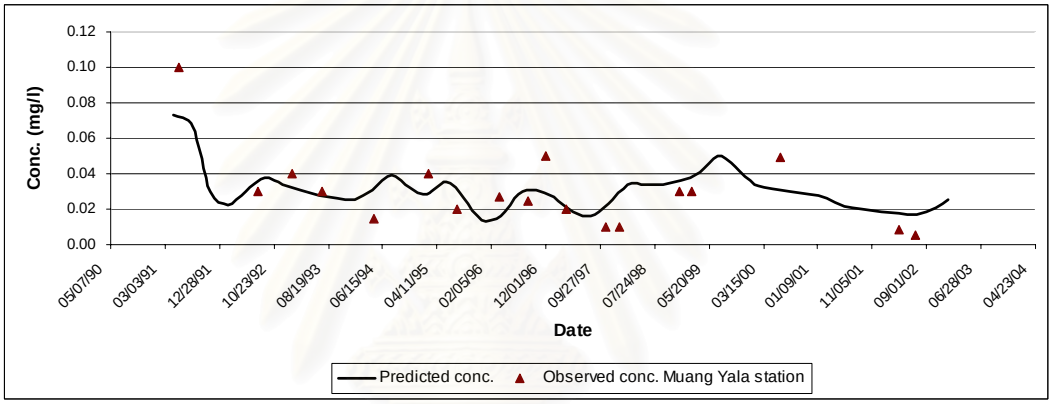

Figure 4.6 Comparison between simulated and measured amounts of total lead concentration in the Pattani River at Muang Yala, Yala Province

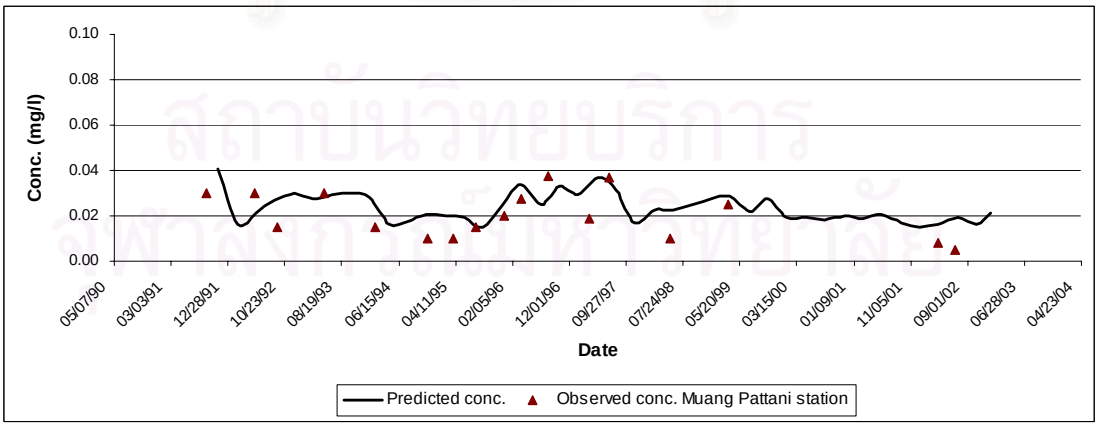

Figure 4.7 Comparison between simulated and measured amounts of total lead concentration in the Pattani River at Muang Pattani, Pattani Province

From calibration, the flows are found to be the major parameter that influences whether the total lead concentration increase or decrease in Figures 4.5 to 4.7. The upstream flows influence the total lead concentration at the upstream part of the Pattani Dam, while the outflows from the Pattani Dam influence the total lead concentration at the downstream part of the dam. Increasing the flow reduces the total lead concentration in the stream at certain segments due to the equation 2.8 in chapter 2 that concentration of the water quality constituent will reduce when the advective velocities increase. Thus, when the flows increase the total lead concentration in the stream will go down. In contrast, when the flows go down the total lead concentration in the stream will go up. Another reason is that the total lead concentrations were decreased because of dilution, i.e., the incoming flow did not have a high concentration of lead, so it diluted the lead concentration that was presented. Both calibrated upstream flows and outflows from the Pattani Dam are shown in Appendix H. The calibrated flows was in the same range of observed flows that was about 20-150 m^3/sec. The root mean square errors (RMSE) of the calibrated upstream flows and outflows from the Pattani Dam were 45.96 and 27.91 m^3/sec. The averages percent change of the calibrated upstream flow and outflow from the Pattani dam were 42 % and 32 %. The comparison between observed and calibrated upstream flow and outflow from the Pattani dam are shown in Figures 4.8 to 4.9.

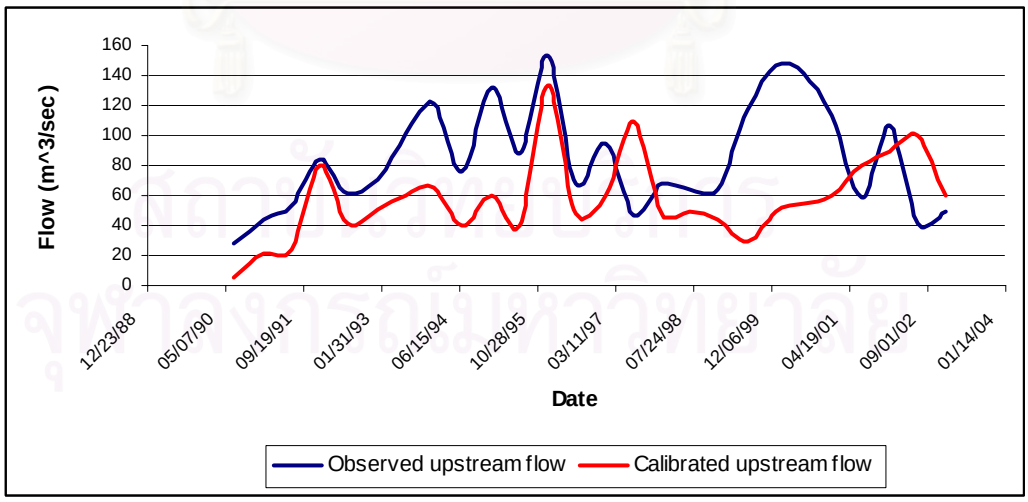

Figure 4.8 Comparison between observed upstream flow and calibrated upstream flow of the Pattani River

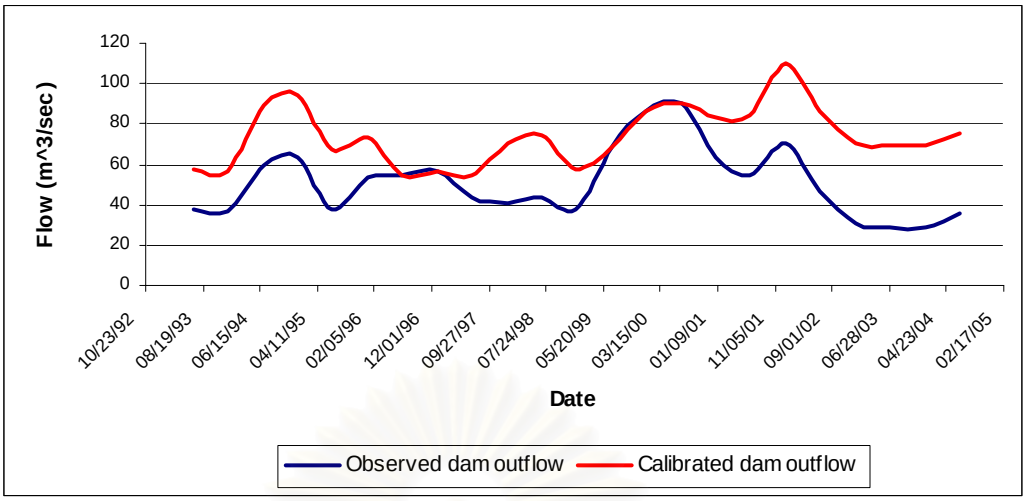

Figure 4.9 Comparison between observed outflow and calibrated outflow of the Pattani Dam

The calibrated values for other significant parameters such as the partition coefficient, the diffusion coefficient and the boundary solid concentration are shown in Table 4.1. From calibration, the calibrated value for partition coefficient was based on the observed information by the Pollution Control Department in 2002, but the value was quite less than that was recommended by U.S. EPA. The recommended partition coefficient for suspended matter/water of U.S. EPA was 0.1754 l/kg (Ambrose, 1999). The calibrated value for diffusion coefficient agreed with the value that was tested in laboratory and recommended by UFA Ventures Inc. in 2004. The calibrated value for boundary solid concentration in the Pattani River was in the range of values that were observed by the Pollution Control Department since 1996 to date.

Table 4.1 The Calibrated Values for Significant Parameters in this study

No.	Segment Name	Partition Coefficient (l/kg)	Diffusion Coefficient (m^2/s)	Boundary Solid Conc. (mg/l)
1	Yelapun, Bannangsta	0.1546	4.83E-10	50
2	Thasarp Bridge	0.1546	6.43E-10	50
3	Train Bridge, Muang Yala	0.1546	6.43E-10	50
4	Su-ngai baru mosque	0.1546	6.43E-10	50
5	Talubo, Muang Pattani	0.1546	8.09E-10	50
6	Dechanuchit Bridge	0.1546	1.31E-09	50

With reference to statistical testing for the calibrated model, the root mean square errors (RMSE) at Bannangsta, Muang Yala and Muang Pattani are 0.0140, 0.0135 and 0.0101, respectively. The 2-tailed significances of the Paired Samples T-test at Bannangsta, Muang Yala and Muang Pattani are 0.8225, 0.8032 and 0.0877, respectively. The 2-tailed significance determined that the simulated and measured total of lead concentration did not have a significant difference at the confidence of 95 %. Finally, the correlation between the simulated and measured amounts of total lead concentration was observed in terms of the correlation coefficient (R^2). The R^2 at Bannangsta, Muang Yala and Muang Pattani segments are 0.6694, 0.6884 and 0.6987 respectively (Figures 4.10 to 4.12).

Table 4.2 Summary of the Results from Statistical Analysis

Segment Name	RMSE (mg/l)	R^2	Sig. (2-tailed)
Yelapun, Bannangsta district	0.0140	0.6694	0.8225
Muang Yala	0.0135	0.6884	0.8032
Talubo, Muang Pattani	0.0101	0.3483	0.0877

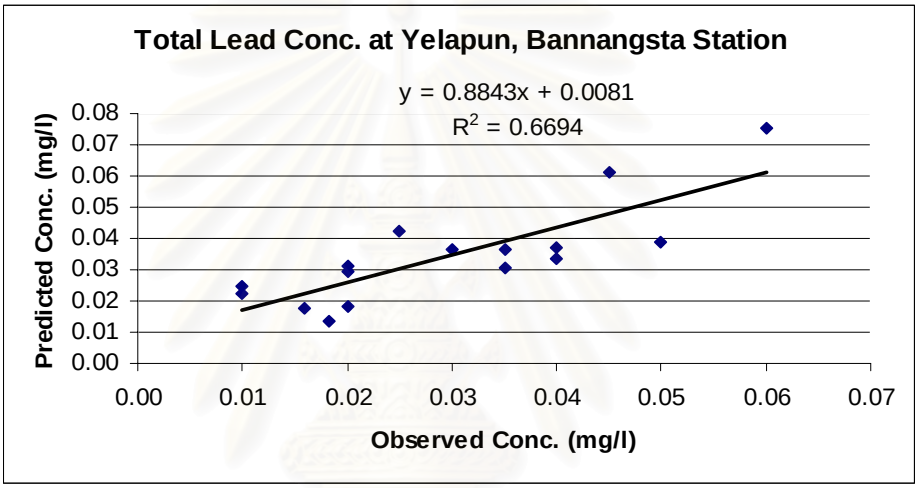

Figure 4.10 The Correlation and R^2 between the simulated and measured total lead concentrations at the Bannangsta district segment, Yala Province

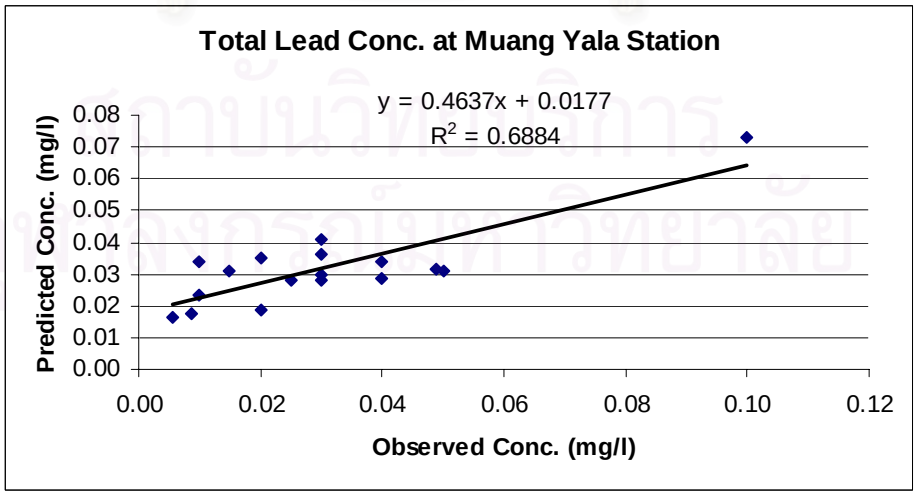

Figure 4.11 The Correlation and R^2 between the simulated and measured total lead concentrations at the Muang Yala segment, Yala Province

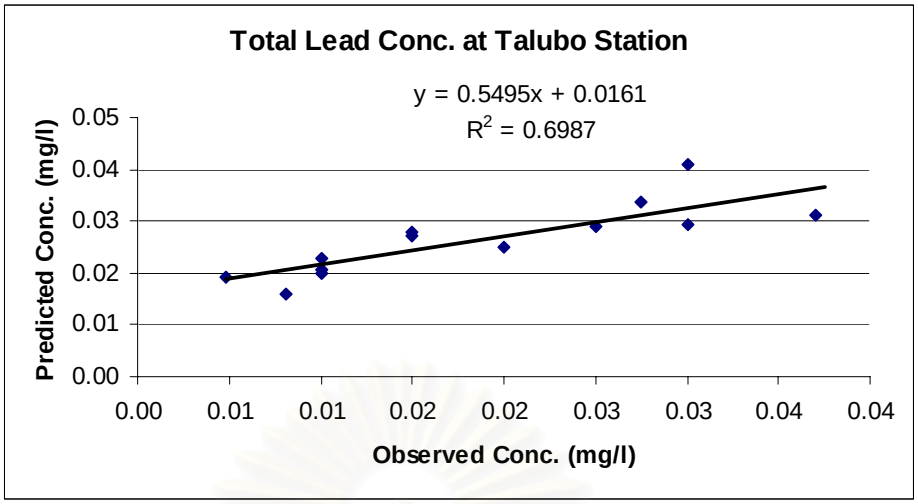

Figure 4.12 The Correlation and R^2 between the simulated and measured total lead concentrations at the Muang Pattani segment, Pattani Province

From Figure 4.10 to 4.12, the correlation was found from a best fit line to the data. At Bannangsta, Muang Yala and Muang Pattani segments. The correlation coefficients are quite high and acceptable at over 0.6 (Hitoshi et al., 2003).

4.1.3 Results of Model Sensitivity Analysis

There are four parameters in this research, the partition coefficient, boundary solid concentration, the diffusion coefficient and the segment volume, which were tested in the sensitivity analysis. The objective of this analysis is to investigate the sensitivity of the model results, in this case, the predicted total lead concentration in the Pattani River, by varying the parameters.

For the sensitivity test of the partition coefficient, the coefficient was varied from -50 % to +3500 %. The predicted total lead concentration at each percentage was observed. Tables 4.3 to 4.5 show the results of the model sensitivity analysis of the partition coefficient at Bannangsta district, Muang Yala and Muang Pattani, respectively. The graphs of each model execution are shown in Appendix F.

Although the range in which the partition coefficient was varied is large, Tables 4.3 to 4.5 show that the percentage change in the predicted total lead concentration is low in every segment of the investigation.

Table 4.3 The Results of Model Sensitivity Analysis through Varying the Partition Coefficient at Yelapun, Bannangsta district, Yala province

Date	% Change in Partition Coefficient	% Change in Predicted Total Lead Concentration
01/10/91	-50 to 3500	0.00198 to -0.14500
07/29/91	-50 to 3500	0.00180 to -0.12100
02/14/92	-50 to 3500	0.00000 to -0.00928
09/01/92	-50 to 3500	0.00054 to -0.04580
12/10/92	-50 to 3500	0.00059 to -0.03740
08/02/94	-50 to 3500	0.00051 to -0.04780
02/18/95	-50 to 3500	0.00034 to -0.02320
05/29/95	-50 to 3500	0.00055 to -0.03780
07/02/96	-50 to 3500	0.00032 to -0.02110
11/14/97	-50 to 3500	0.00000 to -0.00939
02/22/98	-50 to 3500	0.00029 to -0.03420
12/19/98	-50 to 3500	0.00055 to -0.03890
03/29/99	-50 to 3500	0.00071 to -0.05070
10/15/99	-50 to 3500	0.00096 to -0.05760
05/02/00	-50 to 3500	0.00032 to -0.02610
average	**-50 to 3500**	**0.00063 to -0.04396**

Table 4.4 The Results of Model Sensitivity Analysis through Varying the Partition Coefficient at Muang Yala, Yala province

Date	% Change in Partition Coefficient	% Change in Predicted Total Lead Concentration
04/20/91	-50 to 3500	0.00342 to -0.24300
05/24/92	-50 to 3500	0.00067 to -0.04880
12/10/92	-50 to 3500	0.00088 to -0.07010
06/28/93	-50 to 3500	0.00071 to -0.04280
04/24/94	-50 to 3500	0.00064 to -0.05210
02/18/95	-50 to 3500	0.00069 to -0.04270
05/29/95	-50 to 3500	0.00114 to -0.06750
07/02/96	-50 to 3500	0.00071 to -0.03550
10/10/96	-50 to 3500	0.00064 to -0.05330
11/14/97	-50 to 3500	0.00000 to -0.01660
02/22/98	-50 to 3500	0.00088 to -0.06190
12/19/98	-50 to 3500	0.00111 to -0.07080
03/29/99	-50 to 3500	0.00146 to -0.08990
05/02/00	-50 to 3500	0.00064 to -0.04930
average	**-50 to 3500**	**0.00097 to -0.06745**

Table 4.5 The Results of Model Sensitivity Analysis through Varying the Partition Coefficient at Muang Pattani, Pattani province

Date	% Change in Partition Coefficient	% Change in Predicted Total Lead Concentration
11/06/91	-50 to 3500	0.00318 to -0.23479
05/24/92	-50 to 3500	0.00304 to -0.21007
09/01/92	-50 to 3500	0.00160 to -0.12883
06/28/93	-50 to 3500	0.00213 to -0.15392
01/14/94	-50 to 3500	0.00235 to -0.14842
11/10/94	-50 to 3500	0.00062 to -0.04790
02/18/95	-50 to 3500	0.00104 to -0.06026
09/06/95	-50 to 3500	0.00151 to -0.08016
12/15/95	-50 to 3500	0.00281 to -0.17231
03/24/96	-50 to 3500	0.00184 to -0.12486
07/02/96	-50 to 3500	0.00072 to -0.04120
04/28/97	-50 to 3500	0.00158 to -0.08449
08/06/97	-50 to 3500	0.00185 to -0.11495
06/02/98	-50 to 3500	0.00030 to -0.00865
04/02/02	-50 to 3500	0.00057 to -0.04679
07/11/02	-50 to 3500	0.00120 to -0.06135
Average	**-50 to 3500**	**0.00165 to -0.10744**

For the sensitivity test to the boundary solid concentration, the solid concentration was varied from -50 % to +5000 % in Yelapun, Bannangsta district segment and Muang Yala segment. In Talubo, Muang Pattani segment, the solid concentration was varied from -50 % to +500 %. The reason that the solid concentration in this segment cannot be varied over +500 % is that the maximum solid in the benthic segment is limited. So, too high of an input boundary solid concentration will make the solid in benthic segment reach a maximum value and cause an error in model.

The predicted total lead concentration at each percentage was observed. Tables 4.6 to 4.8 show the results of the model sensitivity analysis of the boundary solid concentration at Bannangsta district, Muang Yala and Muang Pattani, respectively. The graphs of each model execution are shown in Appendix F.

Although the range in which the boundary solid concentration was varied is large, Tables 4.6 to 4.8 show the percentage change in the predicted total lead concentration is low in every segment of the investigation.

Table 4.6 The Results of Model Sensitivity Analysis through Varying the Boundary Solid Concentration at Yelapun, Bannangsta district, Yala province

Date	% Change in Boundary Solid Concentration	% Change in Predicted Total Lead Concentration
01/10/91	-50 to 5000	-0.00013 to -0.03454
02/14/92	-50 to 5000	0.00000 to -0.02209
09/01/92	-50 to 5000	-0.00080 to -0.03029
12/10/92	-50 to 5000	0.00059 to -0.02911
08/02/94	-50 to 5000	0.00103 to -0.02983
02/18/95	-50 to 5000	-0.00034 to -0.02758
05/29/95	-50 to 5000	0.00000 to -0.02759
07/02/96	-50 to 5000	0.00000 to -0.02596
11/14/97	-50 to 5000	-0.00041 to -0.02491
02/22/98	-50 to 5000	-0.00029 to -0.02951
12/19/98	-50 to 5000	0.00164 to -0.03120
03/29/99	-50 to 5000	-0.00071 to -0.03134
10/15/99	-50 to 5000	-0.00048 to -0.03394
05/02/00	-50 to 5000	0.00097 to -0.03122
04/02/02	-50 to 5000	-0.00173 to -0.02473
07/11/02	-50 to 5000	-0.00120 to -0.01921
average	**-50 to 5000**	**-0.00012 to -0.02832**

Table 4.7 The Results of Model Sensitivity Analysis through Varying the Boundary Solid Concentration at Muang Yala, Yala province

Date	% Change in Boundary Solid Concentration	% Change in Predicted Total Lead Concentration
04/20/91	-50 to 5000	0.00000 to -0.0396
05/24/92	-50 to 5000	0.00100 to -0.03241
12/10/92	-50 to 5000	0.00000 to -0.03517
06/28/93	-50 to 5000	0.00178 to -0.03385
04/24/94	-50 to 5000	0.00096 to -0.02478
02/18/95	-50 to 5000	0.00000 to -0.03816
05/29/95	-50 to 5000	0.00057 to -0.03932
03/24/96	-50 to 5000	0.00304 to -0.02742
07/02/96	-50 to 5000	0.00070 to -0.03475
10/10/96	-50 to 5000	-0.00032 to -0.03887
04/28/97	-50 to 5000	0.00160 to -0.03585
11/14/97	-50 to 5000	-0.00085 to -0.03500
02/22/98	-50 to 5000	0.00029 to -0.04078
12/19/98	-50 to 5000	-0.00027 to -0.04174
03/29/99	-50 to 5000	0.00000 to -0.04374
05/02/00	-50 to 5000	-0.00127 to -0.03965
04/02/02	-50 to 5000	-0.00229 to -0.03092
07/11/02	-50 to 5000	0.00181 to -0.03440
average	**-50 to 5000**	**0.00032 to -0.03592**

Table 4.8 The Results of Model Sensitivity Analysis through Varying the Boundary Solid Concentration at Muang Pattani, Pattani province

Date	% Change in Boundary Solid Concentration	% Change in Predicted Total Lead Concentration
05/24/92	-50 to 500	-0.00101 to -0.02465
09/01/92	-50 to 500	0.00000 to -0.02138
06/28/93	-50 to 500	-0.00248 to -0.00957
01/14/94	-50 to 500	-0.00195 to -0.01370
02/18/95	-50 to 500	-0.00173 to -0.00519
03/24/96	-50 to 500	0.00061 to -0.01774
07/02/96	-50 to 500	-0.00143 to -0.02651
04/28/97	-50 to 500	-0.00158 to -0.00369
08/06/97	-50 to 500	-0.00370 to -0.02224
06/02/98	-50 to 500	0.00119 to -0.01074
03/29/99	-50 to 500	0.00024 to -0.00219
04/02/02	-50 to 500	0.00228 to -0.00913
07/11/02	-50 to 500	0.00000 to -0.01202
average	**-50 to 500**	**-0.00070 to -0.01459**

For the sensitivity test of the segment volume, the volume was varied from -50 % to +50 %. The predicted total lead concentration at each percentage was observed. Tables 4.9 to 4.11 show the results of the model sensitivity analysis of the segment volume at Bannangsta district, Muang Yala and Muang Pattani, respectively. The graphs of each model execution are shown in Appendix F.

Although the range in which the segment volume was varied is large, Tables 4.9 to 4.11 show that the percentage change in the predicted total lead concentration is low in every segment of the investigation.

Table 4.9 The Results of Model Sensitivity Analysis through Varying the Segment Volume at Yelapun, Bannangsta district, Yala province

Date	% Change in Boundary Solid Concentration	% Change in Predicted Total Lead Concentration
04/14/92	-50 to 50	1.43 to -0.92
02/18/95	-50 to 50	1.21 to -0.73
05/29/95	-50 to 50	2.02 to -1.82
07/02/96	-50 to 50	5.56 to -4.46
11/14/97	-50 to 50	2.79 to -2.44
02/22/98	-50 to 50	0.14 to -0.96
12/19/98	-50 to 50	0.62 to -0.60
03/29/99	-50 to 50	1.94 to -1.68
07/11/02	-50 to 50	0.39 to -0.12
average	**-50 to 50**	**1.79 to -1.52**

Table 4.10 The Results of Model Sensitivity Analysis through Varying the Segment Volume at Muang Yala, Yala province

Date	% Change in Boundary Solid Concentration	% Change in Predicted Total Lead Concentration
05/24/92	-50 to 50	4.91 to -4.13
04/24/94	-50 to 50	3.49 to -3.03
02/18/95	-50 to 50	1.97 to -0.65
05/29/95	-50 to 50	3.56 to -3.10
03/24/96	-50 to 50	3.30 to -2.91
11/14/97	-50 to 50	4.89 to -4.12
02/22/98	-50 to 50	0.75 to -2.84
average	**-50 to 50**	**3.27 to -2.97**

Table 4.11 The Results of Model Sensitivity Analysis through Varying the Segment Volume at Muang Pattani, Pattani province

Date	% Change in Boundary Solid Concentration	% Change in Predicted Total Lead Concentration
05/24/92	-50 to 50	0.30 to -0.31
09/01/92	-50 to 50	0.23 to -0.24
06/28/93	-50 to 50	0.08 to -0.09
10/06/93	-50 to 50	0.03 to -0.03
08/02/94	-50 to 50	0.13 to -0.14
02/18/95	-50 to 50	0.04 to -0.04
12/15/95	-50 to 50	0.35 to -0.37
10/10/96	-50 to 50	0.32 to -0.31
04/28/97	-50 to 50	0.28 to -0.28
06/02/98	-50 to 50	0.01 to -0.01
10/15/99	-50 to 50	0.17 to -0.17
06/06/01	-50 to 50	0.09 to -0.09
07/11/02	-50 to 50	0.12 to -0.11
01/01/03	-50 to 50	0.32 to -0.36
average	**-50 to 50**	**0.18 to -0.18**

For the sensitivity test of the diffusion coefficient, the coefficient was varied from -50 % to $+1\times10^{7}$ %. The predicted total lead concentration at each percentage of variation was observed. Although the coefficient was increased to very high level, no percentage of change in the predicted total lead concentrations was observed. Thus, for the conditions of this problem, the simulation results are not sensitive to the partition coefficient, the boundary solid concentration, the segment volume and the diffusion coefficient. Rather, as stated before, the results are more sensitive to the flows.

4.2 MODEL PREDICTION

After calibrating and testing the "goodness of fit" of the model results, a real scenario was applied to predict the effect of reducing the waste loading at the first segment of the model, which is at Yelapun, Bannangsta district, Yala Province to the total lead concentration in each segment of the Pattani River. The objectives are to simulate the total lead concentration in the river after remediation and identify the percentage the waste loading that should be reduced in order to keep the total lead concentration to a level that is lower than that of the water quality standard.

Another application study is to simulate the effects of varying the upstream flows and the outflows from the Pattani Dam when executing the model in order to predict the total lead concentration in the segments that use the changed flow functions.

4.2.1 Results of Reducing Waste Loading

First, the scenario of waste load reduction was simulated. The waste loading of total lead concentration was reduced incrementally from 10% to 70%. The results of model execution are presented in Figures 4.13 to 4.15.

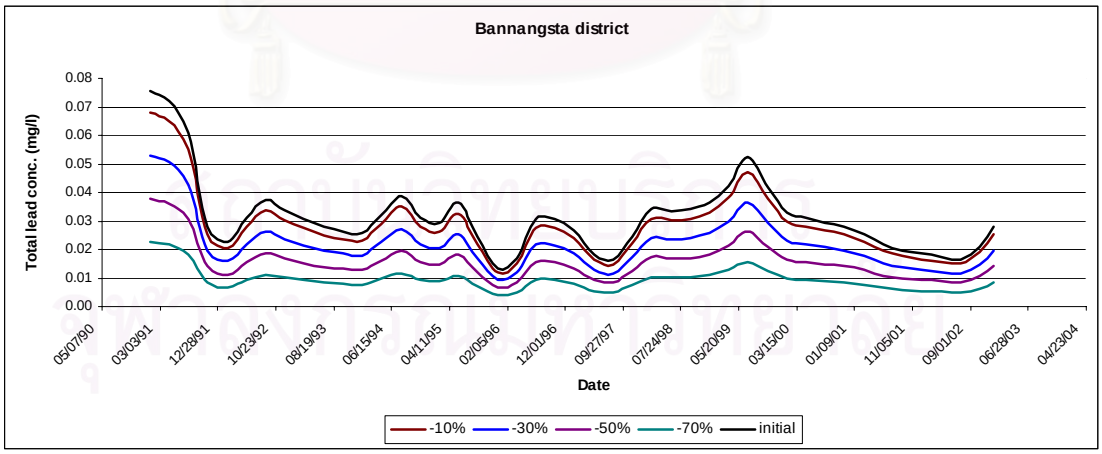

Figure 4.13 The effect of waste loading reduction (%) to the simulated total lead concentrations at the Bannangsta district segment, Yala Province

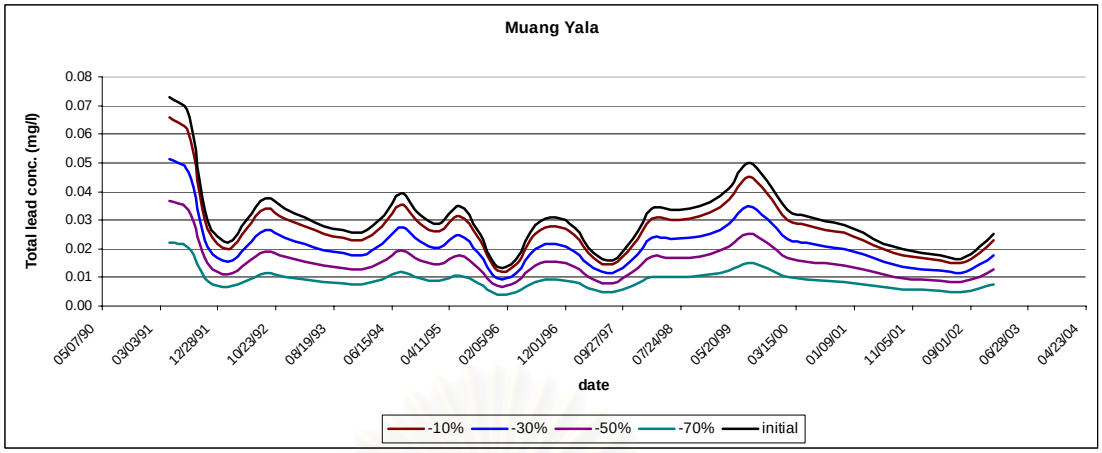

Figure 4.14 The effect of waste loading reduction (%) to the simulated total lead concentrations at the Muang Yala segment, Yala Province

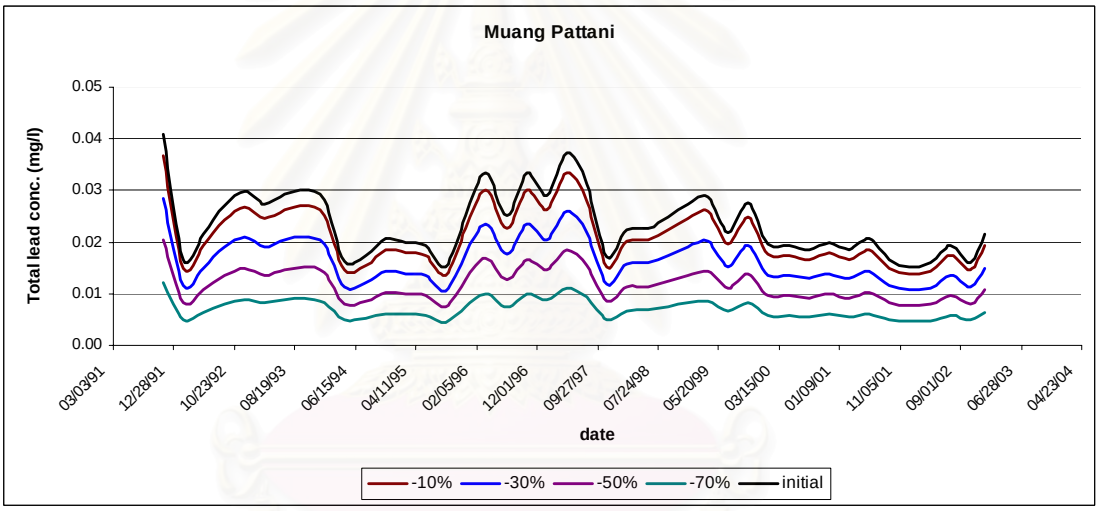

Figure 4.15 The effect of waste loading reducing (%) to the simulated total lead concentrations at the Muang Pattani segment, Pattani Province

From Figure 4.13 to 4.15, it can be seen that the total lead concentrations in the normal situation were not over the water quality standard at 0.05 mg/l. except for early times in Figures 4.13 and 4.14. In the simulation, although the total lead concentrations in the normal situation were not over the water quality standard, the levels of total lead concentrations in some events were quite high and close to surpassing the water quality standard. Thus, the waste loading should be reduced by about 10-30 % to keep the total lead concentration at background levels at about 0.02-0.03 mg/l. The remediation target was to reduce lead loading from 142.17 kg/day to 127.95-99.52 kg/day, reliant upon the desired percentage of reduction. The total lead

concentrations of the stream in the abandoned mine area that should be after the remediation was presented in Table 4.12.

Table 4.12 The percent reduction of lead loading, the numbers of lead loading and the total lead concentrations of the stream in the abandoned mine area for set up the remediation target

The Percent Reduction of Lead Loading	Lead Loading (kg/day)	The Total Lead Concentration of the Stream in the Abandoned Mine Area (mg/l)
0 %	142.17	0.040
10 %	127.95	0.033
20 %	113.73	0.030
30 %	99.52	0.026

4.2.2 Cost Analysis of Acid Mine Drainage Treatment with Chemicals

With regard to the suggested percent reduction of lead loading, the cost for remediation was estimated and based on the cost analysis of acid mine drainage (AMD) treatment with chemicals by the West Virginia University in 1996 (Skousen, 1996). Treatment of AMD includes neutralization and precipitation of lead ions to meet the water quality standard. Enough alkalinity must be added to raise water pH and supply hydroxides (OH^-) or carbonate (CO_3^-) so dissolved lead in the water will form insoluble lead hydroxide ($Pb(OH)_2$) or lead carbonate ($PbCO_3$) and settle out of the water. There are three chemicals, limestone, hydrated lime and caustic soda that were selected to estimate the cost of remediation in this study.

Limestone ($CaCO_3$) has been used for decades to raise pH and precipitate metals in AMD. It has lowest material cost and is the safest and easiest to handle of the AMD chemicals. Unfortunately, its successful application has been limited due to its low solubility and tendency to develop an external coating, or armor, of ferric hydroxide when added to AMD.

Hydrated lime ($Ca(OH)_2$) is a commonly-used chemical for treating AMD. It is sold as a powder that tends to be hydrophobic. Extensive mechanical mixing is

required to disperse it in water. Hydrated lime is particularly useful and cost effective in large flow, high acidity situations where a lime treatment plant with a mixer or aerator is constructed to help disperse and mix the chemical with the water. However, due to the kinetics of lime dissolution and its neutralization increases the volume of unreacted lime that enters the metal floc settling pond.

Caustic soda (NaOH) is often used in remote locations, where electricity is unavailable, and in low flow, high acidity situations. The system can be gravity fed by dripping liquid caustic directly into the AMD. Caustic is very soluble in water, disperses rapidly, and raises the pH of the water quickly. Caustic should be applied at the surface of ponded water because the chemical is denser than water and sinks. The major disadvantages of using liquid caustic for AMD treatment are high cost and dangers in handling.

The information of technical and economic factors for three primary chemicals that have been used to treat AMD was presented in Table 4.13 (Skousen, 1996).

Table 4.13 Chemical compounds used in AMD treatment

Common Name	**Chemical Name**	**Formula**	**Conversion Factor**	**Neutralization Efficiency[1]**	**Cost ($) per ton of chemical**
Limestone	Calcium carbonate	$CaCO_3$	1	30 %	$ 10
Hydrated lime	Calcium hydroxide	$Ca(OH)_2$	0.74	90 %	$ 60
Caustic soda	Sodium hydroxide	NaOH	0.8	100 %	$ 680

[1]Neutralization efficiency estimates the relative effectiveness of the chemical in neutralizing AMD acidity. For example, if 100 tons of acid/year was the amount of acid to be neutralized, then it can be estimated that 82 tons of hydrated lime would be needed to neutralize the acidity in the water ((100*0.74)/0.90).

The chemical costs at each percentage of lead load reducing were estimated and presented in Tables 4.14 to 4.16.

Table 4.14 The chemical cost at 10 % of lead load reducing

Chemical Name	Chemical Needed (tons/year)	Chemical Cost ($/tons)	Chemical Cost ($)	Chemical Cost (Baht)[1]
Limestone	17.30	10	173.01	6,766.42
Hydrated lime	4.27	60	256.05	10,014.30
Caustic soda	4.15	680	2,823.52	110,427.99

Table 4.15 The chemical cost at 20 % of lead load reducing

Chemical Name	Chemical Needed (tons/year)	Chemical Cost ($/tons)	Chemical Cost ($)	Chemical Cost (Baht)[1]
Limestone	34.60	10	346.02	13,532.84
Hydrated lime	8.54	60	512.11	20,028.61
Caustic soda	8.30	680	5,647.05	220,855.98

Table 4.16 The chemical cost at 30 % of lead load reducing

Chemical Name	Chemical Needed (tons/year)	Chemical Cost ($/tons)	Chemical Cost ($)	Chemical Cost (Baht)[1]
Limestone	51.89	10	518.91	20,294.50
Hydrated lime	12.80	60	767.98	30,035.87
Caustic soda	12.45	680	8,468.58	331,206.32

[1]Chemical Cost (Baht) was calculated with exchange rates at 39.11 Baht/ $

From Table 4.13 to 4.16, Limestone provided a lowest chemical cost but had a lowest efficiency in remediation. Caustic soda had a highest efficiency in remediation but provided a highest cost. Thus, hydrated lime was the best choice that should be used for remediation because it provided high efficiency in remediation at 90 % and quite low cost. The total costs of remediation by using hydrated lime at each percentage of lead load reducing for five years of the operation were presented in Table 4.17.

Table 4.17 The total costs of lead load reducing by using hydrated lime

Reduction of Lead Loading	**Chemical Cost ($)**	**Repair Cost ($)**	**Labor Cost ($)**	**Electricity Cost ($)**	**Installation Cost ($)**	**Total Cost ($)**	**Total Cost (Baht)[1]**
10 %	1,280.27	15,500	56,160	55,000	102,000	229,940	8,992,964
20 %	2,560.55	15,500	56,160	55,000	102,000	231,221	9,043,036
30 %	3,839.92	15,500	56,160	55,000	102,000	232,500	9,093,072

[1]Total Cost (Baht) was calculated with exchange rates at 39.11 Baht/ $

From Table 4.17, the total costs of neutralization at each percentage of lead load reducing by using hydrated lime was not much difference. Thus, the recommendation is that the highest percent reduction of lead loading, 30 % should be selected.

To remediate acid mine drainage onsite by using hydrated lime, the channel should be constructed to connect the water treatment plant with the pit that plenty of acidic water and the contaminated tributary. In the plant, the extensive mechanical mixing is required to disperse hydrated lime in water. A lime treatment plant with a mixer or aerator has to be constructed to help disperse and mix the chemical with the water. However, due to the kinetics of lime dissolution and its neutralization increases the volume of unreacted lime; the settling pond is needed in order to settle the metal

floc into the pond. The effluent from water treatment plant has to be monitored the quality, especially the level of total lead and other metals before releasing into the Pattani river.

4.2.3 Results of Varying the Upstream Flows

Second, the scenarios of upstream flow variations were simulated. The upstream flows were varied from -40% to +40%. The condition to increase the upstream flow was used to simulate the total lead concentration by the effect of rainy season, while the condition to decrease the upstream flow was used to simulate the total lead concentration by the effect of dry season. The results of model execution at the Bannangsta district segment and Muang Yala segment, Yala Province were observed and presented in Figures 4.16 to 4.17.

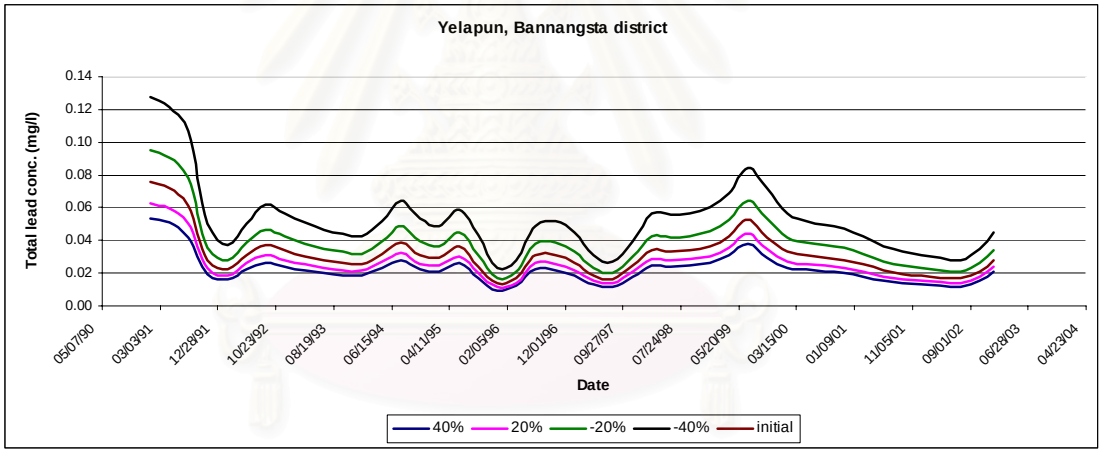

Figure 4.16 The effect of the varying upstream flow to the simulated total lead concentrations at the Bannangsta district segment, Yala Province

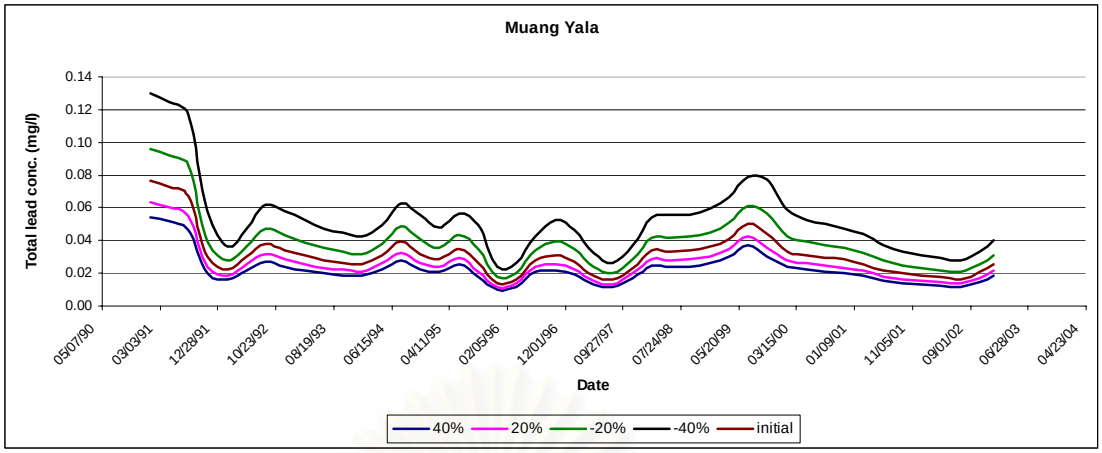

Figure 4.17 The effect of the varying upstream flow to the simulated total lead concentrations at the Muang Yala segment, Yala Province

From Figure 4.16 and 4.17**,** varying the upstream flow affects the total lead concentration in the river, especially reducing the upstream flow. Reducing the upstream flow increases the total lead concentration at Bannangsta and Muang Yala segments. A 40 % reduction of upstream flow can raise the total lead concentration in the river above the water quality standard, 0.05 mg/l. Thus, the level of upstream flow reducing in the Pattani River has to be of concern, especially in the low flows or dry season.

In addition, from this application study, the result can be applied to be an optional of the remediation. A 40 % increasing of upstream flow can keep the total lead concentration in the river in the background level, 0.02 – 0.03 mg/l. However, the cost for increasing the flow might be higher than the cost for reducing lead load by using neutralization process with the chemical.

4.2.4 Results of Varying the Outflow from the Pattani Dam

Third, the scenario of varied outflows from the Pattani Dam was simulated. The outflows were varied from -20% to 60%. The condition to increase the outflow from the Pattani dam was used to simulate the total lead concentration in the Pattani river by the effect of dam operation in rainy season, while the condition to decrease the outflow from the Pattani dam was used to simulate the total lead concentration in the river by the effect of dam operation in dry season. The results of model execution

at the Talubo Bridge segment, Muang Pattani, Pattani Province were observed and presented in Figure 4.18.

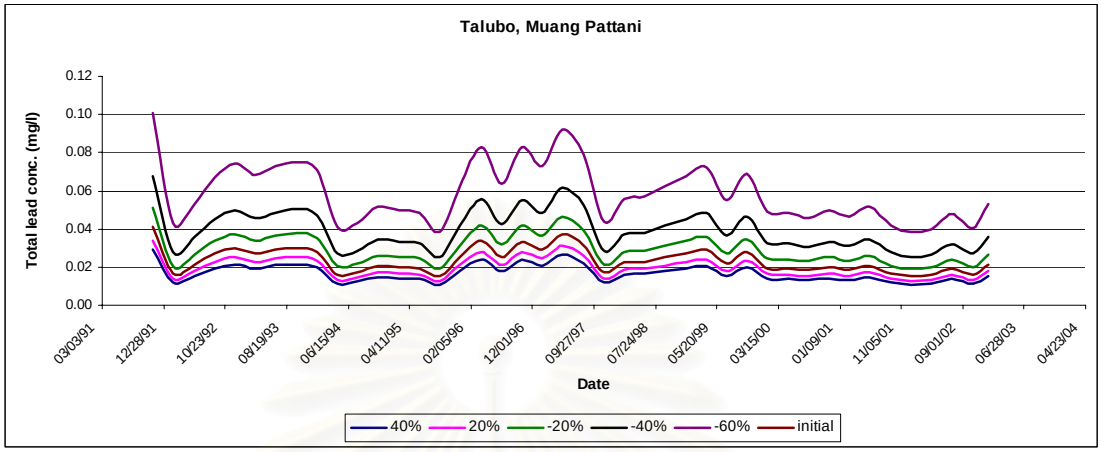

Figure 4.18 The effect of varying the outflow from the Pattani Dam to the simulated total lead concentrations at the Muang Pattani segment, Pattani Province

From Figure 4.18**,** reducing the outflow also affects the total lead concentration in the river. Reducing the outflow increases the total lead concentration at Muang Pattani segments. A 60 % reduction of outflow from the Pattani dam can raise the total lead concentration in the river above the water quality standard, 0.05 mg/l. Thus, the level of outflow reducing from the dam operation has to be of concern, especially in the low flows or hot season.

4.3 RESEARCH LIMITATIONS

1) For the six segments of model execution in this study, there were only 3 segments with which to calibrate the total lead concentration because of the limitation of the total lead concentration that was observed by agencies over the past ten years.
2) The scenarios did not cover the diffusion of lead into the groundwater system due to a limitation of information. However, the distribution of lead in the groundwater system should be very low because the rock type in the abandoned mines area, which is the area of contamination, is $CaCO_3$ that can precipitate lead in the form of $PbCO_3$. Moreover, the liner of the pit in the abandoned mine area, which is the main source of the contamination in the

surface water, is hard rock, so the possibly of contamination to the groundwater is low.

3) The model execution in this study did not cover the area of the estuary or its tidal influence at Pattani Bay due to the limited information on the sea level. So, the decision was made against simulating the contamination in that area since the lack of necessary information could adversely affect the model's execution.
4) There are some field parameters that were assumed due to the limited information. The solids concentration and suspended solid density were assumed constant for all segments. The upstream flows were assumed as time-variable flows but uniform flows through the stream segments one to three in the upstream of the Pattani Dam, while the outflows from the Pattani Dam were assumed as time-variable flows but uniform flows through the stream segments four to six in the downstream of the Pattani Dam .
5) The volume of water segments in this study was assumed constant due to the limited information of the river's cross section. Actually, the volume of segments should increase every year due to the erosion of river's bank. However, the sensitivity of model result by the varying of segment volume was also investigated in this study.

4.4 RECOMMENDATIONS

1) With regard to the application study of the model for investigate the proper technique to remediate the surface water in the abandoned mine area, although to reduce lead load and to increase the water flow provided the same result in the reducing of total lead contamination in the river but the reduction of lead load is more proper than increasing the flow due to the efficiency of remediation and the economic reason. The cost for reduce lead loading in water by neutralization with chemical should be more less than constructing the dam or water gate to increase the flow. Moreover, reducing lead loading can solve long term problem because if the choice of increasing the flow is selected, lead will transport from abandoned mine area to the downstream by

the effect of flow and accumulate somewhere such as at the Pattani Dam or the Estuary of Pattani river.

2) The percent of lead load reduction that should be selected is 30 % due to the cost analysis study.

3) The reagent that should be used for neutralizing water pH and precipitating lead in the river is hydrated lime due to the cost analysis study.

4) The government section that responsible in remediation and public welfare of people should provide new water source for people who live in Bannangsta district, Yala province because the surface water quality is not proper for drinking or consuming. Moreover, the groundwater quality in Bannagsta district should be observed and monitored to ensure that lead and other heavy metals did not pollute into groundwater system.

5) Although, the calibrated model from this study can be applied to simulate the effect of waste loading reducing effectively. However, more measurements are required in order to verify the accuracy and predictability of the present modeling results. For further study, it should have more stations in order to observe the surface water quality and river's cross sections. More observed stations can provide more information for designing a model, especially for designing more segments. Moreover, the sample of sediment from the Pattani River should be collected and investigated the total lead concentration that accumulated in the benthic of river.

CHAPTER V

CONCLUSIONS

As a preliminary step in this research, a simple scenario simulation and analysis confirmed that the Water Quality Analysis Simulation Program (WASP) version 6.2 provides highly accurate results. The graphs between the numerical calculation and analytical calculation for all four conditions showed very good fits. Moreover, the process of obtaining results from this preliminary study provided understanding of the model and methods for inputting and creating more complicated scenarios.

The objective of this study which is to investigate the ability of the Water Quality Analysis Simulation Program version 6.2 to predict the concentration of total lead in the Pattani River, was met through the simulation of lead contamination in the Pattani River from 1990-2002.

With regard to the graphs that presented the total lead concentration in the Pattani River, the total lead in the river during 1990-2002 ranged in concentration from 0.02-0.05 mg/l. The concentration was most sensitive to the stream flows at that time.

The predicted concentration was compared with observed concentrations that were taken by the Department of Health from 1990–2000 and the Pollution Control Department in 2002. The first statistical parameter that was selected for calibrating the model, the root mean square error (RMSE), showed that errors were approximately 0.014 mg/l. The results of the Paired Samples T-test did not present any significance of difference between the predicted and observed concentrations. Furthermore, a strong correlation between the predicted and observed concentrations was observed at three segments of calibration, at Bannangsta district and Muang district of Yala province, and Muang district of Pattani province.

The sensitivity of the model's results was tested by varying three parameters: the partition coefficient, boundary solid concentration and diffusion coefficient. The results indicated that under the conditions of this problem, the simulation results were not sensitive to the partition coefficient, the boundary solid concentration and the diffusion coefficient. The results can also be used to conclude that advection, as determined by the total flow rate, is the most influential process that affects the

distribution of total lead in the river, while other processes and transformations have low impacts to the distribution.

Altogether, through this real scenario simulation, it was found that the model can predict observed concentrations within reason, as measured by statistical analyses, and thus it can be used in other application studies.

The next objective of this study was to simulate a scenario for reducing the total lead concentration in the river. This objective was met through the simulation of a reduction of the lead loading in the Pattani River from 1990-2002. In the simulation, although the total lead concentrations in the normal situation were not over the water quality standard at 0.05 mg/l, the levels of total lead concentrations in some events were quite high and close to surpassing the water quality standard. Thus, the waste loading should be reduced by about 10-30 % to keep the total lead concentration at background levels. The remediation target was to reduce lead loading from 142.17 kg/day to 127.95-99.52 kg/day, reliant upon the desired percentage of reduction.

In a subsequent application study, the effect of varying the upstream flow on the simulated total lead concentrations was also observed. Reducing the upstream flow was found to increase the total lead concentrations at the Bannangsta and Muang Yala segments. A 40 % reduction of the upstream flow raised the total lead concentration in the river above the water quality standard of 0.05 mg/l. In addition, reducing the outflow of the Pattani Dam was found to increase the total lead concentration at Muang Pattani segments. A 60 % reduction of outflow raised the total lead concentration in the river above the water quality standard. Thus, reducing the level of the upstream flow of the Pattani River has to be of concern, especially in the low-flow or dry season.

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APPENDICES

APPENDIX A

FLOWS DATA OF THE PATTANI RIVER

Flows data of the Pattani River at each segments (Royal Irrigation Department, 1996-2002)

Station name	Date	Flows (MCM/month)	Flows (MCM/day)	Flows (m^3/sec)
Bannangsta	01/31/96	77.38	2.58	29.85
Bannangsta	02/28/96	101.03	3.37	38.98
Bannangsta	03/31/96	112.8	3.76	43.52
Bannangsta	04/31/96	71.57	2.39	27.61
Bannangsta	05/31/96	270.63	9.02	104.41
Bannangsta	06/31/96	224.8	7.49	86.73
Bannangsta	07/31/96	187.89	6.26	72.49
Bannangsta	08/31/96	226.56	7.55	87.41
Bannangsta	09/31/96	245.63	8.19	94.76
Bannangsta	10/31/96	215.88	7.20	83.29
Bannangsta	11/31/96	140.42	4.68	54.17
Bannangsta	12/31/96	147.17	4.91	56.78
Bannangsta	01/31/97	81.81	2.73	31.56
Bannangsta	02/31/97	50.53	1.68	19.49
Bannangsta	03/31/97	82.43	2.75	31.80
Bannangsta	04/31/97	77.02	2.57	29.71
Bannangsta	05/31/97	118.52	3.95	45.73
Bannangsta	06/31/97	76.76	2.56	29.61
Bannangsta	07/31/97	50.45	1.68	19.46
Bannangsta	08/31/97	68.71	2.29	26.51
Bannangsta	09/31/97	117.32	3.91	45.26
Bannangsta	10/31/97	112.95	3.77	43.58
Bannangsta	11/31/97	64.41	2.15	24.85
Bannangsta	12/31/97	226.23	7.54	87.28
Bannangsta	01/31/98	133.29	4.44	51.42
Bannangsta	02/31/98	164.28	5.48	63.38
Bannangsta	03/31/98	185.67	6.19	71.63
Bannangsta	04/31/98	153.63	5.12	59.27
Bannangsta	05/31/98	95.68	3.19	36.91
Bannangsta	06/31/98	124.85	4.16	48.17
Bannangsta	07/31/98	93.96	3.13	36.25
Bannangsta	08/31/98	103.44	3.45	39.91
Bannangsta	09/31/98	103.48	3.45	39.92
Bannangsta	10/31/98	101.64	3.39	39.21
Bannangsta	11/31/98	81.23	2.71	31.34
Bannangsta	12/31/98	108.38	3.61	41.81
Bannangsta	01/31/99	474.6	15.82	183.10
Bannangsta	02/31/99	165.68	5.52	63.92
Bannangsta	03/31/99	112.38	3.75	43.36
Bannangsta	04/31/99	352.78	11.76	136.10
Bannangsta	05/31/99	397.4	13.25	153.32

Flows data of the Pattani River at each segments (cont.)

Bannangsta	06/31/99	162.53	5.42	62.70
Bannangsta	07/31/99	190.46	6.35	73.48
Bannangsta	08/31/99	305.42	10.18	117.83
Bannangsta	09/31/99	224.74	7.49	86.71
Bannangsta	10/31/99	259.6	8.65	100.15
Bannangsta	11/31/99	361.98	12.07	139.65
Bannangsta	12/31/99	560.51	18.68	216.25
Bannangsta	01/31/00	271.91	9.06	104.90
Bannangsta	02/31/00	200.54	6.68	77.37
Bannangsta	03/31/00	131.79	4.39	50.84
Bannangsta	04/31/00	472.82	15.76	182.42
Bannangsta	05/31/00	446.03	14.87	172.08
Bannangsta	06/31/00	373.64	12.45	144.15
Bannangsta	07/31/00	224.08	7.47	86.45
Bannangsta	08/31/00	177.81	5.93	68.60
Bannangsta	09/31/00	169.57	5.65	65.42
Bannangsta	10/31/00	223.07	7.44	86.06
Bannangsta	11/31/00	270.54	9.02	104.38
Bannangsta	12/31/00	164.58	5.49	63.50
Bannangsta	01/31/01	70.45	2.35	27.18
Bannangsta	02/31/01	74.29	2.48	28.66
Bannangsta	03/31/01	132.21	4.41	51.01
Bannangsta	04/31/01	109.31	3.64	42.17
Bannangsta	05/31/01	80.08	2.67	30.90
Bannangsta	06/31/01	102.38	3.41	39.50
Bannangsta	07/31/01	158.66	5.29	61.21
Bannangsta	08/31/01	140.93	4.70	54.37
Bannangsta	09/31/01	188.69	6.29	72.80
Bannangsta	10/31/01	270.38	9.01	104.31
Bannangsta	11/31/01	313.45	10.45	120.93
Bannangsta	12/31/01	165.43	5.51	63.82
Bannangsta	01/31/02	52.67	1.76	20.32
Bannangsta	02/31/02	39.43	1.31	15.21
Bannangsta	03/31/02	74.49	2.48	28.74
Bannangsta	04/31/02	91.45	3.05	35.28
Bannangsta	05/31/02	128.7	4.29	49.65
Bannangsta	06/31/02	60.94	2.03	23.51
Bannangsta	07/31/02	65.36	2.18	25.22
Bannangsta	08/31/02	61.34	2.04	23.67
Bannangsta	09/31/02	42.34	1.41	16.33
Bannangsta	10/31/02	87.07	2.90	33.59
Bannangsta	11/31/02	58.03	1.93	22.39
Bannangsta	12/31/02	78.84	2.63	30.42
Yaha, Yala	01/31/90	6.639	0.22	2.56
Yaha, Yala	02/31/90	3.59	0.12	1.39
Yaha, Yala	03/31/90	3.488	0.12	1.35
Yaha, Yala	05/31/90	3.654	0.12	1.41
Yaha, Yala	06/31/90	2.368	0.08	0.91
Yaha, Yala	07/31/90	1.852	0.06	0.71
Yaha, Yala	08/31/90	1.382	0.05	0.53
Yaha, Yala	09/31/90	2.705	0.09	1.04

Flows data of the Pattani River at each segments (cont.)

Yaha, Yala	10/31/90	13.585	0.45	5.24
Yaha, Yala	11/31/90	27.394	0.91	10.57
Yaha, Yala	12/31/90	70.732	2.36	27.29
Yaha, Yala	01/31/91	16.3	0.54	6.29
Yaha, Yala	02/31/91	6.28	0.21	2.42
Yaha, Yala	03/31/91	3.85	0.13	1.49
Yaha, Yala	04/31/91	2.33	0.08	0.90
Yaha, Yala	05/31/91	7.99	0.27	3.08
Yaha, Yala	06/31/91	9.29	0.31	3.58
Yaha, Yala	07/31/91	4.62	0.15	1.78
Yaha, Yala	08/31/91	2.88	0.10	1.11
Yaha, Yala	09/31/91	2.67	0.09	1.03
Yaha, Yala	10/31/91	16.42	0.55	6.33
Yaha, Yala	11/31/91	80.06	2.67	30.89
Yaha, Yala	12/31/91	79.13	2.64	30.53
Yaha, Yala	01/31/96	26.92	0.90	10.39
Yaha, Yala	02/31/96	13.55	0.45	5.23
Yaha, Yala	03/31/96	6.86	0.23	2.65
Yaha, Yala	04/31/96	4.26	0.14	1.64
Yaha, Yala	05/31/96	11.24	0.37	4.34
Yaha, Yala	06/31/96	41.82	1.39	16.13
Yaha, Yala	07/31/96	26.61	0.89	10.27
Yaha, Yala	08/31/96	25.02	0.83	9.65
Yaha, Yala	09/31/96	23.39	0.78	9.02
Yaha, Yala	10/31/96	75.36	2.51	29.07
Yaha, Yala	11/31/96	50.21	1.67	19.37
Yaha, Yala	12/31/96	175.61	5.85	67.75
Yaha, Yala	01/31/97	26.06	0.87	10.05
Yaha, Yala	02/31/97	8.24	0.27	3.18
Yaha, Yala	03/31/97	0.47	0.02	0.18
Yaha, Yala	04/31/97	5.27	0.18	2.03
Yaha, Yala	05/31/97	4.05	0.14	1.56
Yaha, Yala	06/31/97	7.74	0.26	2.99
Yaha, Yala	07/31/97	10.86	0.36	4.19
Yaha, Yala	08/31/97	17.9	0.60	6.91
Yaha, Yala	09/31/97	41.85	1.40	16.15
Yaha, Yala	10/31/97	37.24	1.24	14.37
Yaha, Yala	11/31/97	37.21	1.24	14.36
Yaha, Yala	12/31/97	118.51	3.95	45.72
Yaha, Yala	01/31/98	68.88	2.30	26.57
Yaha, Yala	02/31/98	39.89	1.33	15.39
Yaha, Yala	03/31/98	37.6	1.25	14.51
Yaha, Yala	04/31/98	14.24	0.47	5.49
Yaha, Yala	05/31/98	17.97	0.60	6.93
Yaha, Yala	06/31/98	24.66	0.82	9.51
Yaha, Yala	07/31/98	36.68	1.22	14.15
Yaha, Yala	08/31/98	55.85	1.86	21.55
Yaha, Yala	09/31/98	42.49	1.42	16.39
Yaha, Yala	10/31/98	47.06	1.57	18.16
Yaha, Yala	11/31/98	66.43	2.21	25.63
Yaha, Yala	12/31/98	105.27	3.51	40.61

Flows data of the Pattani River at each segments (cont.)

Yaha, Yala	01/31/99	48.77	1.63	18.82
Yaha, Yala	02/31/99	27.46	0.92	10.59
Yaha, Yala	03/31/99	39.37	1.31	15.19
Yaha, Yala	04/31/99	33.42	1.11	12.89
Yaha, Yala	05/31/99	59.33	1.98	22.89
Yaha, Yala	06/31/99	27.1	0.90	10.46
Yaha, Yala	07/31/99	26.29	0.88	10.14
Yaha, Yala	08/31/99	22.9	0.76	8.83
Yaha, Yala	09/31/99	24	0.80	9.26
Yaha, Yala	10/31/99	53.36	1.78	20.59
Yaha, Yala	11/31/99	84.27	2.81	32.51
Yaha, Yala	12/31/99	220.34	7.34	85.01
Yaha, Yala	01/31/00	87.59	2.92	33.79
Yaha, Yala	02/31/00	21.72	0.72	8.38
Yaha, Yala	03/31/00	22.42	0.75	8.65
Yaha, Yala	04/31/00	101.96	3.40	39.34
Yaha, Yala	05/31/00	31.11	1.04	12.00
Yaha, Yala	06/31/00	20.64	0.69	7.96
Yaha, Yala	07/31/00	16.19	0.54	6.25
Yaha, Yala	08/31/00	21.99	0.73	8.48
Yaha, Yala	09/31/00	23.26	0.78	8.97
Yaha, Yala	10/31/00	33.16	1.11	12.79
Yaha, Yala	11/31/00	129.68	4.32	50.03
Yaha, Yala	12/31/00	53.58	1.79	20.67
Yaha, Yala	01/31/01	17.5	0.58	6.75
Yaha, Yala	02/31/01	6.95	0.23	2.68
Yaha, Yala	03/31/01	6.24	0.21	2.41
Yaha, Yala	04/31/01	10.74	0.36	4.14
Yaha, Yala	05/31/01	12.11	0.40	4.67
Yaha, Yala	06/31/01	8.21	0.27	3.17
Yaha, Yala	07/31/01	6.07	0.20	2.34
Yaha, Yala	08/31/01	6.89	0.23	2.66
Yaha, Yala	09/31/01	8.73	0.29	3.37
Yaha, Yala	10/31/01	60.75	2.03	23.44
Yaha, Yala	11/31/01	66.8	2.23	25.77
Yaha, Yala	12/31/01	55.45	1.85	21.39
Yaha, Yala	01/31/02	26.47	0.88	10.21
Yaha, Yala	02/31/02	8.33	0.28	3.21
Yaha, Yala	03/31/02	9.01	0.30	3.48
Yaha, Yala	04/31/02	7.62	0.25	2.94
Yaha, Yala	05/31/02	9.86	0.33	3.80
Yaha, Yala	06/31/02	11.17	0.37	4.31
Yaha, Yala	07/31/02	6.61	0.22	2.55
Yaha, Yala	08/31/02	4.92	0.16	1.90
Yaha, Yala	09/31/02	6.33	0.21	2.44
Yaha, Yala	10/31/02	51.02	1.70	19.68
Yaha, Yala	11/31/02	44.06	1.47	17.00
Yaha, Yala	12/31/02	63.63	2.12	24.55
Thasarp, Yala	01/31/90	109.5	3.65	42.25
Thasarp, Yala	02/31/90	75.8	2.53	29.24
Thasarp, Yala	03/31/90	75.1	2.50	28.97

Flows data of the Pattani River at each segments (cont.)

Thasarp, Yala	04/31/90	58	1.93	22.38
Thasarp, Yala	05/31/90	68.4	2.28	26.39
Thasarp, Yala	06/31/90	53.5	1.78	20.64
Thasarp, Yala	07/31/90	89.1	2.97	34.38
Thasarp, Yala	08/31/90	110.8	3.69	42.75
Thasarp, Yala	09/31/90	104	3.47	40.12
Thasarp, Yala	10/31/90	79.1	2.64	30.52
Thasarp, Yala	11/31/90	86.4	2.88	33.33
Thasarp, Yala	12/31/90	219.5	7.32	84.68
Thasarp, Yala	01/31/91	160.19	5.34	61.80
Thasarp, Yala	02/31/91	110.07	3.67	42.47
Thasarp, Yala	03/31/91	144.63	4.82	55.80
Thasarp, Yala	04/31/91	107.67	3.59	41.54
Thasarp, Yala	05/31/91	152.24	5.07	58.73
Thasarp, Yala	06/31/91	146.5	4.88	56.52
Thasarp, Yala	07/31/91	130.02	4.33	50.16
Thasarp, Yala	08/31/91	186.63	6.22	72.00
Thasarp, Yala	09/31/91	167.92	5.60	64.78
Thasarp, Yala	10/31/91	168.76	5.63	65.11
Thasarp, Yala	11/31/91	336.59	11.22	129.86
Thasarp, Yala	12/31/91	321.64	10.72	124.09
Thasarp, Yala	01/31/92	125.38	4.18	48.37
Thasarp, Yala	02/31/92	134.98	4.50	52.08
Thasarp, Yala	03/31/92	189.27	6.31	73.02
Thasarp, Yala	04/31/92	152.58	5.09	58.87
Thasarp, Yala	05/31/92	176.49	5.88	68.09
Thasarp, Yala	06/31/92	182.44	6.08	70.39
Thasarp, Yala	07/31/92	205.23	6.84	79.18
Thasarp, Yala	08/31/92	151.39	5.05	58.41
Thasarp, Yala	09/31/92	120.88	4.03	46.64
Thasarp, Yala	10/31/92	162.73	5.42	62.78
Thasarp, Yala	11/31/92	254.78	8.49	98.29
Thasarp, Yala	12/31/92	204.35	6.81	78.84
Thasarp, Yala	01/31/93	409.85	13.66	158.12
Thasarp, Yala	02/31/93	269.25	8.98	103.88
Thasarp, Yala	03/31/93	245.92	8.20	94.88
Thasarp, Yala	04/31/93	181.22	6.04	69.92
Thasarp, Yala	05/31/93	232.69	7.76	89.77
Thasarp, Yala	06/31/93	235.38	7.85	90.81
Thasarp, Yala	07/31/93	179.14	5.97	69.11
Thasarp, Yala	08/31/93	183.8	6.13	70.91
Thasarp, Yala	09/31/93	211.52	7.05	81.60
Thasarp, Yala	10/31/93	222.13	7.40	85.70
Thasarp, Yala	11/31/93	398.36	13.28	153.69
Thasarp, Yala	12/31/93	701.59	23.39	270.68
Thasarp, Yala	01/31/94	174	5.80	67.13
Thasarp, Yala	02/31/94	143.17	4.77	55.24
Thasarp, Yala	03/31/94	159.94	5.33	61.71
Thasarp, Yala	04/31/94	220.2	7.34	84.95
Thasarp, Yala	05/31/94	271.05	9.04	104.57
Thasarp, Yala	06/31/94	206.38	6.88	79.62

Flows data of the Pattani River at each segments (cont.)

Thasarp, Yala	07/31/94	236.02	7.87	91.06
Thasarp, Yala	08/31/94	267.13	8.90	103.06
Thasarp, Yala	09/31/94	308.19	10.27	118.90
Thasarp, Yala	10/31/94	314.25	10.48	121.24
Thasarp, Yala	11/31/94	609.69	20.32	235.22
Thasarp, Yala	12/31/94	317.67	10.59	122.56
Thasarp, Yala	01/31/95	271.95	9.07	104.92
Thasarp, Yala	02/31/95	271.43	9.05	104.72
Thasarp, Yala	03/31/95	237.46	7.92	91.61
Thasarp, Yala	04/31/95	161.46	5.38	62.29
Thasarp, Yala	05/31/95	234.84	7.83	90.60
Thasarp, Yala	06/31/95	196.47	6.55	75.80
Thasarp, Yala	07/31/95	122.77	4.09	47.36
Thasarp, Yala	08/31/95	329.15	10.97	126.99
Thasarp, Yala	09/31/95	404.87	13.50	156.20
Thasarp, Yala	10/31/95	382.09	12.74	147.41
Thasarp, Yala	11/31/95	680.27	22.68	262.45
Thasarp, Yala	12/31/95	458.72	15.29	176.98
Thasarp, Yala	01/31/96	183.56	6.12	70.82
Thasarp, Yala	02/31/96	177.08	5.90	68.32
Thasarp, Yala	03/31/96	164.23	5.47	63.36
Thasarp, Yala	04/31/96	141.72	4.72	54.68
Thasarp, Yala	05/31/96	289.17	9.64	111.56
Thasarp, Yala	06/31/96	298.85	9.96	115.30
Thasarp, Yala	07/31/96	243.73	8.12	94.03
Thasarp, Yala	08/31/96	263.39	8.78	101.62
Thasarp, Yala	09/31/96	246.49	8.22	95.10
Thasarp, Yala	10/31/96	323.25	10.78	124.71
Thasarp, Yala	11/31/96	252.9	8.43	97.57
Thasarp, Yala	12/31/96	433.56	14.45	167.27
Thasarp, Yala	01/31/97	190.05	6.34	73.32
Thasarp, Yala	02/31/97	117.26	3.91	45.24
Thasarp, Yala	03/31/97	157.84	5.26	60.90
Thasarp, Yala	04/31/97	167.81	5.59	64.74
Thasarp, Yala	05/31/97	162.89	5.43	62.84
Thasarp, Yala	06/31/97	159.05	5.30	61.36
Thasarp, Yala	07/31/97	147.82	4.93	57.03
Thasarp, Yala	08/31/97	177.31	5.91	68.41
Thasarp, Yala	09/31/97	246.02	8.20	94.92
Thasarp, Yala	10/31/97	289.59	9.65	111.72
Thasarp, Yala	11/31/97	174.02	5.80	67.14
Thasarp, Yala	12/31/97	419.87	14.00	161.99
Thasarp, Yala	01/31/98	233.62	7.79	90.13
Thasarp, Yala	02/31/98	139.25	4.64	53.72
Thasarp, Yala	03/31/98	191.7	6.39	73.96
Thasarp, Yala	04/31/98	171.04	5.70	65.99
Thasarp, Yala	05/31/98	174.16	5.81	67.19
Thasarp, Yala	06/31/98	220.28	7.34	84.98
Thasarp, Yala	07/31/98	194.92	6.50	75.20
Thasarp, Yala	08/31/98	202.22	6.74	78.02
Thasarp, Yala	09/31/98	221.88	7.40	85.60

Flows data of the Pattani River at each segments (cont.)

Thasarp, Yala	10/31/98	190.62	6.35	73.54
Thasarp, Yala	11/31/98	243.78	8.13	94.05
Thasarp, Yala	12/31/98	348.03	11.60	134.27
Thasarp, Yala	01/31/99	520.23	17.34	200.71
Thasarp, Yala	02/31/99	261.33	8.71	100.82
Thasarp, Yala	03/31/99	218.18	7.27	84.17
Thasarp, Yala	04/31/99	332.03	11.07	128.10
Thasarp, Yala	05/31/99	441.68	14.72	170.40
Thasarp, Yala	06/31/99	213.52	7.12	82.38
Thasarp, Yala	07/31/99	243.44	8.11	93.92
Thasarp, Yala	08/31/99	310.98	10.37	119.98
Thasarp, Yala	09/31/99	256.45	8.55	98.94
Thasarp, Yala	10/31/99	354.37	11.81	136.72
Thasarp, Yala	11/31/99	515.26	17.18	198.79
Thasarp, Yala	12/31/99	970.31	32.34	374.35
Thasarp, Yala	01/31/00	501.3	16.71	193.40
Thasarp, Yala	02/31/00	297.5	9.92	114.78
Thasarp, Yala	03/31/00	227.6	7.59	87.81
Thasarp, Yala	04/31/00	591.2	19.71	228.09
Thasarp, Yala	05/31/00	510.8	17.03	197.07
Thasarp, Yala	06/31/00	379.3	12.64	146.33
Thasarp, Yala	07/31/00	301.9	10.06	116.47
Thasarp, Yala	08/31/00	292	9.73	112.65
Thasarp, Yala	09/31/00	282.6	9.42	109.03
Thasarp, Yala	10/31/00	357.9	11.93	138.08
Thasarp, Yala	11/31/00	628.3	20.94	242.40
Thasarp, Yala	12/31/00	430.6	14.35	166.13
Thasarp, Yala	01/31/01	285.56	9.52	110.17
Thasarp, Yala	02/31/01	156.25	5.21	60.28
Thasarp, Yala	03/31/01	233.01	7.77	89.90
Thasarp, Yala	04/31/01	208.7	6.96	80.52
Thasarp, Yala	05/31/01	183.72	6.12	70.88
Thasarp, Yala	06/31/01	190.54	6.35	73.51
Thasarp, Yala	07/31/01	224.69	7.49	86.69
Thasarp, Yala	08/31/01	220.55	7.35	85.09
Thasarp, Yala	09/31/01	245.39	8.18	94.67
Thasarp, Yala	10/31/01	387.92	12.93	149.66
Thasarp, Yala	11/31/01	502.15	16.74	193.73
Thasarp, Yala	12/31/01	485.08	16.17	187.15
Thasarp, Yala	01/31/02	133.35	4.45	51.45
Thasarp, Yala	02/31/02	82.84	2.76	31.96
Thasarp, Yala	03/31/02	128.6	4.29	49.61
Thasarp, Yala	04/31/02	163.93	5.46	63.24
Thasarp, Yala	05/31/02	191.35	6.38	73.82
Thasarp, Yala	06/31/02	148.63	4.95	57.34
Thasarp, Yala	07/31/02	143.91	4.80	55.52
Thasarp, Yala	08/31/02	145.36	4.85	56.08
Thasarp, Yala	09/31/02	99.65	3.32	38.45
Thasarp, Yala	10/31/02	294.09	9.80	113.46
Thasarp, Yala	11/31/02	179.47	5.98	69.24
Thasarp, Yala	12/31/02	299.75	9.99	115.64

APPENDIX B

OUTFLOWS DATA OF THE PATTANI DAM

Outflows data of the Pattani Dam (Royal Irrigation Department, 1993-2004)

Date	Outflows (m3/s)
01/31/93	21.6481
02/28/93	32.2300
03/31/93	39.5155
04/30/93	35.9003
05/31/93	47.8710
06/30/93	47.3823
07/31/93	33.8248
08/31/93	33.3313
09/30/93	42.4533
10/31/93	36.5258
11/30/93	25.3603
12/31/93	50.4616
01/31/94	81.4342
02/28/94	68.9200
03/31/94	52.5452
04/30/94	54.1223
05/31/94	65.1087
06/30/94	36.1113
07/31/94	55.9865
08/31/94	72.7458
09/30/94	84.2400
10/31/94	64.3961
11/30/94	58.9927
12/31/94	46.4594
01/31/95	28.7106
02/28/95	37.1571
03/31/95	36.1013
04/30/95	36.8300
05/31/95	48.6442
06/30/95	38.5713
07/31/95	17.4687
08/31/95	48.5390
09/30/95	85.4173
10/31/95	55.2216
11/30/95	90.7667
12/31/95	22.0681
01/31/96	36.7748
02/29/96	59.9931
03/31/96	50.0190
04/30/96	35.3293
05/31/96	80.2555
06/30/96	64.0733
07/31/96	64.1539
08/31/96	63.3771

Outflows data of the Pattani Dam (Cont.)

09/30/96	72.5427
10/31/96	65.0000
11/30/96	48.5333
12/31/96	26.2903
01/31/97	33.0706
02/28/97	45.0568
03/31/97	43.7129
04/30/97	43.7853
05/31/97	54.4674
06/30/97	44.6627
07/31/97	32.0545
08/31/97	39.5973
09/30/97	49.0917
10/31/97	50.6290
11/30/97	31.8333
12/31/97	39.1935
01/31/98	36.2071
02/28/98	33.1561
03/31/98	44.9445
04/30/98	55.5163
05/31/98	43.6006
06/30/98	51.1303
07/31/98	40.5748
08/31/98	40.7494
09/30/98	39.6963
10/31/98	42.8352
11/30/98	30.0333
12/31/98	30.1232
01/31/99	39.8365
02/28/99	54.9157
03/31/99	60.6813
04/30/99	94.4883
05/31/99	100.8839
06/30/99	61.3223
07/31/99	65.6213
08/31/99	94.0468
09/30/99	76.9013
10/31/99	80.4035
11/30/99	101.6333
12/31/99	97.2903
01/31/00	115.0861
02/29/00	54.0390
03/31/00	49.2390
04/30/00	111.7680
05/31/00	112.0535
06/30/00	100.0343
07/31/00	72.5658
08/31/00	58.9590
09/30/00	66.5480
10/31/00	74.2632
11/30/00	58.0667

Outflows data of the Pattani Dam (Cont.)

12/31/00	50.5816
01/31/01	67.6016
02/28/01	69.8611
03/31/01	49.9823
04/30/01	52.0550
05/31/01	37.5655
06/30/01	49.7163
07/31/01	63.5535
08/31/01	61.5971
09/30/01	69.6570
10/31/01	71.6774
11/30/01	94.7000
12/31/01	61.2903
01/31/02	34.2161
02/28/02	46.1661
03/31/02	67.8003
04/30/02	48.7497
06/30/02	36.3033
07/31/02	35.7803
08/31/02	34.0081
09/30/02	24.3630
10/31/02	32.4839
11/30/02	27.5000
12/31/02	29.5806
01/31/03	21.2994
02/28/03	22.6407
03/31/03	35.5358
04/30/03	33.8283
05/31/03	31.1948
06/30/03	30.7730
07/31/03	30.8326
08/31/03	27.0071
09/30/03	21.1760
10/31/03	23.6326
11/30/03	33.2523
12/31/03	38.0645
01/31/04	29.4629
02/29/04	39.3755
03/31/04	43.0281
04/30/04	34.4767
05/31/04	31.7874

APPENDIX C

THE OBSERVED TOTAL LEAD CONCENTRATION IN THE PATTANI RIVER

The observed total lead concentration in the Pattani River at Yelapun station, Bannangsta district, Yala province (1986-2002)

Segment No.	Segment Name	Date (m/d/y)	Total Lead (mg/l)
1	Yelapun Bridge, Bannangsta	03/03/86	0.06
1	Yelapun Bridge, Bannangsta	08/20/86	0.09
1	Yelapun Bridge, Bannangsta	02/03/87	0
1	Yelapun Bridge, Bannangsta	03/30/88	0.03
1	Yelapun Bridge, Bannangsta	01/10/89	0.08
1	Yelapun Bridge, Bannangsta	05/02/89	0.02
1	Yelapun Bridge, Bannangsta	02/12/91	0.06
1	Yelapun Bridge, Bannangsta	07/02/91	0.045
1	Yelapun Bridge, Bannangsta	03/10/92	0.01
1	Yelapun Bridge, Bannangsta	07/20/92	0.04
1	Yelapun Bridge, Bannangsta	01/20/93	0.04
1	Yelapun Bridge, Bannangsta	07/10/94	0.05
1	Yelapun Bridge, Bannangsta	03/10/95	0.02
1	Yelapun Bridge, Bannangsta	07/01/95	0.035
1	Yelapun Bridge, Bannangsta	12/22/95	0.0183
1	Yelapun Bridge, Bannangsta	03/19/96	0.0363
1	Yelapun Bridge, Bannangsta	08/30/96	0.0350
1	Yelapun Bridge, Bannangsta	03/20/97	0.0200
1	Yelapun Bridge, Bannangsta	10/28/97	0.0100
1	Yelapun Bridge, Bannangsta	03/10/98	0.05
1	Yelapun Bridge, Bannangsta	11/12/98	0.0300
1	Yelapun Bridge, Bannangsta	03/20/99	0.025
1	Yelapun Bridge, Bannangsta	09/22/99	0.0600
1	Yelapun Bridge, Bannangsta	06/14/00	0.0200
1	Yelapun Bridge, Bannangsta	03/31/02	0.0159
1	Yelapun Bridge, Bannangsta	06/30/02	0.0531

The observed total lead concentration in the Pattani River at Train Bridge station, Muang district, Yala province (1986-2002)

Segment No.	Segment Name	Date (m/d/y)	Total Lead (mg/l)
2	Train Bridge, Muang Yala	03/05/86	0.01
2	Train Bridge, Muang Yala	05/20/86	0.14
2	Train Bridge, Muang Yala	02/08/87	0.1
2	Train Bridge, Muang Yala	03/30/88	0.04
2	Train Bridge, Muang Yala	01/30/89	0.08
2	Train Bridge, Muang Yala	05/09/89	0.06
2	Train Bridge, Muang Yala	04/13/90	0.02
2	Train Bridge, Muang Yala	08/08/90	0.013
2	Train Bridge, Muang Yala	05/15/91	0.1
2	Train Bridge, Muang Yala	07/30/92	0.03
2	Train Bridge, Muang Yala	01/30/93	0.04
2	Train Bridge, Muang Yala	07/15/93	0.03
2	Train Bridge, Muang Yala	04/28/94	0.015
2	Train Bridge, Muang Yala	02/20/95	0.04
2	Train Bridge, Muang Yala	07/30/95	0.02
2	Train Bridge, Muang Yala	03/19/96	0.0267
2	Train Bridge, Muang Yala	08/28/96	0.0250
2	Train Bridge, Muang Yala	11/29/96	0.0500
2	Train Bridge, Muang Yala	03/20/97	0.02
2	Train Bridge, Muang Yala	10/28/97	0.0100
2	Train Bridge, Muang Yala	01/13/98	0.0100
2	Train Bridge, Muang Yala	12/11/98	0.0300
2	Train Bridge, Muang Yala	02/17/99	0.0300
2	Train Bridge, Muang Yala	06/14/00	0.0490
2	Train Bridge, Muang Yala	03/31/02	0.0086
2	Train Bridge, Muang Yala	06/30/02	0.0056

The observed total lead concentration in the Pattani River at Talubo Bridge station, Muang district, Pattani province (1986-2002)

Segment No.	Segment Name	Date (m/d/y)	Total Lead (mg/l)
3	Talubo, Muang Pattani	03/05/86	0.11
3	Talubo, Muang Pattani	07/16/87	0.1
3	Talubo, Muang Pattani	03/28/88	0.025
3	Talubo, Muang Pattani	01/18/89	0.11
3	Talubo, Muang Pattani	05/02/89	0.02
3	Talubo, Muang Pattani	02/18/90	0.01
3	Talubo, Muang Pattani	06/14/90	0.05
3	Talubo, Muang Pattani	03/18/91	0.03
3	Talubo, Muang Pattani	09/03/91	0.03
3	Talubo, Muang Pattani	05/16/92	0.03
3	Talubo, Muang Pattani	09/11/92	0.015
3	Talubo, Muang Pattani	05/20/93	0.03
3	Talubo, Muang Pattani	02/08/94	0.015
3	Talubo, Muang Pattani	11/13/94	0.01
3	Talubo, Muang Pattani	03/28/95	0.0100
3	Talubo, Muang Pattani	07/30/95	0.015
3	Talubo, Muang Pattani	12/22/95	0.0200
3	Talubo, Muang Pattani	03/24/96	0.0275
3	Talubo, Muang Pattani	08/15/96	0.0375
3	Talubo, Muang Pattani	03/19/97	0.0186
3	Talubo, Muang Pattani	07/01/97	0.037
3	Talubo, Muang Pattani	05/13/98	0.01
3	Talubo, Muang Pattani	03/22/99	0.0250
3	Talubo, Muang Pattani	03/31/02	0.0081
3	Talubo, Muang Pattani	06/30/02	0.0048

APPENDIX D

MODEL CALIBRATION RESULT

The result of the real scenario calibration at the best observed fit at Yelapun station, Bannangsta district, Yala province

Date	Total lead concentration (mg/l)
01/01/85	1.00E-24
04/11/85	1.62E-01
07/20/85	2.43E-01
10/28/85	2.68E-01
02/05/86	2.60E-01
05/16/86	2.38E-01
08/24/86	2.14E-01
12/02/86	1.92E-01
03/12/87	1.74E-01
06/20/87	1.58E-01
09/28/87	1.46E-01
01/06/88	1.35E-01
04/15/88	1.26E-01
07/24/88	1.18E-01
11/01/88	1.11E-01
02/09/89	1.05E-01
05/20/89	9.92E-02
08/28/89	9.42E-02
12/06/89	8.98E-02
03/16/90	8.57E-02
06/24/90	8.21E-02
10/02/90	7.87E-02
01/10/91	7.56E-02
04/20/91	7.21E-02
07/29/91	6.11E-02
11/06/91	2.80E-02
02/14/92	2.26E-02
05/24/92	3.13E-02
09/01/92	3.73E-02
12/10/92	3.37E-02
03/20/93	3.05E-02
06/28/93	2.78E-02
10/06/93	2.64E-02
01/14/94	2.57E-02
04/24/94	3.21E-02
08/02/94	3.89E-02
11/10/94	3.12E-02
02/18/95	2.94E-02
05/29/95	3.62E-02
09/06/95	2.43E-02
12/15/95	1.36E-02

The result of the real scenario calibration at the best observed fit at Yelapun station, Bannangsta district, Yala province (Cont.)

03/24/96	1.69E-02
07/02/96	3.08E-02
10/10/96	3.07E-02
01/18/97	2.65E-02
04/28/97	1.83E-02
08/06/97	1.65E-02
11/14/97	2.45E-02
02/22/98	3.42E-02
06/02/98	3.33E-02
09/10/98	3.41E-02
12/19/98	3.65E-02
03/29/99	4.24E-02
07/07/99	5.22E-02
10/15/99	4.18E-02
01/23/00	3.30E-02
05/02/00	3.11E-02
08/10/00	2.95E-02
11/18/00	2.81E-02
02/26/01	2.53E-02
06/06/01	2.16E-02
09/14/01	1.97E-02
12/23/01	1.85E-02
04/02/02	1.74E-02
07/11/02	1.67E-02
10/19/02	2.11E-02
01/01/03	2.82E-02

The result of the real scenario calibration at the best observed fit at Train Bridge station, Muang district, Yala province (Cont.)

Date	Total lead concentration (mg/l)
01/01/85	1.00E-24
04/11/85	3.21E-02
07/20/85	1.27E-01
10/28/85	2.12E-01
02/05/86	2.50E-01
05/16/86	2.51E-01
08/24/86	2.32E-01
12/02/86	2.08E-01
03/12/87	1.86E-01
06/20/87	1.68E-01
09/28/87	1.53E-01
01/06/88	1.40E-01
04/15/88	1.30E-01
07/24/88	1.21E-01
11/01/88	1.14E-01
02/09/89	1.07E-01

The result of the real scenario calibration at the best observed fit at Train Bridge station, Muang district, Yala province (Cont.)

05/20/89	1.01E-01
08/28/89	9.60E-02
12/06/89	9.13E-02
03/16/90	8.70E-02
06/24/90	8.32E-02
10/02/90	7.97E-02
01/10/91	7.65E-02
04/20/91	7.31E-02
07/29/91	6.71E-02
11/06/91	3.00E-02
02/14/92	2.21E-02
05/24/92	2.99E-02
09/01/92	3.77E-02
12/10/92	3.41E-02
03/20/93	3.08E-02
06/28/93	2.81E-02
10/06/93	2.65E-02
01/14/94	2.55E-02
04/24/94	3.11E-02
08/02/94	3.91E-02
11/10/94	3.20E-02
02/18/95	2.88E-02
05/29/95	3.51E-02
09/06/95	2.63E-02
12/15/95	1.39E-02
03/24/96	1.64E-02
07/02/96	2.82E-02
10/10/96	3.11E-02
01/18/97	2.73E-02
04/28/97	1.87E-02
08/06/97	1.61E-02
11/14/97	2.34E-02
02/22/98	3.41E-02
06/02/98	3.35E-02
09/10/98	3.39E-02
12/19/98	3.62E-02
03/29/99	4.11E-02
07/07/99	5.01E-02
10/15/99	4.38E-02
01/23/00	3.36E-02
05/02/00	3.13E-02
08/10/00	2.97E-02
11/18/00	2.83E-02
02/26/01	2.58E-02
06/06/01	2.19E-02
09/14/01	1.98E-02
12/23/01	1.86E-02
04/02/02	1.75E-02
07/11/02	1.66E-02

The result of the real scenario calibration at the best observed fit at Train Bridge station, Muang district, Yala province (Cont.)

10/19/02	2.06E-02
01/01/03	2.54E-02

The result of the real scenario calibration at the best observed fit at Talubo Bridge station, Muang district, Pattani province

Date	Total lead concentration (mg/l)
01/01/85	1E-24
04/11/85	0.00255
07/20/85	0.010172
10/28/85	0.01713
02/05/86	0.020415
05/16/86	0.020536
08/24/86	0.019054
12/02/86	0.017146
03/12/87	0.015377
06/20/87	0.013894
09/28/87	0.012682
01/06/88	0.011683
04/15/88	0.010849
07/24/88	0.01014
11/01/88	0.009527
02/09/89	0.00899
05/20/89	0.008516
08/28/89	0.008095
12/06/89	0.007717
03/16/90	0.031868
06/24/90	0.031084
10/02/90	0.029839
01/10/91	0.031248
04/20/91	0.029987
07/29/91	0.027645
11/06/91	0.040844
02/14/92	0.016486
05/24/92	0.021449
09/01/92	0.027096
12/10/92	0.029905
03/20/93	0.027214
06/28/93	0.029269
10/06/93	0.030125
01/14/94	0.028075
04/24/94	0.01617
08/02/94	0.017267
11/10/94	0.020682
02/18/95	0.019923
05/29/95	0.01943

The result of the real scenario calibration at the best observed fit at Talubo Bridge station, Muang district, Pattani province (Cont.)

09/06/95	0.015189
12/15/95	0.025147
03/24/96	0.033562
07/02/96	0.025155
10/10/96	0.033354
01/18/97	0.029121
04/28/97	0.037164
08/06/97	0.031127
11/14/97	0.016992
02/22/98	0.022456
06/02/98	0.022759
09/10/98	0.024991
12/19/98	0.027239
03/29/99	0.02885
07/07/99	0.02183
10/15/99	0.027743
01/23/00	0.019532
05/02/00	0.019335
08/10/00	0.018388
11/18/00	0.019921
02/26/01	0.018485
06/06/01	0.020712
09/14/01	0.016685
12/23/01	0.015293
04/02/02	0.015965
07/11/02	0.019291
10/19/02	0.016147
01/01/03	0.021465

APPENDIX E

STATISTICAL ANALYSIS RESULT

The data and result of statistical analysis at Yelapun station, Bannangsta district, Yala province

N	Date	Co Yelapun	Date	Cp	(Co-Cp)2
1	02/12/91	0.06	01/10/91	7.56E-02	2.42E-04
2	07/02/91	0.045	07/29/91	6.11E-02	2.59E-04
3	03/10/92	0.01	02/14/92	2.26E-02	1.60E-04
4	07/20/92	0.04	09/01/92	3.73E-02	7.23E-06
5	01/20/93	0.04	12/10/92	3.37E-02	4.01E-05
6	07/10/94	0.05	08/02/94	3.89E-02	1.24E-04
7	03/10/95	0.02	02/18/95	2.94E-02	8.77E-05
8	07/01/95	0.035	05/29/95	3.62E-02	1.55E-06
9	12/22/95	0.0183	12/15/95	1.36E-02	2.26E-05
10	03/19/96	0.0363	03/24/96	1.69E-02	3.76E-04
11	08/30/96	0.0350	07/02/96	3.08E-02	1.75E-05
12	03/20/97	0.0200	04/28/97	1.83E-02	3.01E-06
13	10/28/97	0.0100	11/14/97	2.45E-02	2.10E-04
14	03/10/98	0.05	02/22/98	3.42E-02	2.49E-04
15	11/12/98	0.0300	12/19/98	3.65E-02	4.27E-05
16	03/20/99	0.025	03/29/99	4.24E-02	3.04E-04
17	09/22/99	0.0600	10/15/99	4.18E-02	3.30E-04
18	06/14/00	0.0200	05/02/00	3.11E-02	1.23E-04
19	03/31/02	0.0159	04/02/02	1.74E-02	2.37E-06
20	06/30/02	0.0531	07/11/02	1.67E-02	1.33E-03
				SUM	3.93E-03
				SUM/N	1.96E-04
				RMSE	0.014018

The data and result of statistical analysis at Train bridge station, Muang district, Yala province

N	Date	Co M.Yala	Date	Cp	(Co-Cp)2
1	05/15/91	0.1	04/20/91	7.31E-02	7.26E-04
2	07/30/92	0.03	05/24/92	2.99E-02	5.23E-09
3	01/30/93	0.04	12/10/92	3.41E-02	3.47E-05
4	07/15/93	0.03	06/28/93	2.81E-02	3.76E-06
5	04/28/94	0.015	04/24/94	3.11E-02	2.58E-04
6	02/20/95	0.04	02/18/95	2.88E-02	1.25E-04
7	07/30/95	0.02	05/29/95	3.51E-02	2.28E-04
8	03/19/96	0.0267	03/24/96	1.64E-02	1.06E-04
9	08/28/96	0.0250	07/02/96	2.82E-02	1.02E-05
10	11/29/96	0.0500	10/10/96	3.11E-02	3.56E-04
11	03/20/97	0.02	04/28/97	1.87E-02	1.72E-06
12	10/28/97	0.0100	11/14/97	2.34E-02	1.80E-04
13	01/13/98	0.0100	02/22/98	3.41E-02	5.80E-04
14	12/11/98	0.0300	12/19/98	3.62E-02	3.81E-05
15	02/17/99	0.0300	03/29/99	4.11E-02	1.24E-04
16	06/14/00	0.0490	05/02/00	3.13E-02	3.14E-04
17	03/31/02	0.0086	04/02/02	1.75E-02	7.88E-05
18	06/30/02	0.0056	07/11/02	1.66E-02	1.21E-04
				SUM	3.29E-03
				SUM/N	1.83E-04
				RMSE	0.013512

The data and result of statistical analysis at Talubo station, Muang district, Pattani province

N	Date	Co Talubo	Date	Cp	(Co-Cp)2
1	09/03/91	0.03	11/06/91	0.0408441	0.000118
2	05/16/92	0.03	05/24/92	0.0214493	7.31E-05
3	09/11/92	0.015	09/01/92	0.0270963	0.000146
4	05/20/93	0.03	06/28/93	0.0292688	5.35E-07
5	02/08/94	0.015	01/14/94	0.0280748	0.000171
6	11/13/94	0.01	11/10/94	0.0206821	0.000114
7	03/28/95	0.0100	02/18/95	0.0199229	9.85E-05
8	07/30/95	0.015	09/06/95	0.0151889	3.57E-08

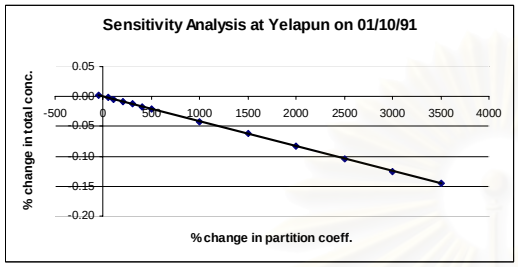
The data and result of statistical analysis at Talubo station, Muang district, Pattani province (Cont.)

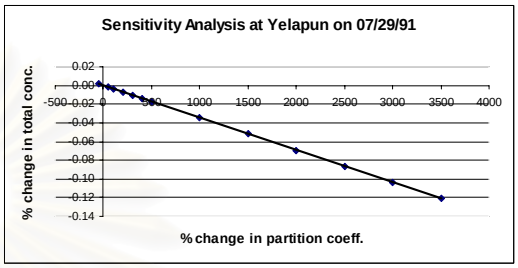
9	12/22/95	0.0200	12/15/95	0.0251473	2.65E-05
10	03/24/96	0.0275	03/24/96	0.0335616	3.67E-05
11	08/15/96	0.0375	07/02/96	0.0251554	0.000152
12	03/19/97	0.0186	04/28/97	0.0371637	0.000345
13	07/01/97	0.037	08/06/97	0.0311269	3.45E-05
14	05/13/98	0.01	06/02/98	0.0227585	0.000163
15	03/22/99	0.0250	03/29/99	0.0288497	1.48E-05
16	03/31/02	0.0081	04/02/02	0.0159646	6.23E-05
17	06/30/02	0.0048	07/11/02	0.019291	0.00021
				SUM	0.001765
				SUM/N	0.000104
				RMSE	0.010191

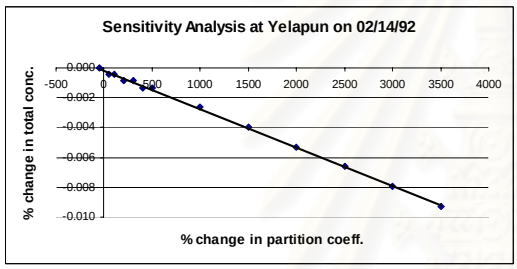
APPENDIX F

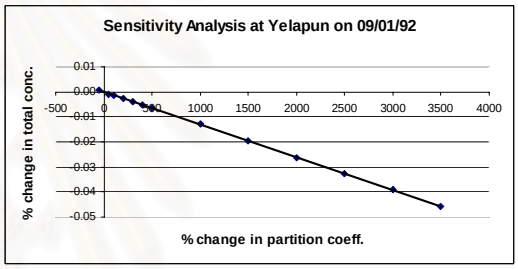
SENSITIVITY ANALYSIS RESULT

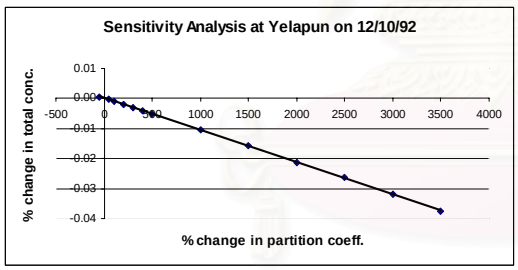
The result of sensitivity analysis by the varying of partition coefficient at Yelapun station, Bannangsta district, Yala province

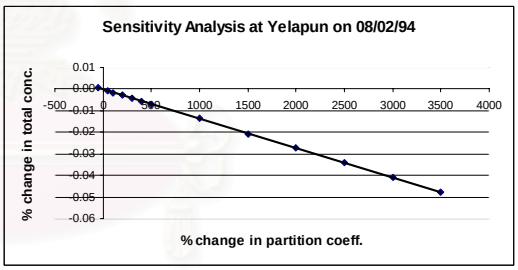


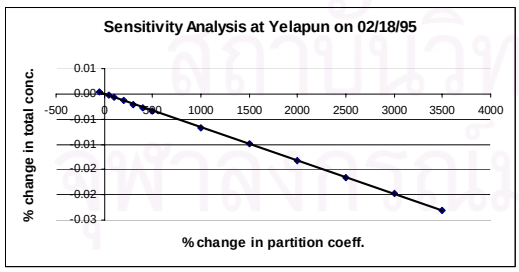


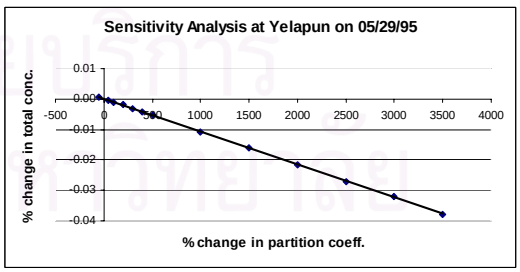




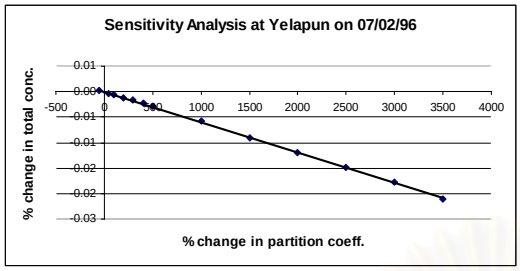


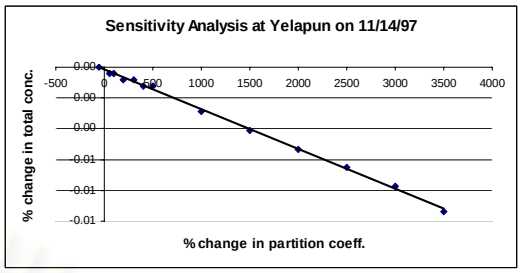


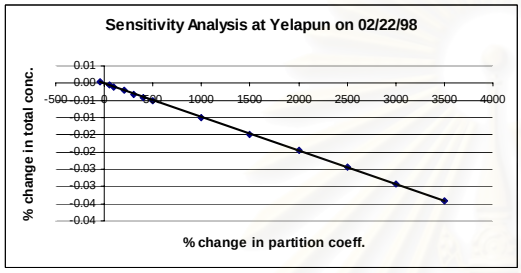


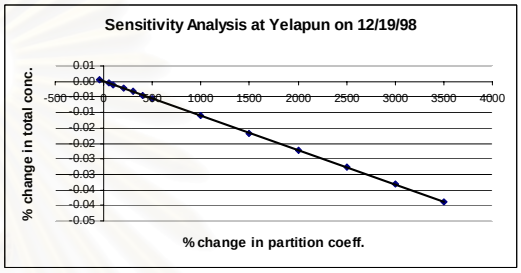


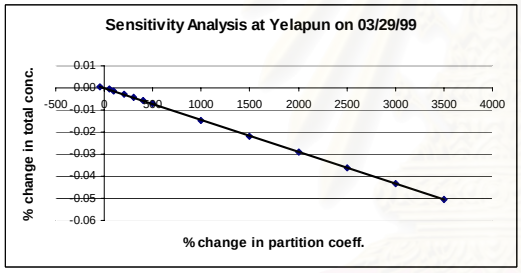
The result of sensitivity analysis by the varying of partition coefficient at Yelapun station, Bannangsta district, Yala province (Cont.)

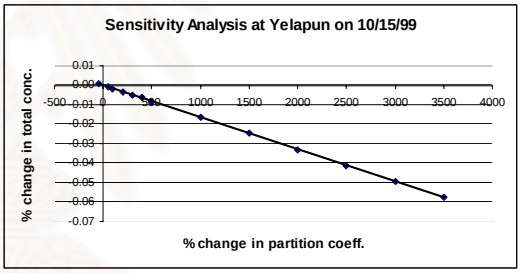


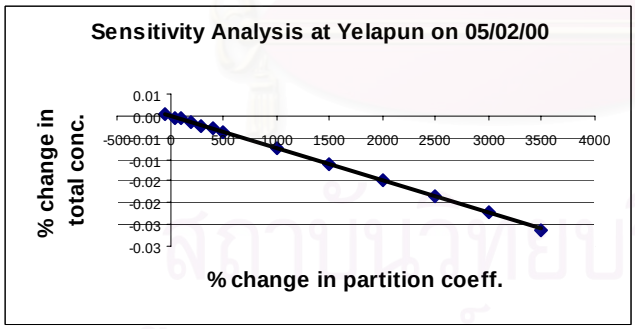




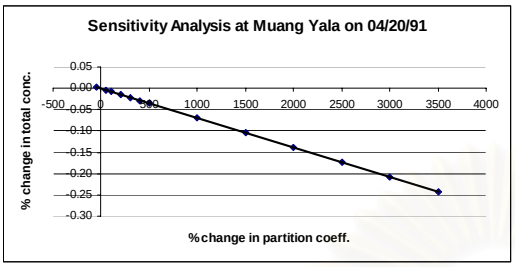


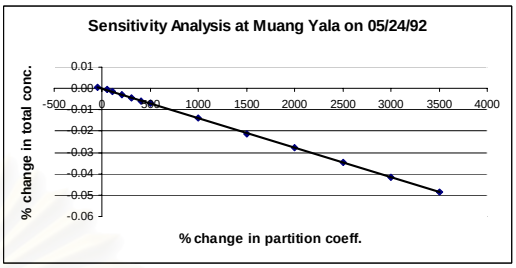


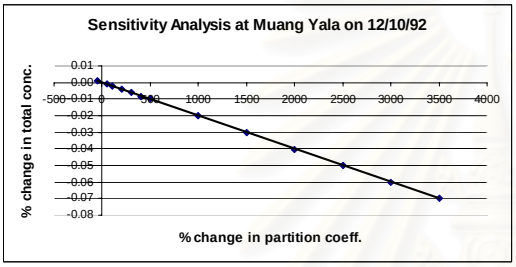


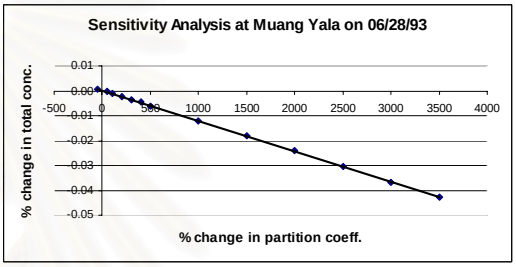


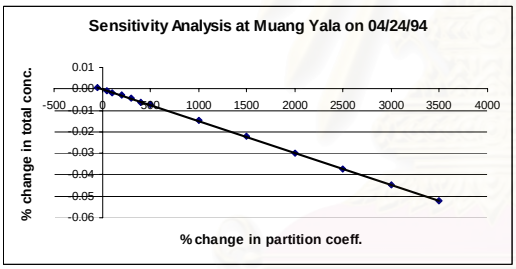
The result of sensitivity analysis by the varying of partition coefficient at Muang district, Yala province

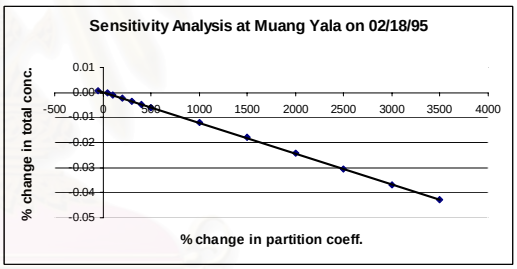


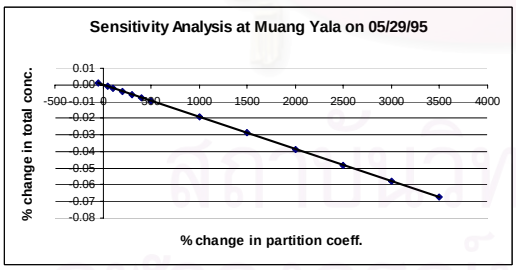


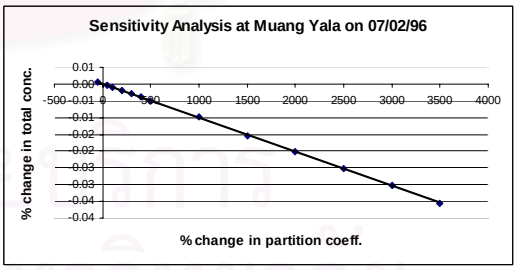


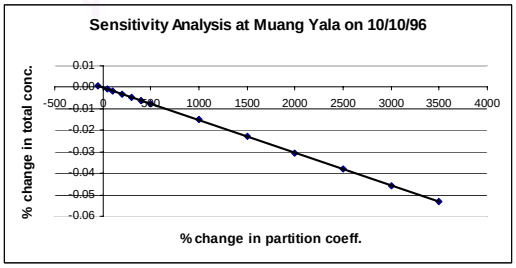


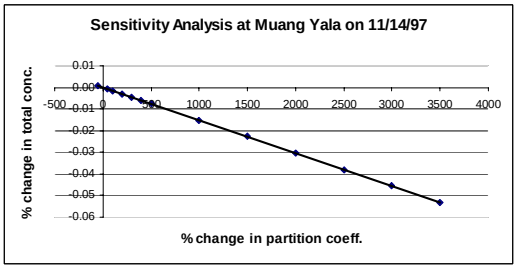




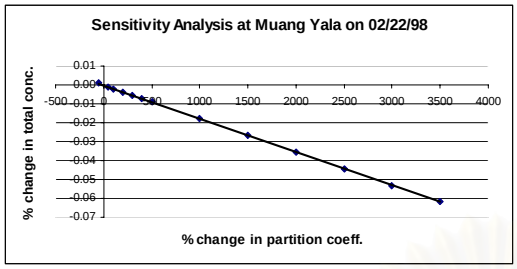


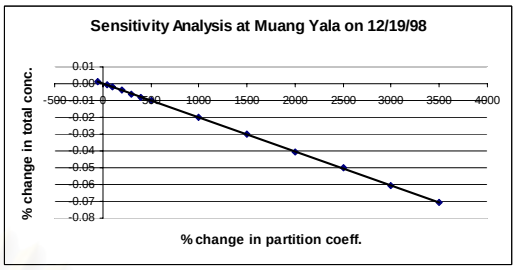


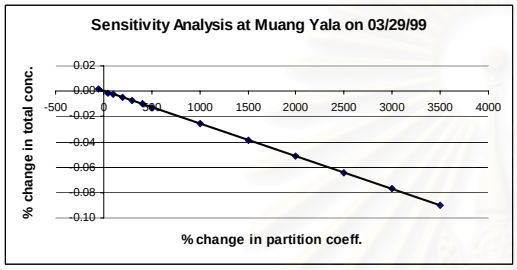


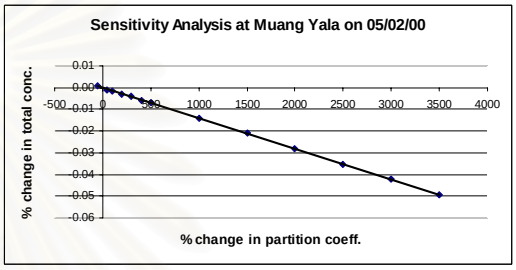


The result of sensitivity analysis by the varying of partition coefficient at Muang district, Yala province (Cont.)

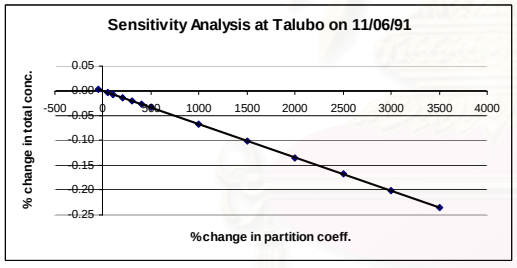


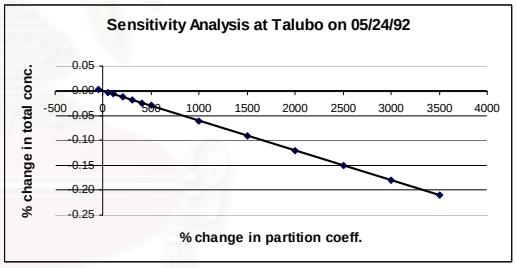


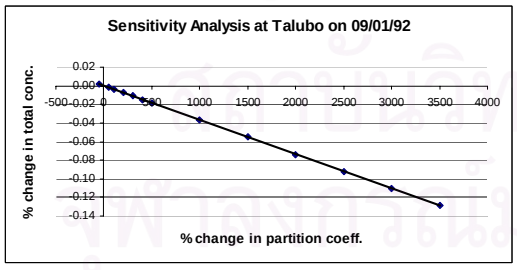


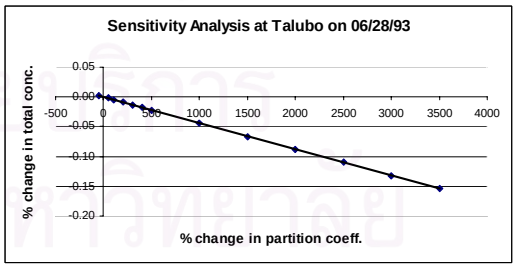


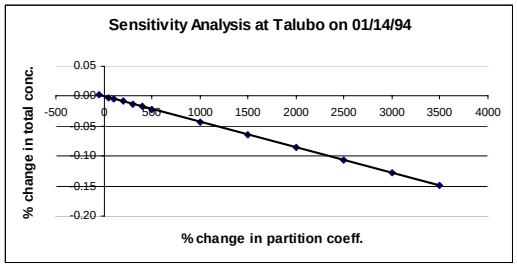
The result of sensitivity analysis by the varying of partition coefficient at Muang district, Pattani province

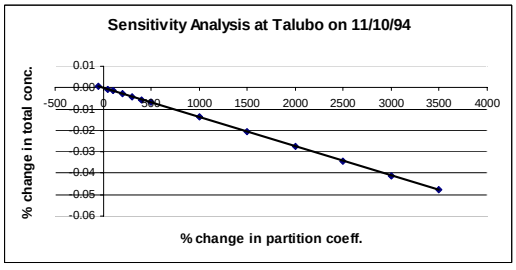




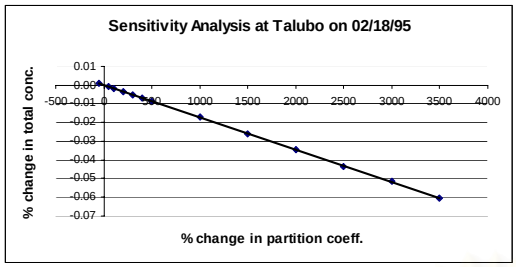


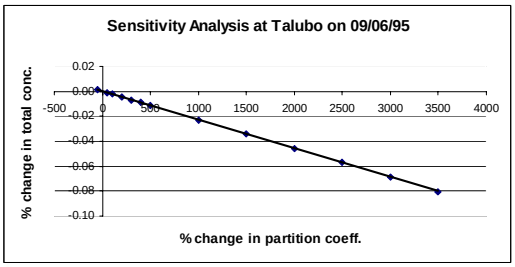


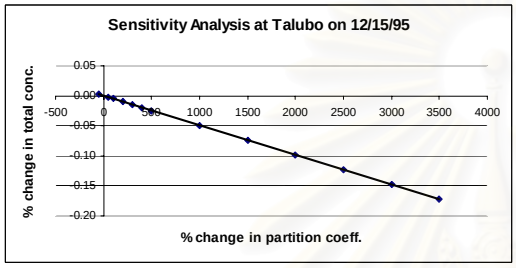


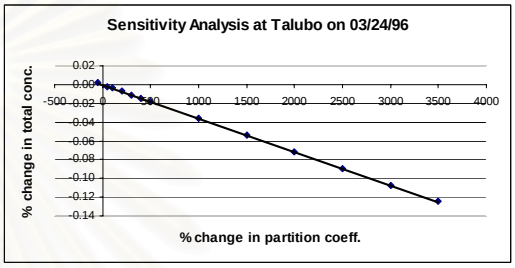


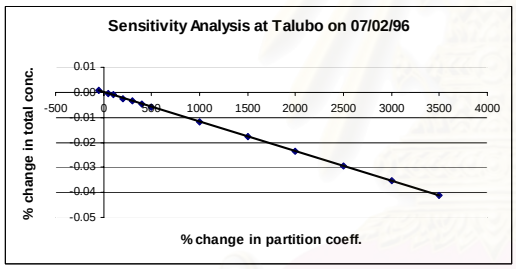
The result of sensitivity analysis by the varying of partition coefficient at Muang district, Pattani province (Cont.)

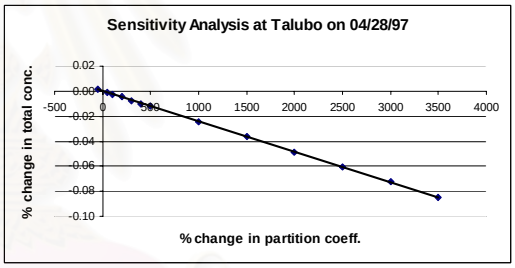


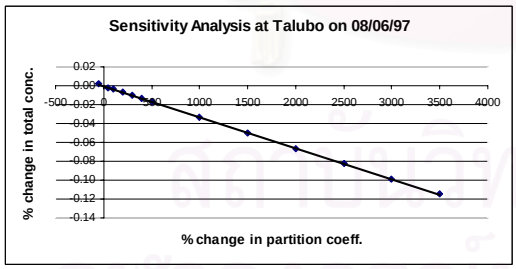


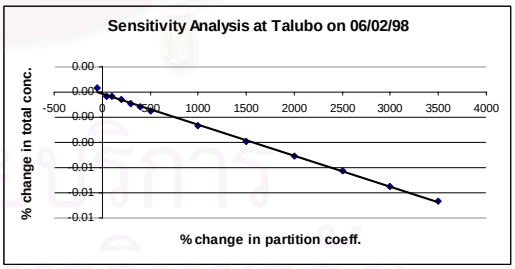


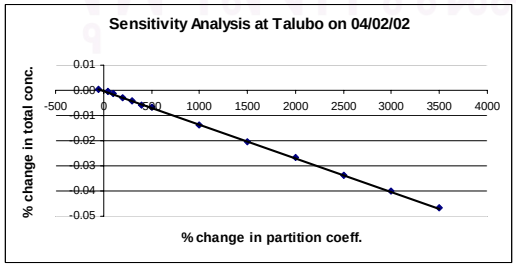


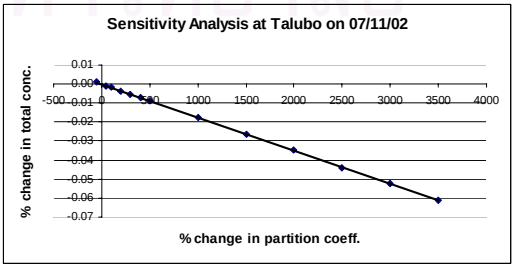




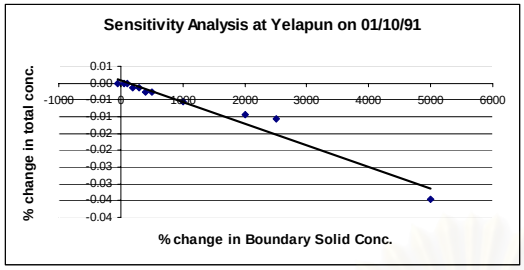


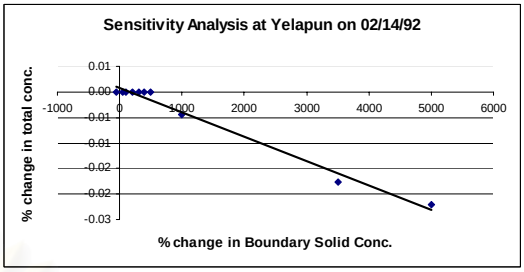


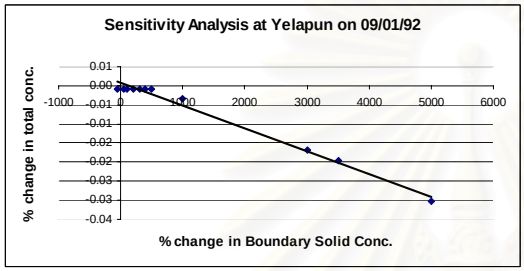


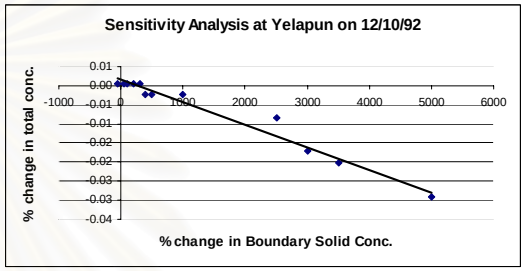


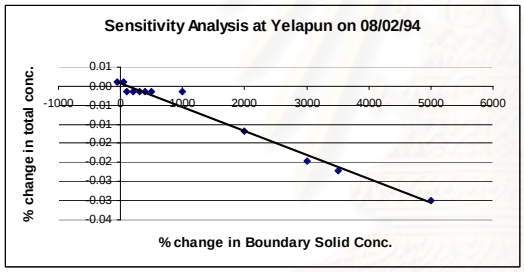
The result of sensitivity analysis by the varying of boundary solid concentration at Yelapun station, Bannangsta district, Yala province

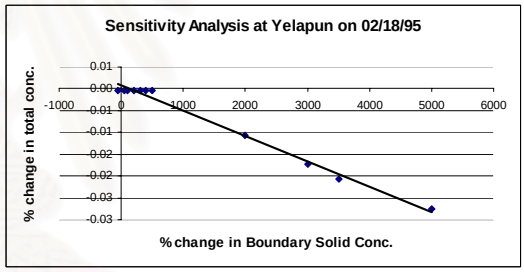


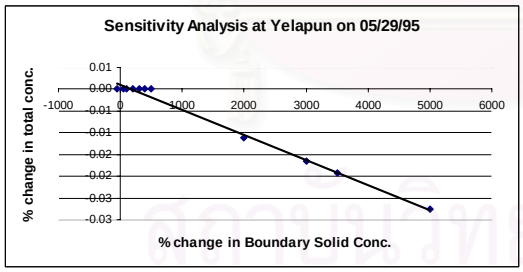


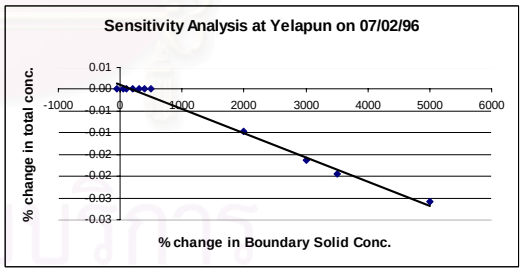


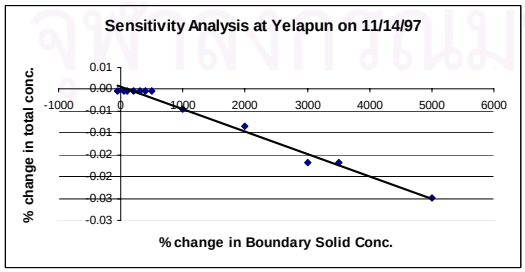


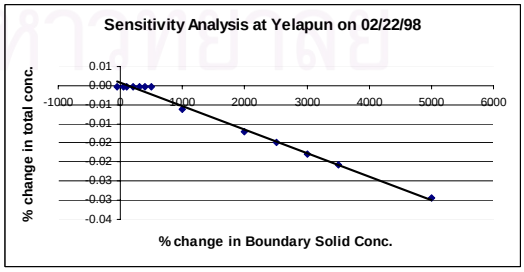




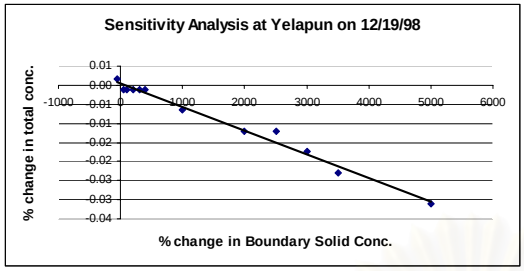


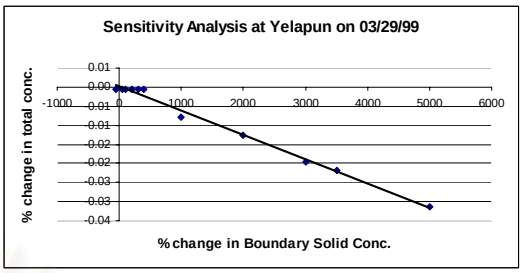


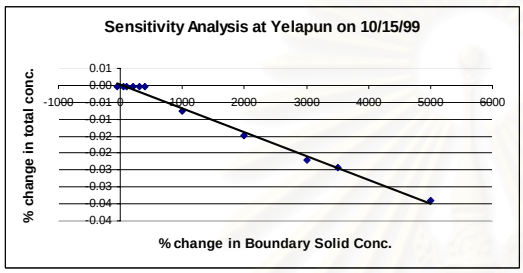


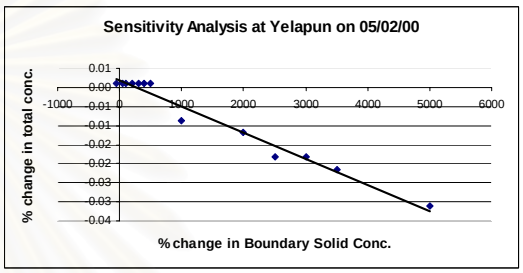


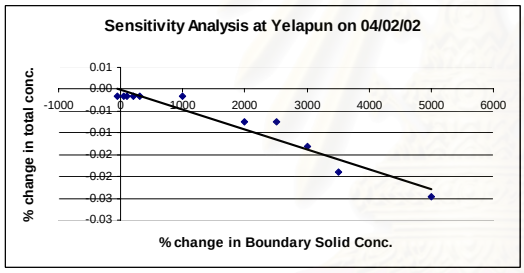
The result of sensitivity analysis by the varying of boundary solid concentration at Yelapun station, Bannangsta district, Yala province (Cont.)

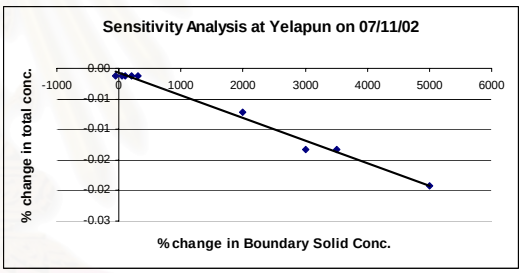




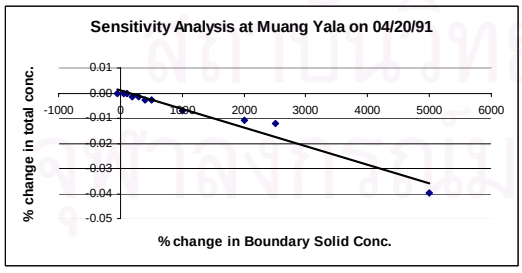


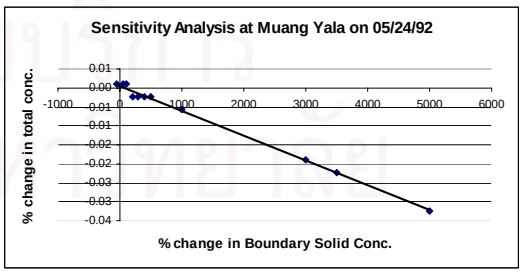


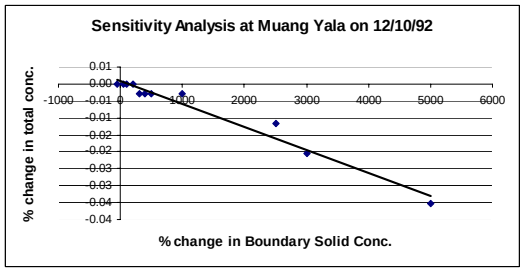


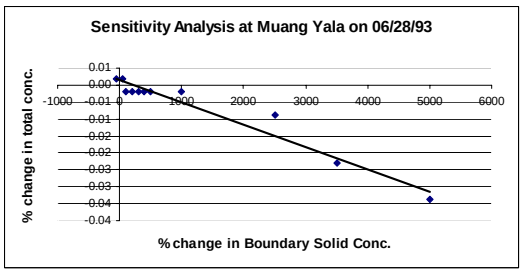


The result of sensitivity analysis by the varying of boundary solid concentration at Muang district, Yala province

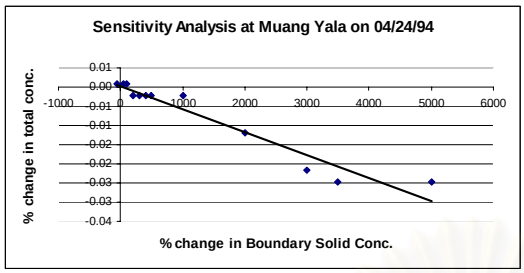


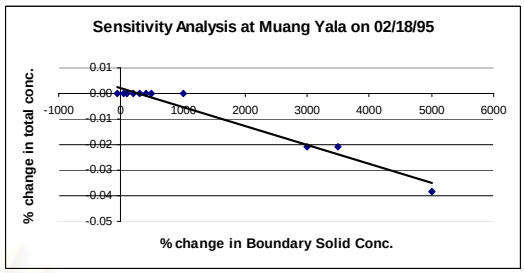


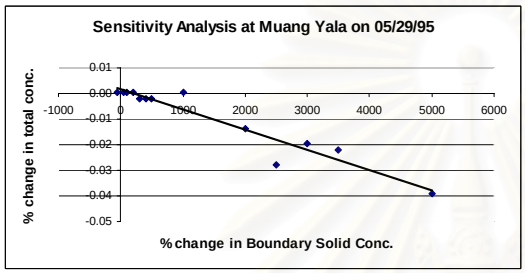


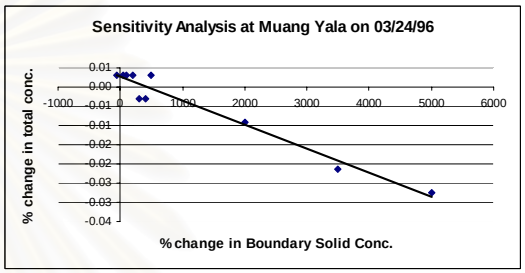


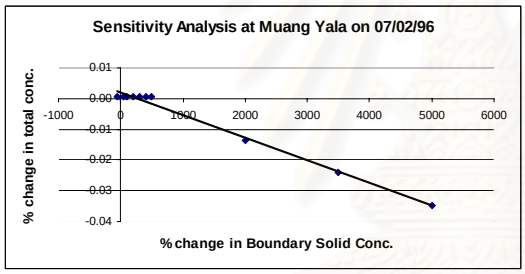
The result of sensitivity analysis by the varying of boundary solid concentration at Muang district, Yala province (Cont.)

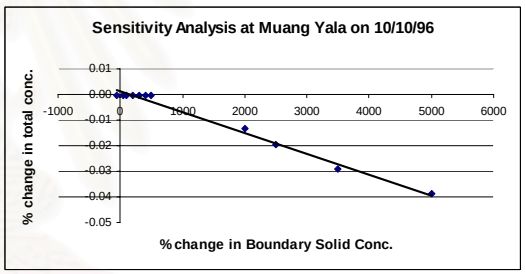


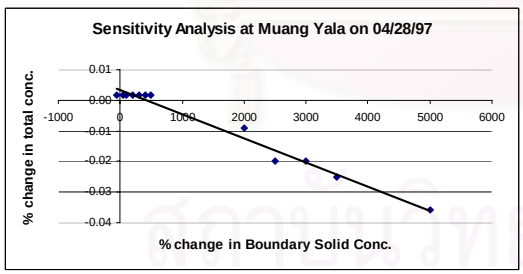


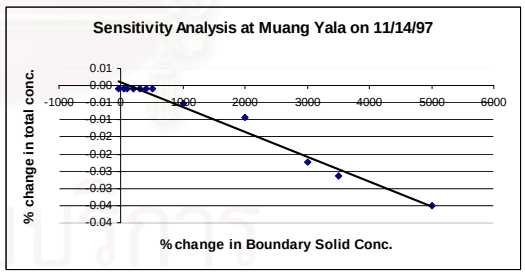


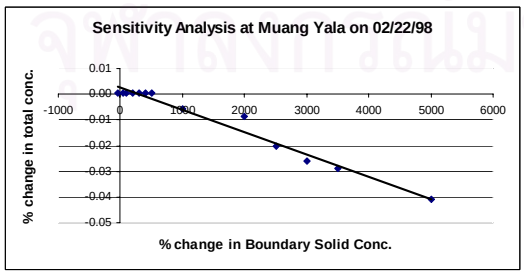


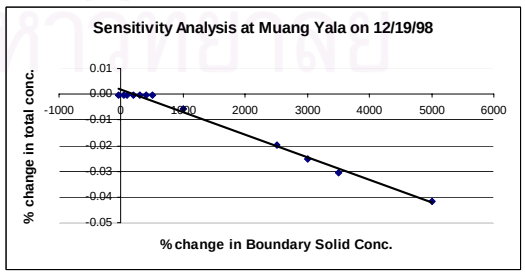




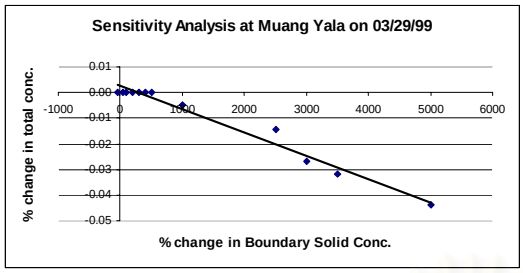


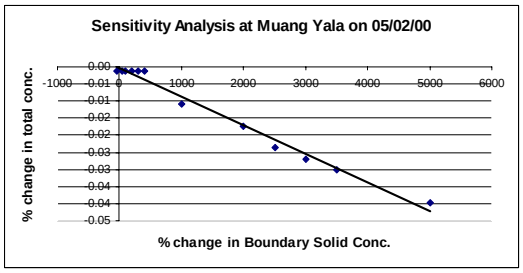


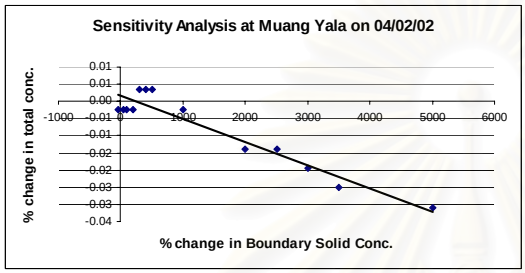


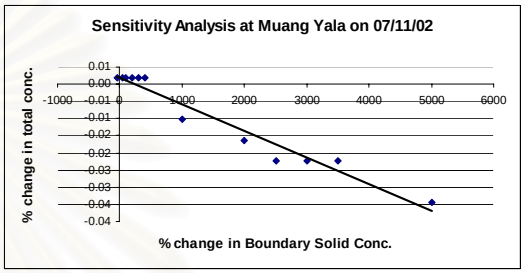


The result of sensitivity analysis by the varying of boundary solid concentration at Muang district, Yala province (Cont.)

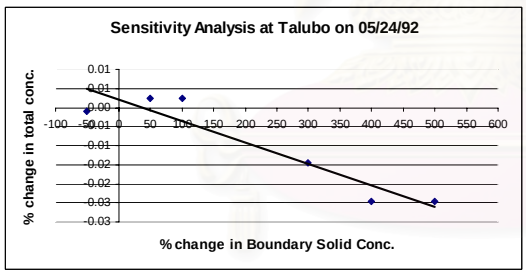


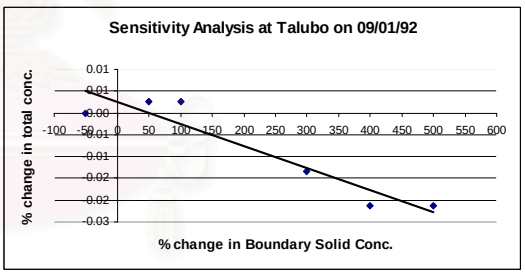


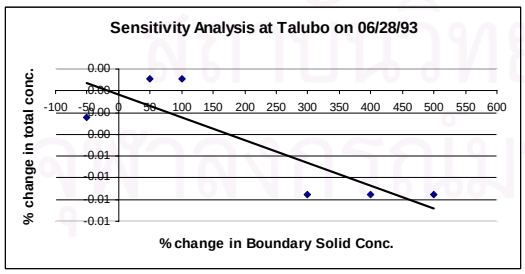


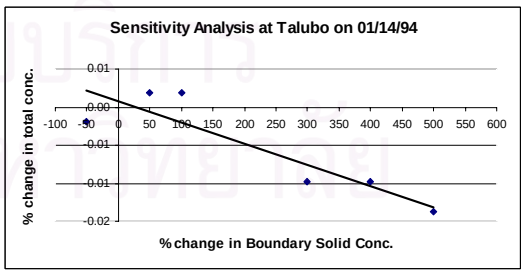


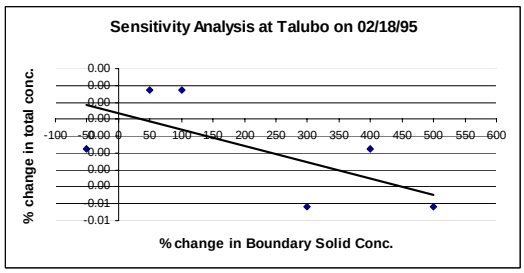
The result of sensitivity analysis by the varying of boundary solid concentration at Muang district, Pattani province

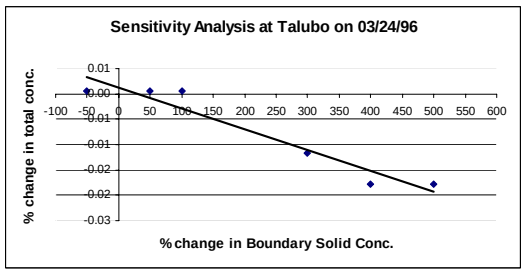




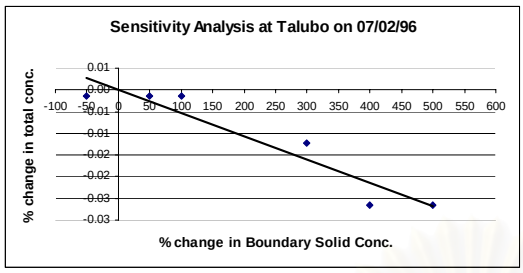


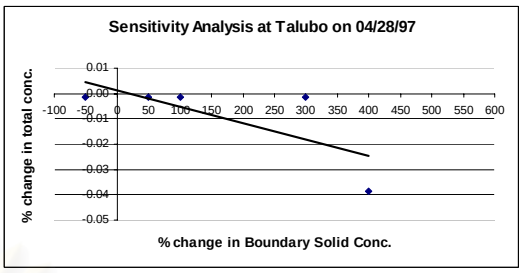


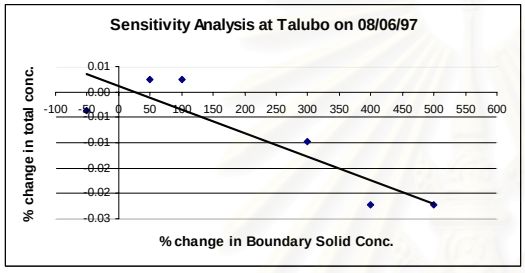


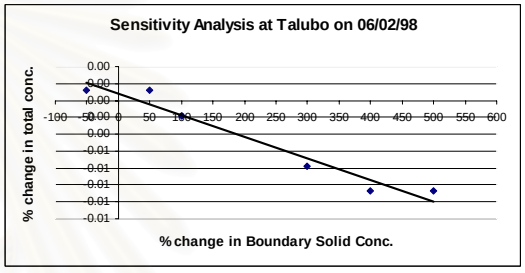


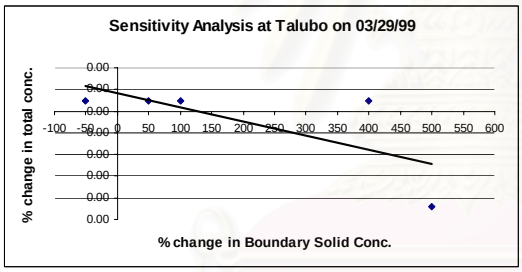
The result of sensitivity analysis by the varying of boundary solid concentration at Muang district, Pattani province (Cont.)

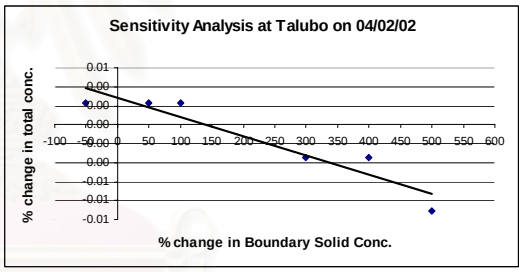


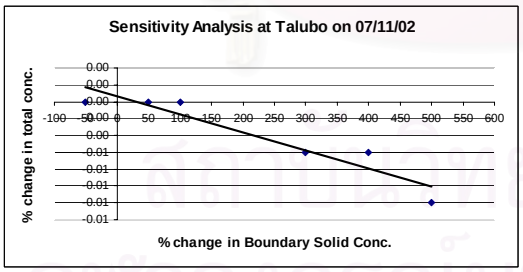




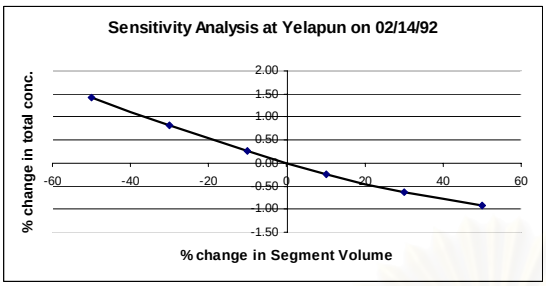


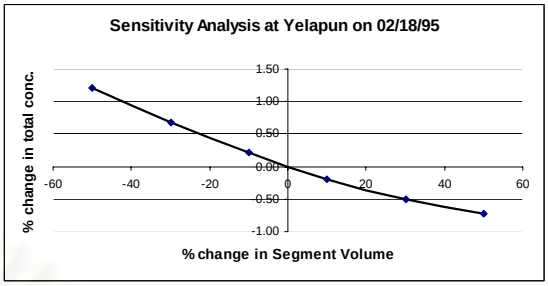


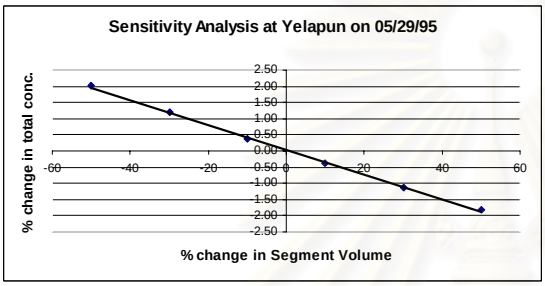


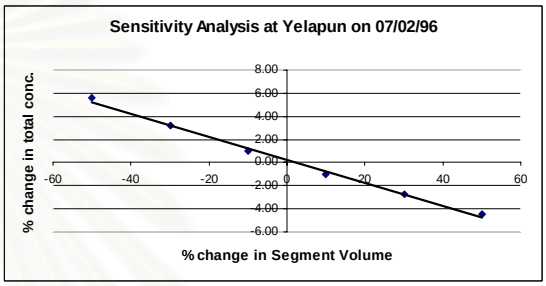


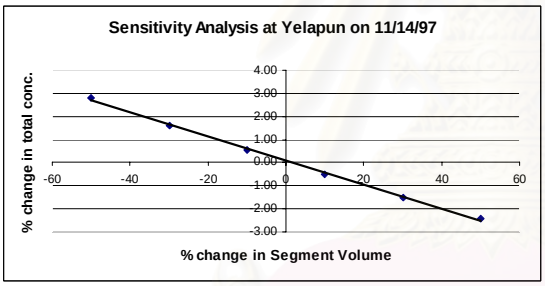
The result of sensitivity analysis by the varying of segment volume at Yelapun station, Bannangsta district, Yala province

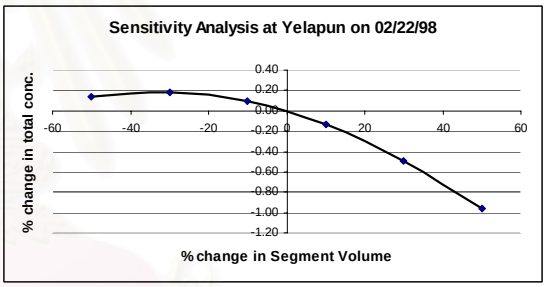


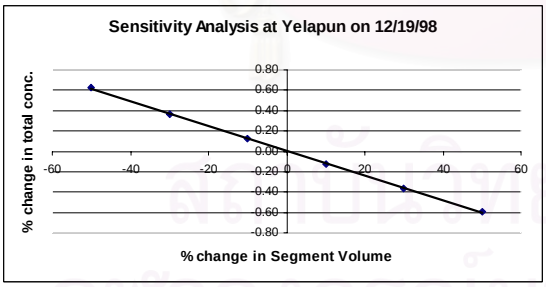


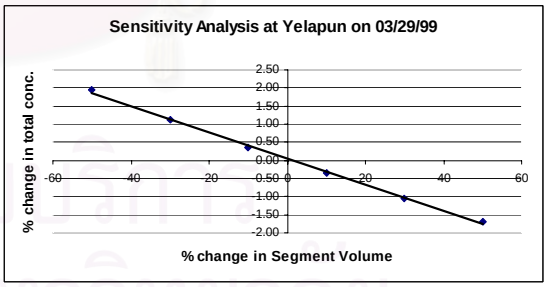


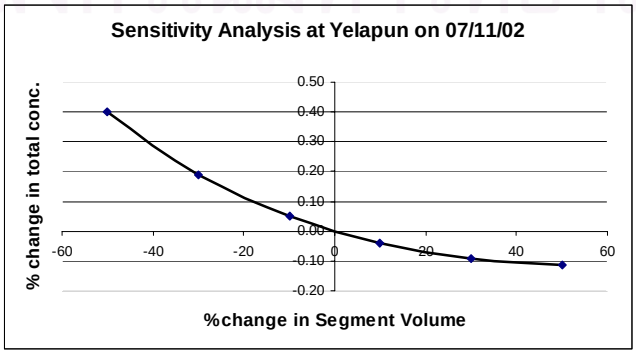




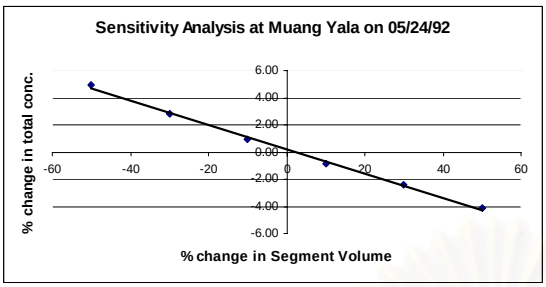


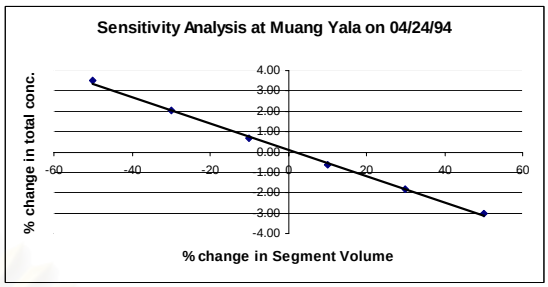


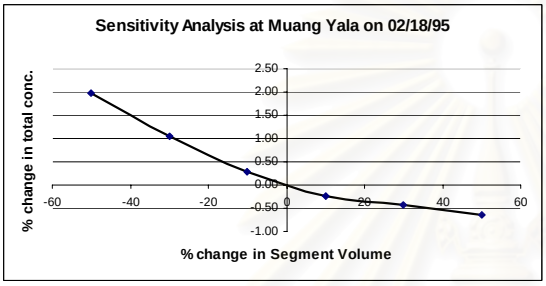


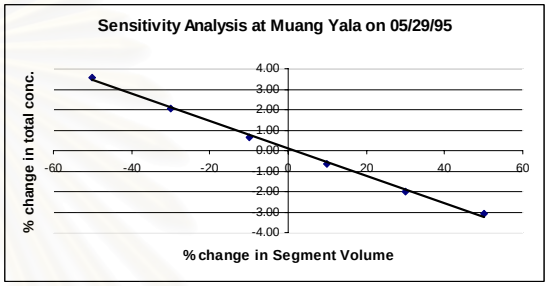


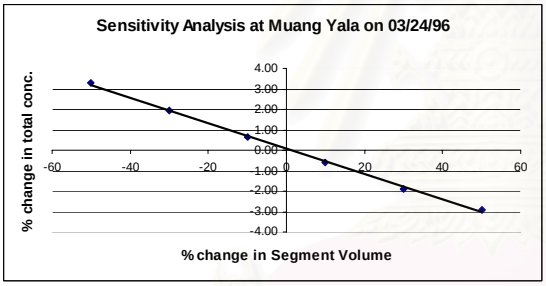
The result of sensitivity analysis by the varying of segment volume at Muang district, Yala province

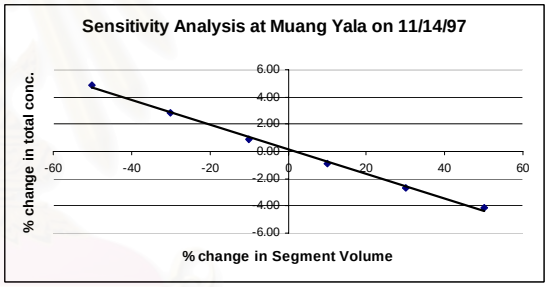


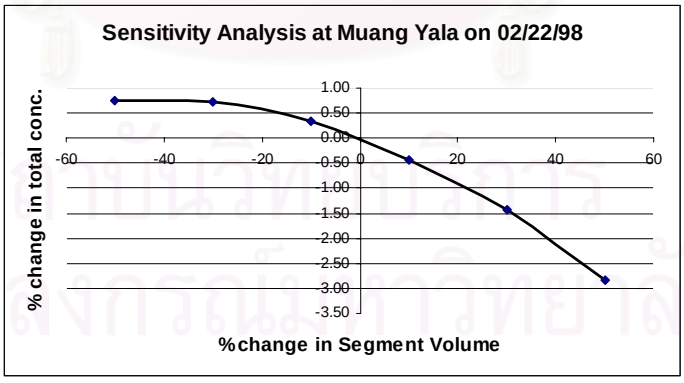




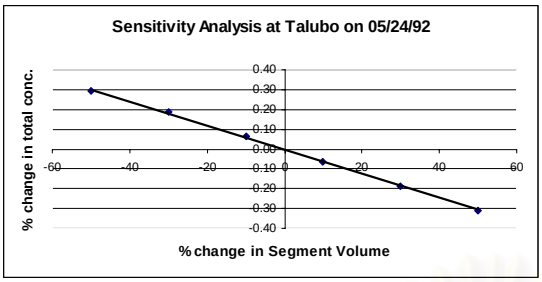


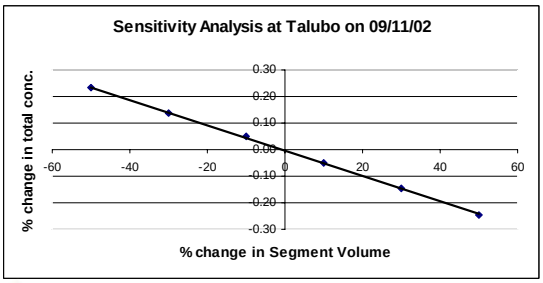


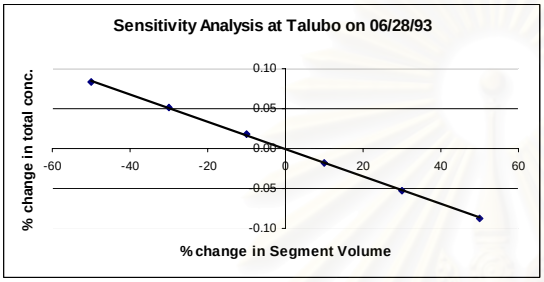


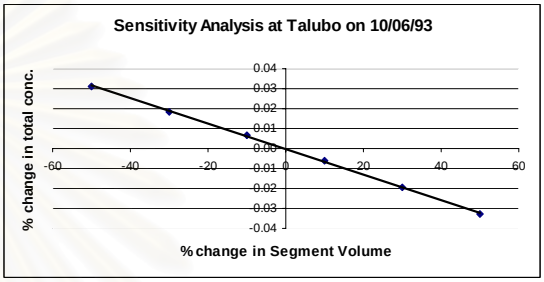


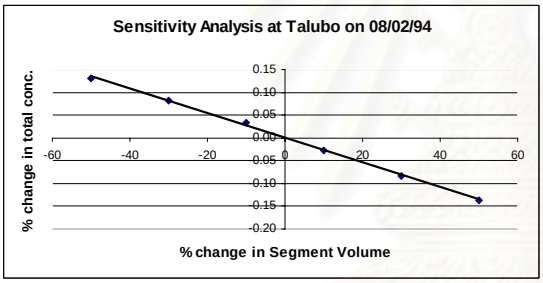
The result of sensitivity analysis by the varying of segment volume at Muang district, Pattani province

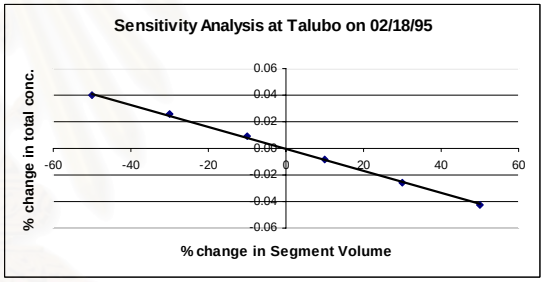


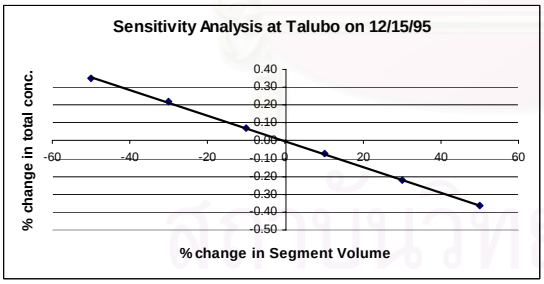


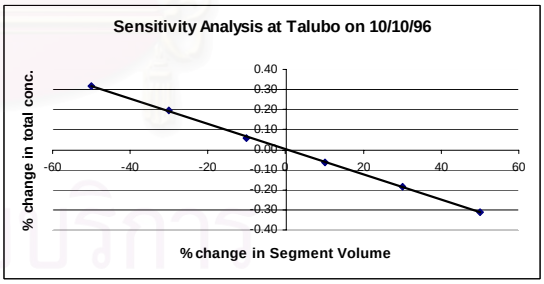


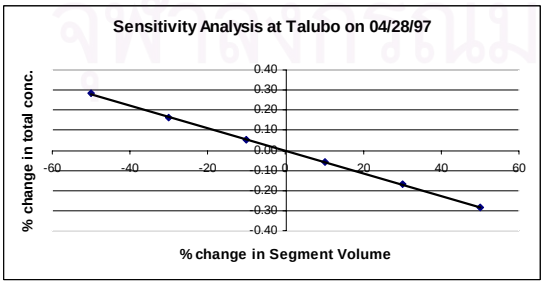


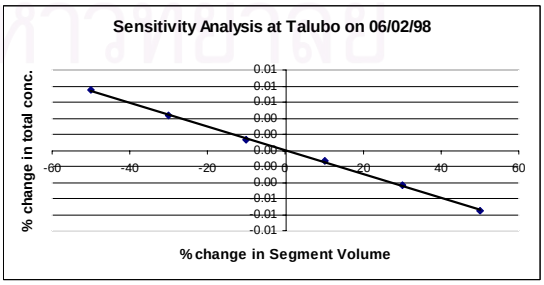




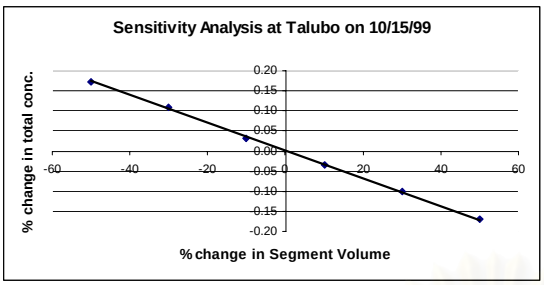


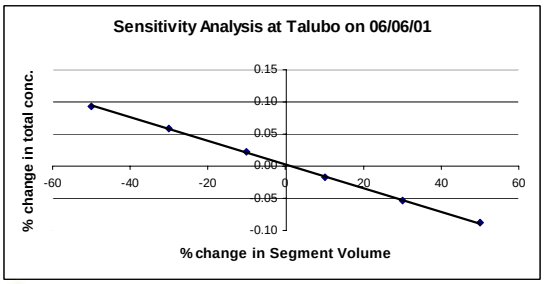


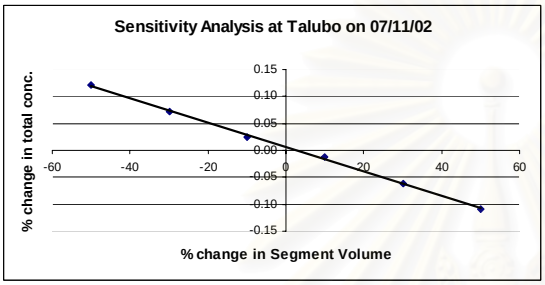


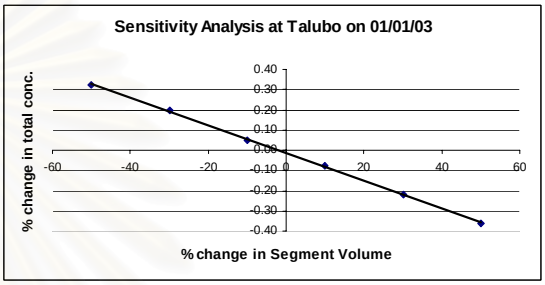


The result of sensitivity analysis by the varying of segment volume at Muang district, Pattani province (Cont.)





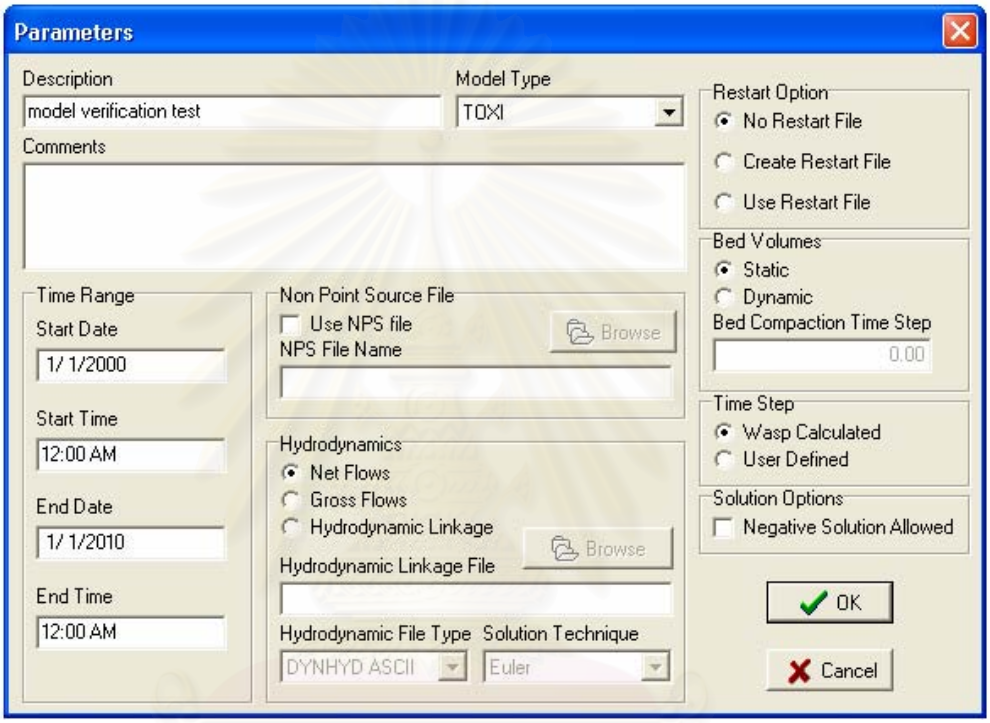




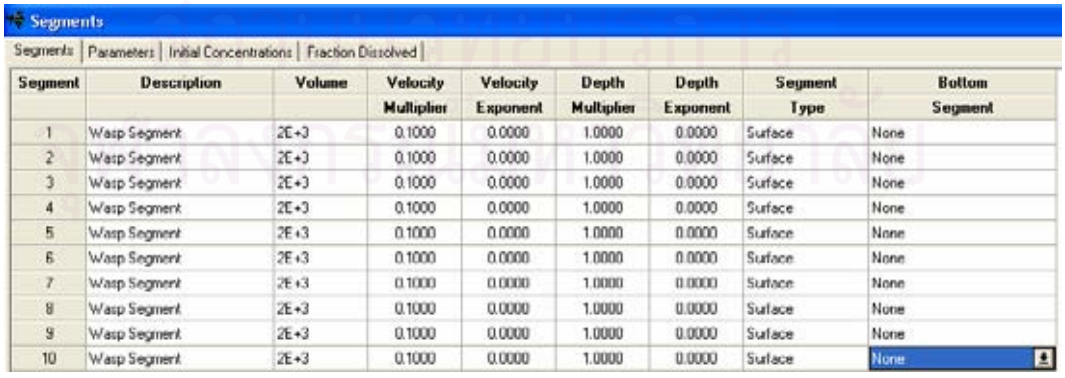
APPENDIX G

WASP DATA SETS FOR MODEL VALIDATION

The selected sub model type, time range, hydrodynamics type, bed volumes type and time step type of WASP in simple scenario study condition 1-4

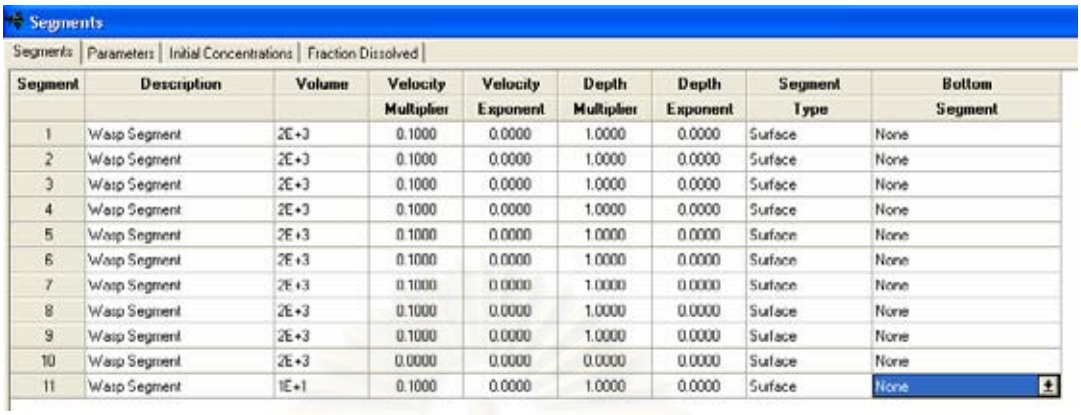


The input segments information for the simple scenario study condition 1-2



Segment	Description	Volume	Velocity Multiplier	Velocity Exponent	Depth Multiplier	Depth Exponent	Segment Type	Bottom Segment
1	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
2	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
3	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
4	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
5	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
6	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
7	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
8	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
9	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
10	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None

The input segments information for the simple scenario study condition 3

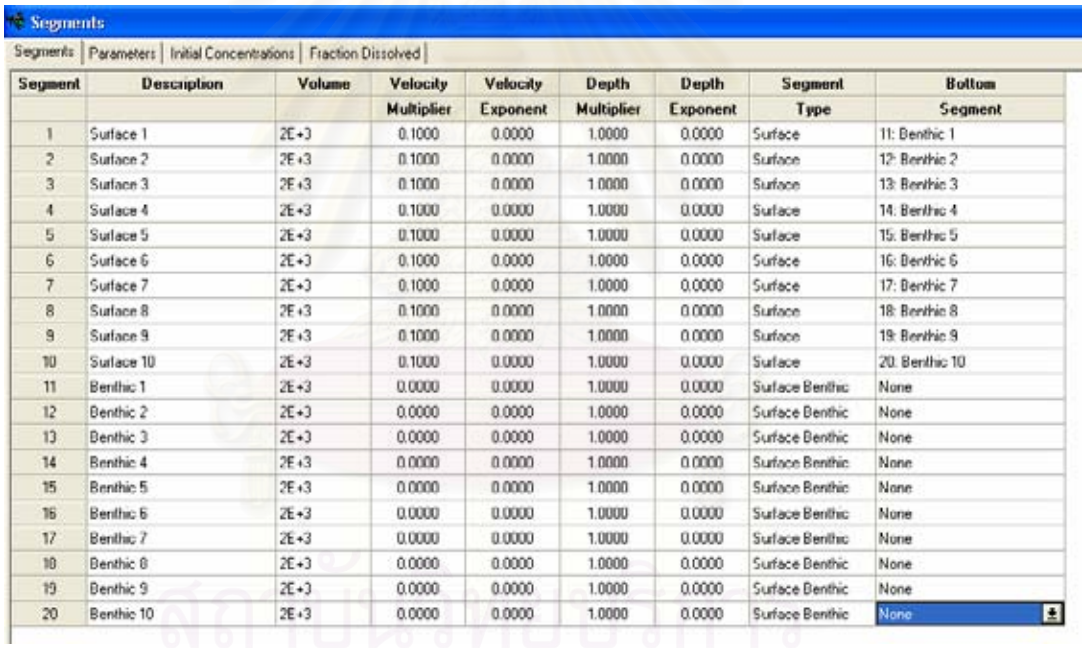


Segments

Segments | Parameters | Initial Concentrations | Fraction Dissolved

Segment	Description	Volume	Velocity Multiplier	Velocity Exponent	Depth Multiplier	Depth Exponent	Segment Type	Bottom Segment
1	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
2	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
3	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
4	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
5	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
6	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
7	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
8	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
9	Wasp Segment	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	None
10	Wasp Segment	2E+3	0.0000	0.0000	0.0000	0.0000	Surface	None
11	Wasp Segment	1E+1	0.1000	0.0000	1.0000	0.0000	Surface	None

The input segments information for the simple scenario study condition 4

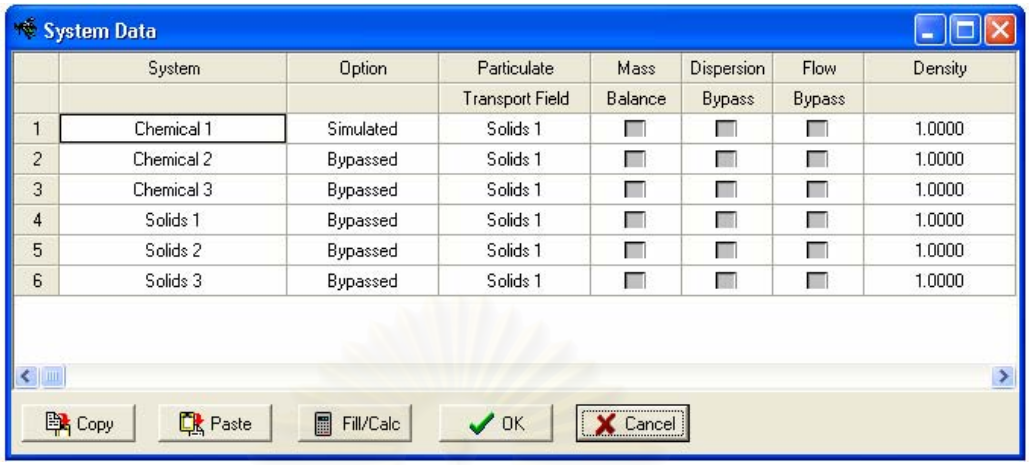


Segments

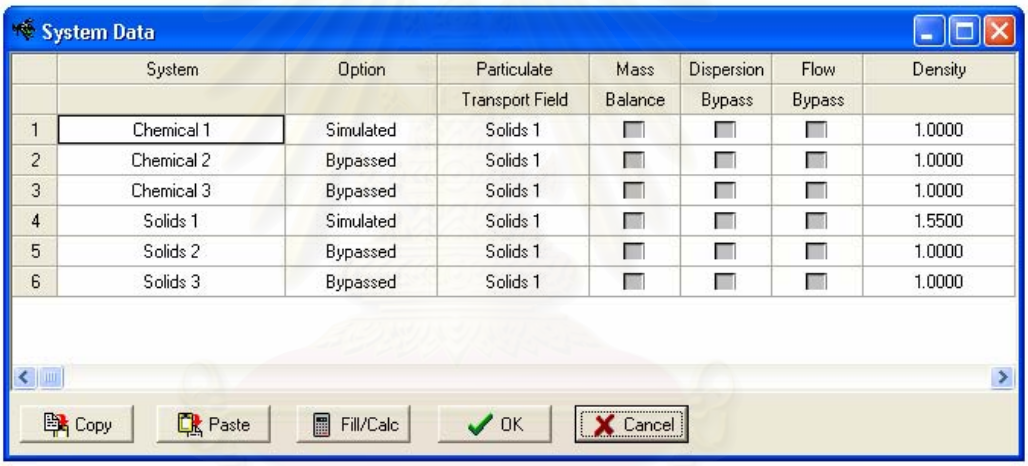
Segments | Parameters | Initial Concentrations | Fraction Dissolved

Segment	Description	Volume	Velocity Multiplier	Velocity Exponent	Depth Multiplier	Depth Exponent	Segment Type	Bottom Segment
1	Surface 1	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	11: Benthic 1
2	Surface 2	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	12: Benthic 2
3	Surface 3	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	13: Benthic 3
4	Surface 4	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	14: Benthic 4
5	Surface 5	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	15: Benthic 5
6	Surface 6	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	16: Benthic 6
7	Surface 7	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	17: Benthic 7
8	Surface 8	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	18: Benthic 8
9	Surface 9	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	19: Benthic 9
10	Surface 10	2E+3	0.1000	0.0000	1.0000	0.0000	Surface	20: Benthic 10
11	Benthic 1	2E+3	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None
12	Benthic 2	2E+3	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None
13	Benthic 3	2E+3	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None
14	Benthic 4	2E+3	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None
15	Benthic 5	2E+3	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None
16	Benthic 6	2E+3	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None
17	Benthic 7	2E+3	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None
18	Benthic 8	2E+3	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None
19	Benthic 9	2E+3	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None
20	Benthic 10	2E+3	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None

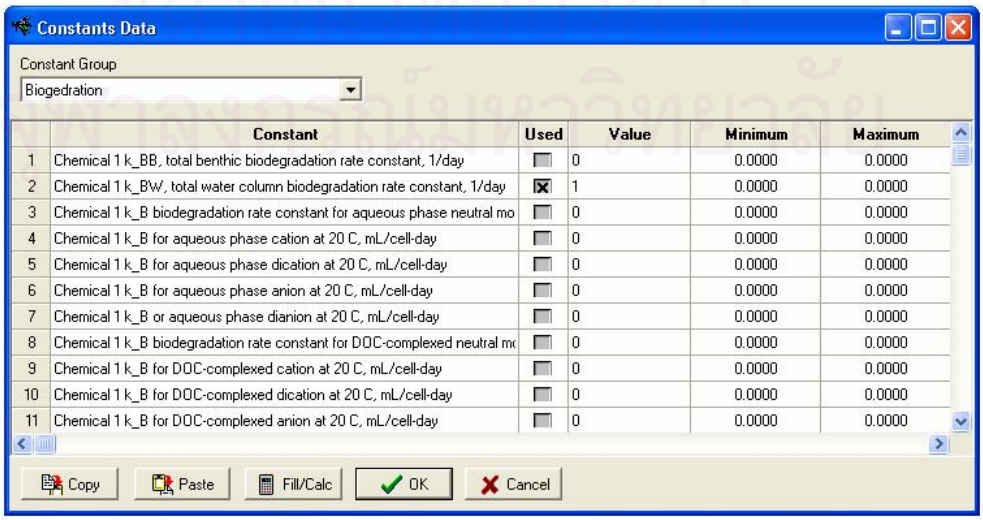
The selected system data of WASP in simple scenario study condition 1-3



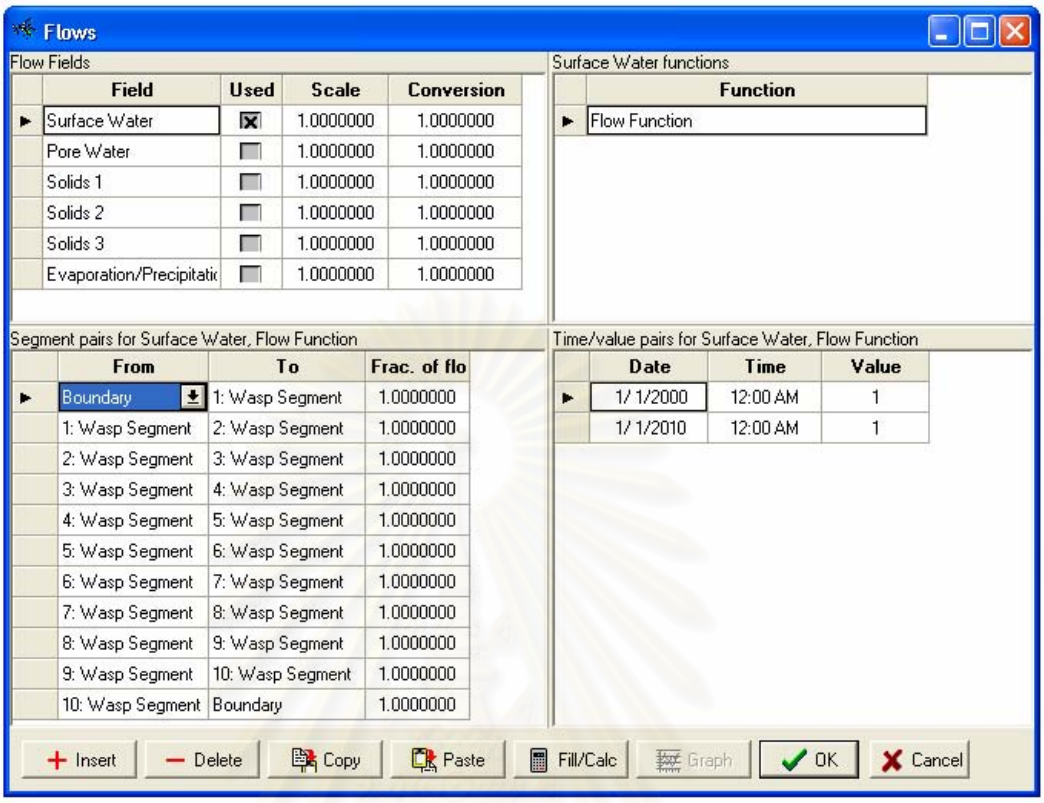
The selected system data of WASP in simple scenario study condition 4



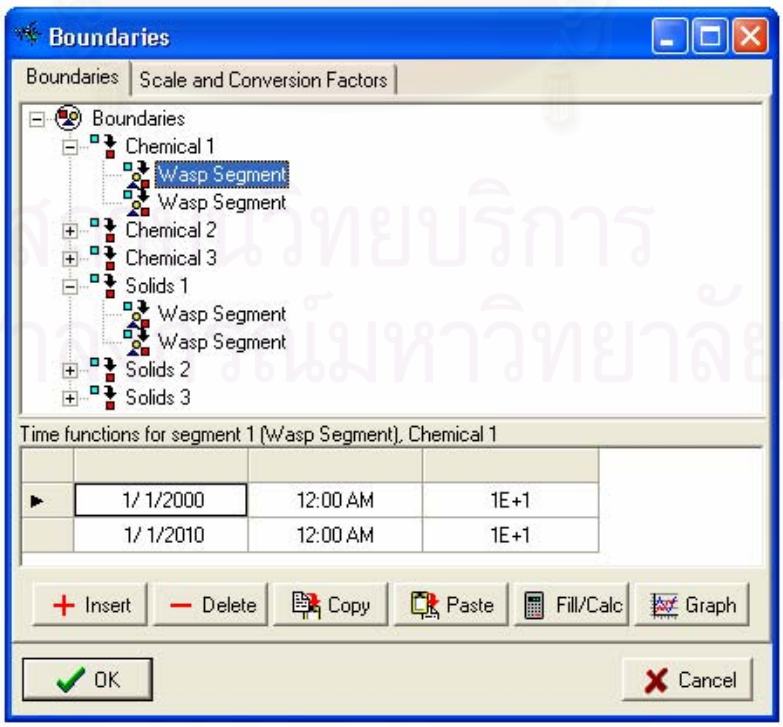
The constant data of WASP in simple scenario study condition 1-4



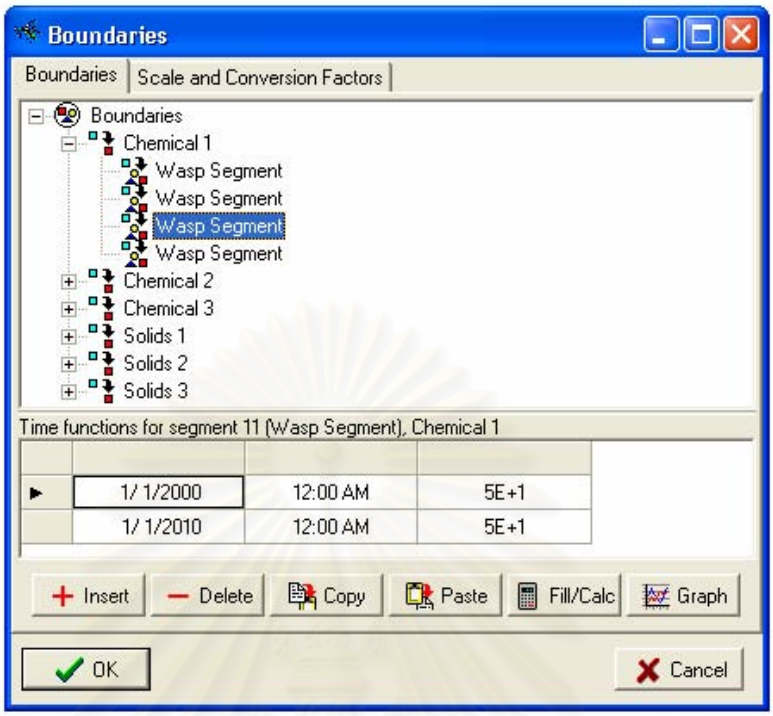
The flow fields information for the simple scenario study condition 1-4



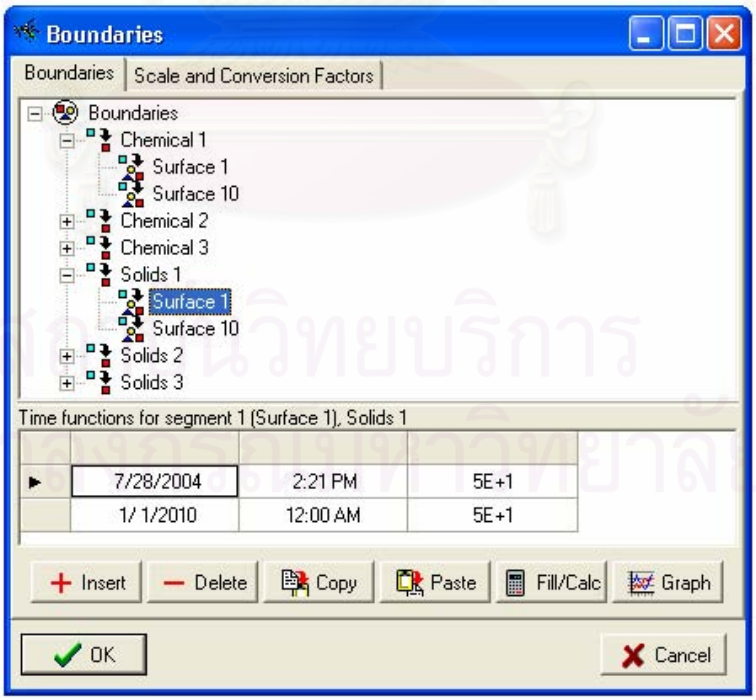
The input boundary chemical concentration for the simple scenario study condition 1-2



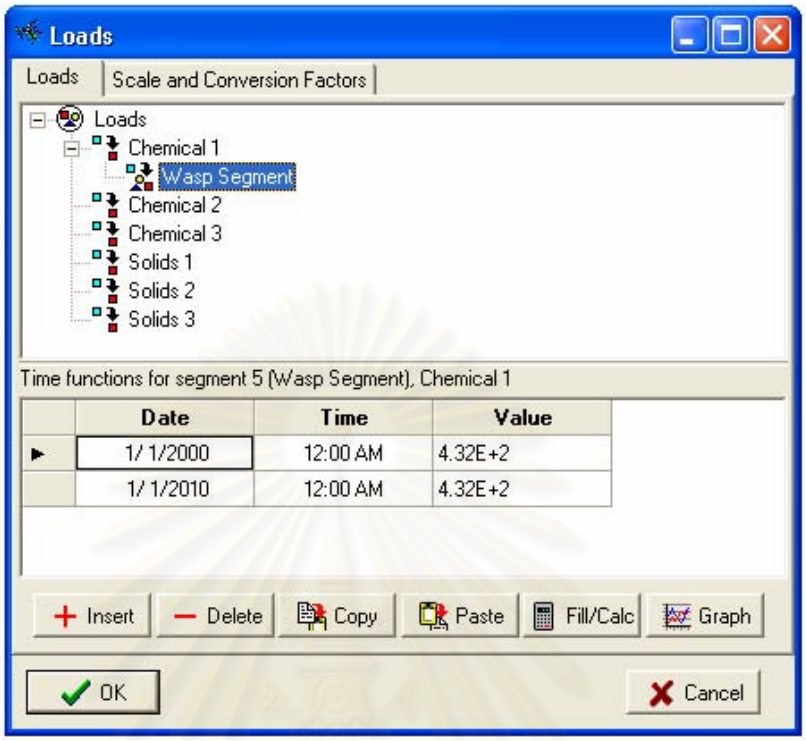
The input boundary chemical concentration for the simple scenario study condition 3



The input boundary solid concentration for the simple scenario study condition 4



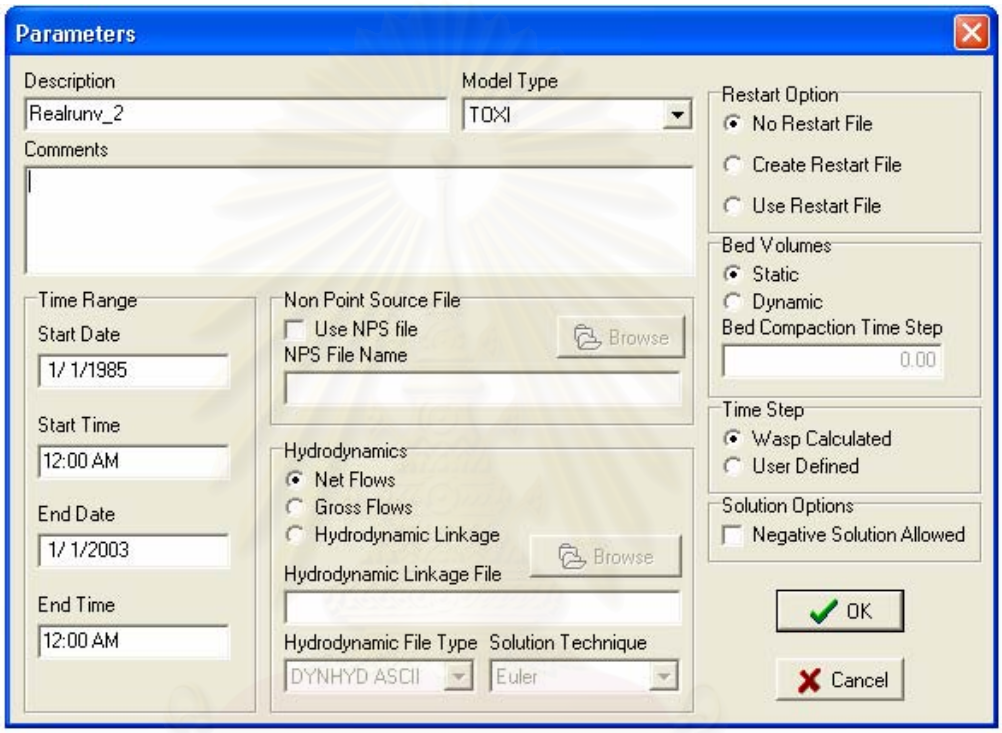
The input waste loading for the simple scenario study condition 2



APPENDIX H

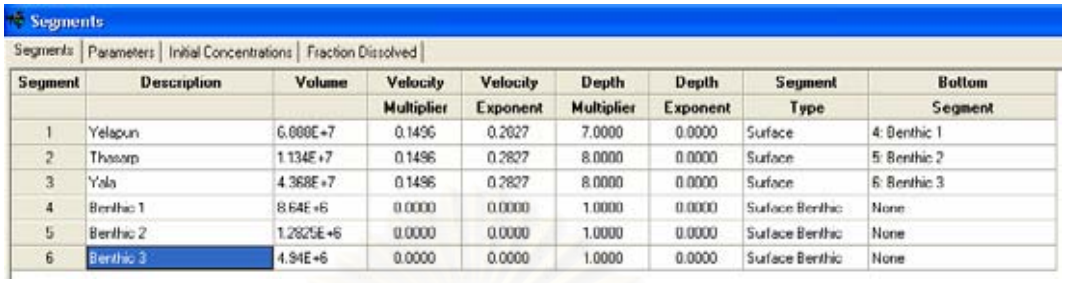
WASP DATA SETS FOR REAL SCENARIO STUDY

The selected sub model type, time range, hydrodynamics type, bed volumes type and time step type of WASP in real scenario study



The input time step and print interval of WASP in real scenario study

The input six segments information for the upstream part of the Pattani Dam

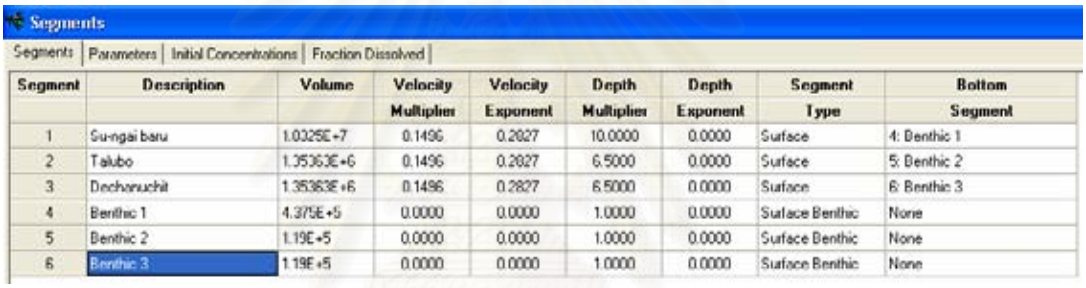


Segments

Segments | Parameters | Initial Concentrations | Fraction Dissolved

Segment	Description	Volume	Velocity Multiplier	Velocity Exponent	Depth Multiplier	Depth Exponent	Segment Type	Bottom Segment
1	Yelapun	6.888E+7	0.1496	0.2827	7.0000	0.0000	Surface	4: Benthic 1
2	Thasorp	1.134E+7	0.1496	0.2827	8.0000	0.0000	Surface	5: Benthic 2
3	Yala	4.368E+7	0.1496	0.2827	8.0000	0.0000	Surface	6: Benthic 3
4	Benthic 1	8.64E+6	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None
5	Benthic 2	1.2825E+6	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None
6	Benthic 3	4.94E+6	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None

The input six segments information for the downstream part of the Pattani Dam

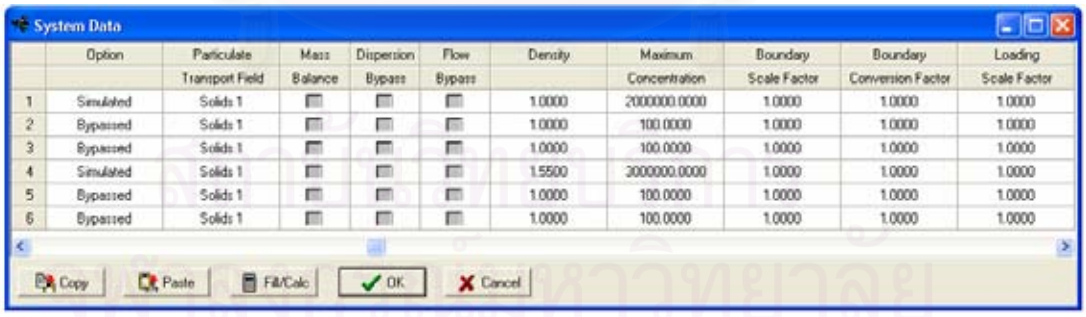


Segments

Segments | Parameters | Initial Concentrations | Fraction Dissolved

Segment	Description	Volume	Velocity Multiplier	Velocity Exponent	Depth Multiplier	Depth Exponent	Segment Type	Bottom Segment
1	Su-ngai baru	1.0325E+7	0.1496	0.2827	10.0000	0.0000	Surface	4: Benthic 1
2	Talubo	1.35363E+6	0.1496	0.2827	6.5000	0.0000	Surface	5: Benthic 2
3	Dechanuchit	1.35363E+6	0.1496	0.2827	6.5000	0.0000	Surface	6: Benthic 3
4	Benthic 1	4.375E+5	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None
5	Benthic 2	1.19E+5	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None
6	Benthic 3	1.19E+5	0.0000	0.0000	1.0000	0.0000	Surface Benthic	None

The selected system data of WASP in real scenario study



System Data

	Option	Particulate Transport Field	Mass Balance	Dispersion Bypass	Flow Bypass	Density	Maximum Concentration	Boundary Scale Factor	Boundary Conversion Factor	Loading Scale Factor
1	Simulated	Solids 1	☐	☐	☐	1.0000	2000000.0000	1.0000	1.0000	1.0000
2	Bypassed	Solids 1	☐	☐	☐	1.0000	100.0000	1.0000	1.0000	1.0000
3	Bypassed	Solids 1	☐	☐	☐	1.0000	100.0000	1.0000	1.0000	1.0000
4	Simulated	Solids 1	☐	☐	☐	1.5500	3000000.0000	1.0000	1.0000	1.0000
5	Bypassed	Solids 1	☐	☐	☐	1.0000	100.0000	1.0000	1.0000	1.0000
6	Bypassed	Solids 1	☐	☐	☐	1.0000	100.0000	1.0000	1.0000	1.0000

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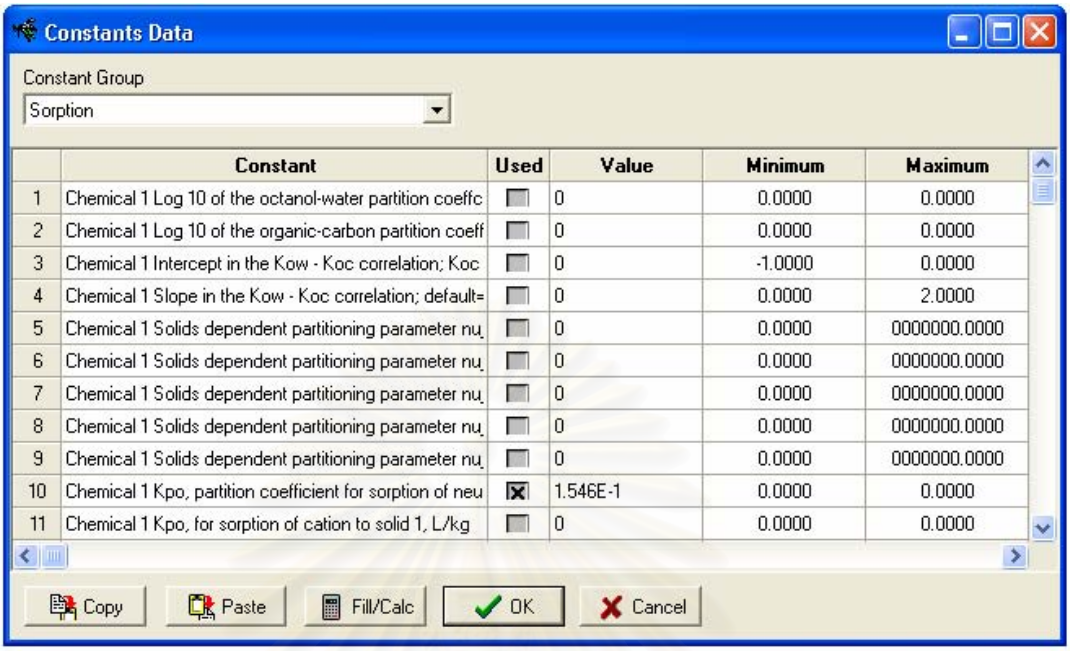
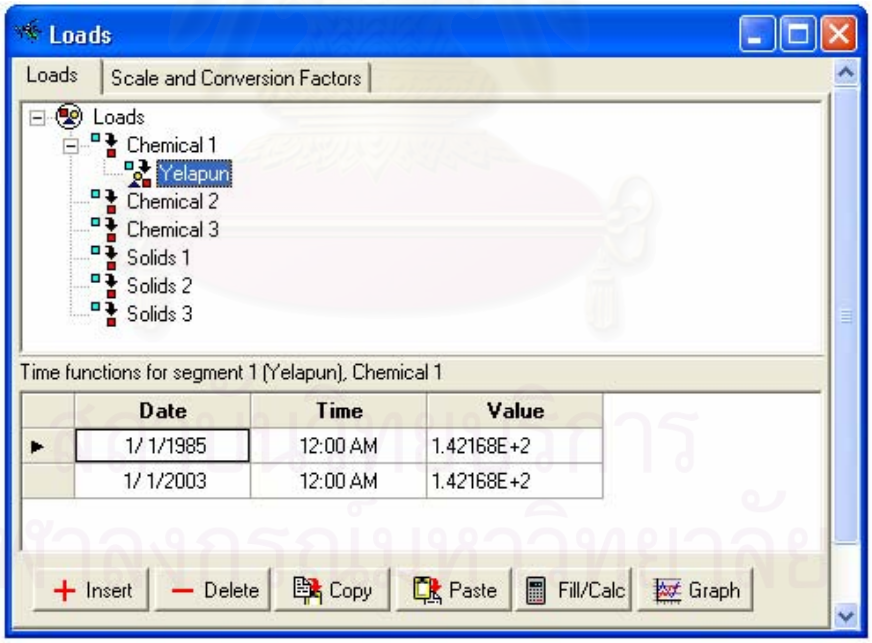
The constant data of WASP in real scenario study



The input waste loading at the first segment of Pattani River



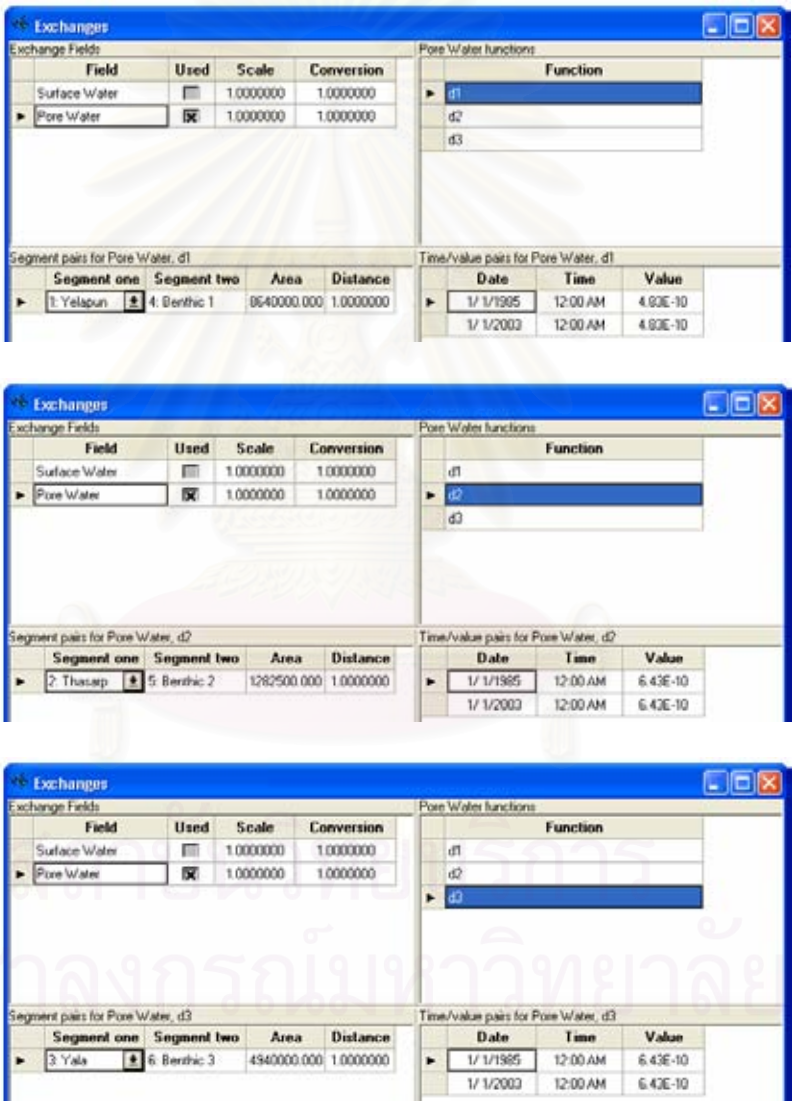
The input waste loading at the first segment of the downstream part of the Pattani Dam

Date	Lead Loading (kg/day)
1/1/1985	0
11/4/1985	13.8524
20/7/1985	54.8787
28/10/1985	91.5002
5/2/1986	108.2143
16/5/1986	108.2449
24/8/1986	100.0223
2/12/1986	89.7489
12/3/1987	80.2958
20/6/1987	72.398
28/9/1987	65.947
6/1/1988	60.6316
15/4/1988	56.1851
24/7/1988	52.3968
1/11/1988	49.1214
9/2/1989	46.2525
20/5/1989	43.7197
28/8/1989	41.462
6/12/1989	39.4353
16/3/1990	165.4527
24/6/1990	158.1371
2/10/1990	151.4594
10/1/1991	158.5502
20/4/1991	151.4868
29/7/1991	139.1989
6/11/1991	207.098
14/2/1992	79.9309
24/5/1992	108.0845
1/9/1992	136.0496
10/12/1992	149.4018

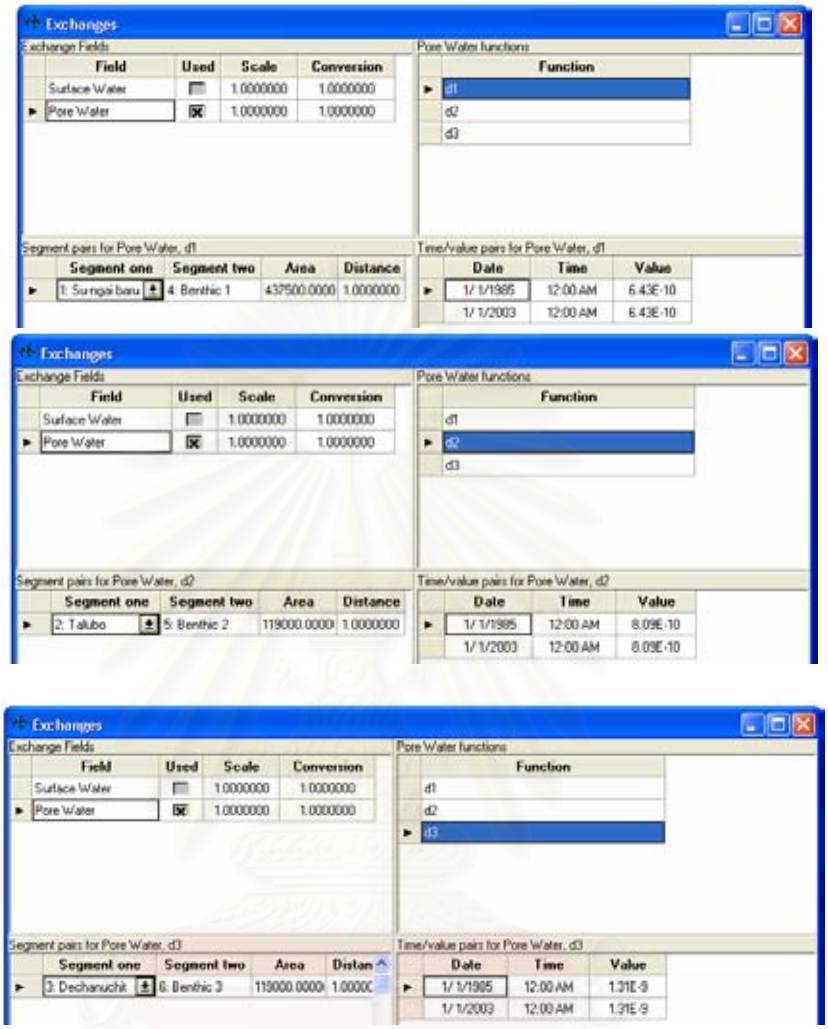
20/3/1993	135.031
28/6/1993	145.4708
6/10/1993	148.9627
14/1/1994	143.281
24/4/1994	107.3769
2/8/1994	135.2779
10/11/1994	165.9658
18/2/1995	149.4132
29/5/1995	121.2842
6/9/1995	90.8589
15/12/1995	159.2103
24/3/1996	188.3886
2/7/1996	116.7426
10/10/1996	161.3577
18/1/1997	141.5201
28/4/1997	177.5984
6/8/1997	153.2425
14/11/1997	95.8315
22/2/1998	139.4239
2/6/1998	144.5887
10/9/1998	146.2437
19/12/1998	137.8046
29/3/1999	156.7444
7/7/1999	129.9346
15/10/1999	189.3815
23/1/2000	145.2924
2/5/2000	148.5779
10/8/2000	141.1192
18/11/2000	146.6647
26/2/2001	133.614
6/6/2001	151.1834
14/9/2001	136.7159
23/12/2001	144.2689

2/4/2002	135.7643
11/7/2002	143.1622
19/10/2002	106.9729
1/1/2003	131.7358

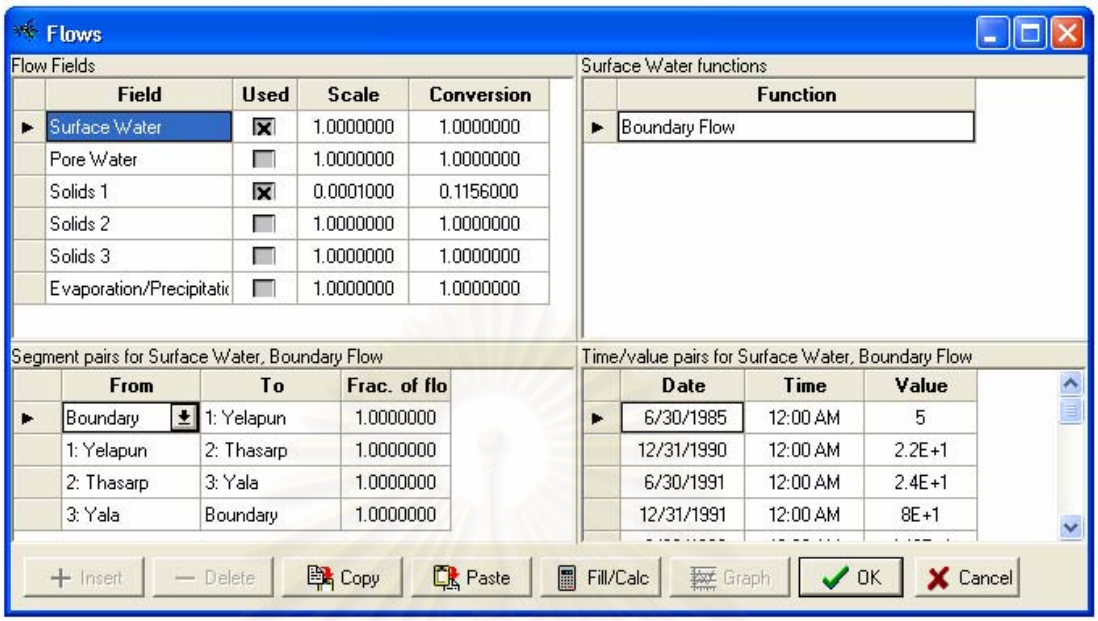
The exchange fields information and the inputted pore water diffusion coefficient in each segments of the model execution



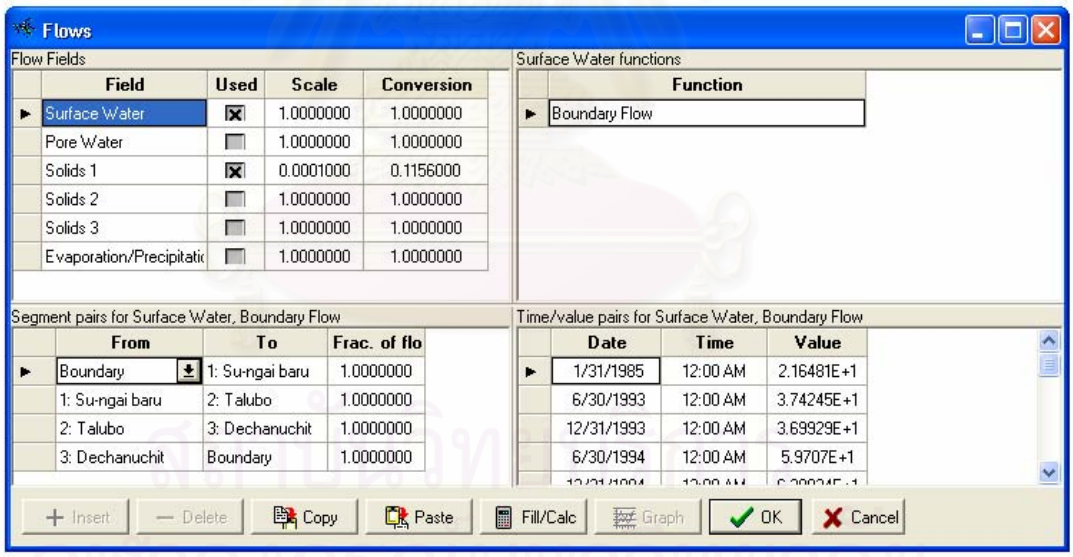
The exchange fields information and the inputted pore water diffusion coefficient in each segments of the model execution (Cont.)



The flow fields information for the upstream part of the Pattani Dam



The flow fields information for the downstream part of the Pattani Dam



The calibrated flows at the upstream part of the Pattani Dam

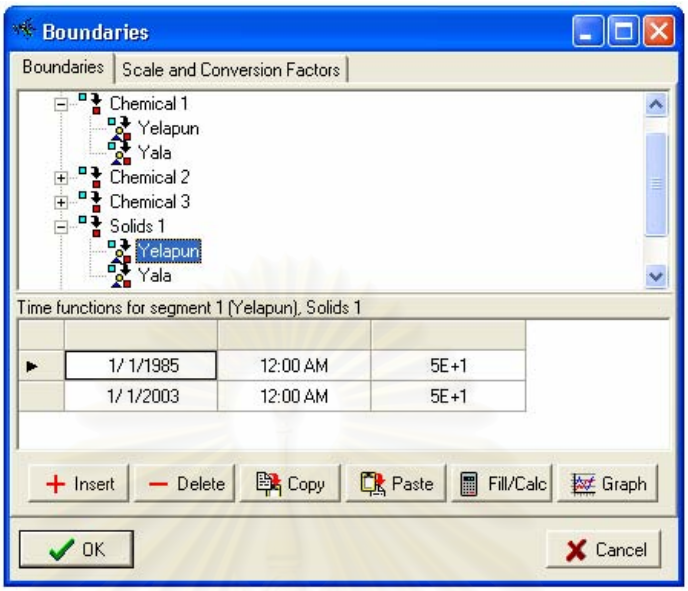
Date	Flows (m^3/sec)
30/6/1985	5
31/12/1990	22
30/6/1991	24
31/12/1991	80
30/6/1992	41.8
31/12/1992	50.69

30/6/1993	60
31/12/1993	65
30/6/1994	40
31/12/1994	60
30/6/1995	40
31/12/1995	132.9
30/6/1996	47.925
31/12/1996	60
30/6/1997	110
31/12/1997	47.345
30/6/1998	50
31/12/1998	44.09
30/6/1999	30
31/12/1999	50
30/6/2000	55
31/12/2000	60
30/6/2001	80
31/12/2001	90
30/6/2002	100
31/12/2002	60

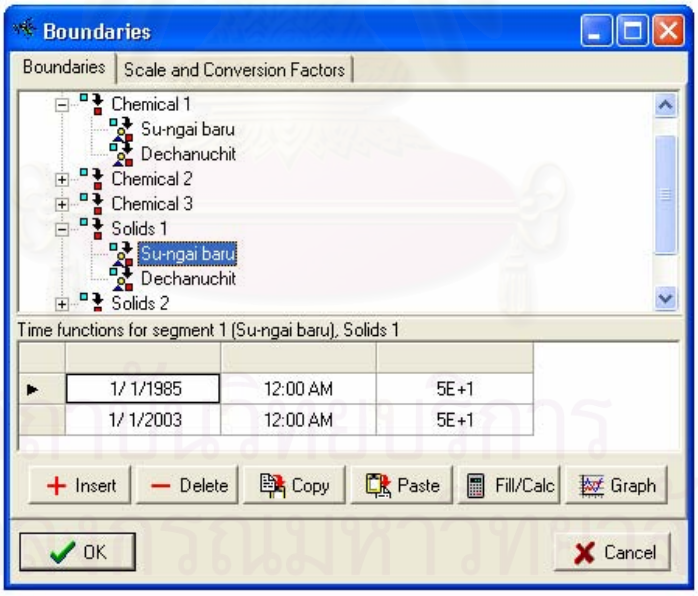
The calibrated flows at the downstream part of the Pattani Dam

Date	**Flows (m^3/sec)**
31/1/1985	61.6481
30/6/1993	57.4245
31/12/1993	56.9929
30/6/1994	89.707
31/12/1994	93.8034
30/6/1995	67.6691
31/12/1995	73.2469
30/6/1996	54.4075
31/12/1996	56.6496
30/6/1997	54.126
31/12/1997	70.3999
30/6/1998	74.0925
31/12/1998	57.3354
30/6/1999	68.688
31/12/1999	85.9828
30/6/2000	90.37
31/12/2000	83.4974
30/6/2001	84.4636
31/12/2001	110.4126
30/6/2002	86.6471
31/12/2002	70.6193
30/6/2003	69.212
31/12/2003	68.9942
30/6/2004	75.6261

The input boundary solid concentration for the upstream part of the Pattani Dam



The input boundary solid concentration for the downstream part of the Pattani Dam



APPENDIX I

THESIS PROPOSAL

Thesis Title: การคาดการณ์การปนเปื้อนของตะกั่วในแม่น้ำปัตตานีด้วยแบบจำลองทางคณิตศาสตร์ วอส 6.2
: The contamination of Lead in Pattani River simulation by Water Quality Analysis Simulation Program (WASP) version 6.2
Student: Pattapol Chaikul **ID:** 468 94560 20
Program: M.Sc.
Credit: 12
Advisor: Assoc. Professor Randall L. Kolar, Ph.D.
Co-advisor: Khemarath Osathaphan, Ph.D.

Introduction

The Pattani River is one of the main tributaries in the south of Thailand (Figure 1). With a length of 210 kilometers, it covered an area which includes Yala and Pattani provinces. The flow direction is from the Thailand-Malaysia boundary to the Gulf of Thailand at Pattani Bay, Pattani province. The upstream part of the river is in Bannangsta district, Yala province. With regard to the land utilization, along the river consists of agricultural, forestry, community and mining activities.

Lead contamination in the Pattani River has been a topic of discussion over the past ten years. There are two principal sources of the contamination. The source of lead in the upstream section of the river is a group of abandoned tin mines in Bannangsta district. While the source of lead in the downstream section, especially in Pattani Bay is a dockyard area where boats are repaired (Pollution Control Department, 2002).

Although the tin mines in Bannangsta district ceased production in 1985 as a result of the collapse of tin prices, tailing piles, waste rock and sludge lagoon were left behind at the site. During the rainy season of every year, lead in the form of galena (PbS) is washed off into the stream and flows into the upstream area of the Pattani River.

In 2002, the Pollution Control Department monitored the water quality of the Pattani River Basin. The increasing tendency for lead contamination in water, sediments and human bodies was found. At the upstream part of the river, especially in the Bannangsta district, the concentration of lead in water was found at five times higher than that of the guideline value for surface water. Lead in sediments was found at the higher level of 1,000-15,000 mg/kg. Furthermore, the lead level in the blood of

people who live nearby the river was found at a high concentration level, 40 µg/dL (Pollution Control Department, 2002).

The contamination of lead in the Pattani River causes effects not only to the ecological system and natural environment but also the people who live nearby and consume water from the river. Therefore, a strategic plan for the control, remediation and rehabilitation of water quality and other related resources of the Pattani River are urgently required. A high quality level of physical information on the contamination and high quality instruments for predicting the long-term distributions of the contamination are required. Therefore, the aims of this study are to investigate the ability of the Water Quality Analysis Simulation Program (WASP) version 6.2 for predicting the concentration of total lead in the Pattani River and to simulate a Scenario for reducing the amount of total lead concentration in the river in order to plan a proper strategy for the future.

Objectives of the study

The objectives of the study can be summarized as follows:-

1. To investigate the ability of the Water Quality Analysis Simulation Program (WASP) version 6.2 for predicting the concentration of total lead in the Pattani River.
2. To simulate a Scenario for reducing the total lead concentration in the river.

Hypotheses

1. The Program WASP 6.2 can be used to simulate the distribution of total lead in the Pattani River
2. The Program WASP 6.2 can be used to simulate a scenario of reducing the total lead concentration in the river.

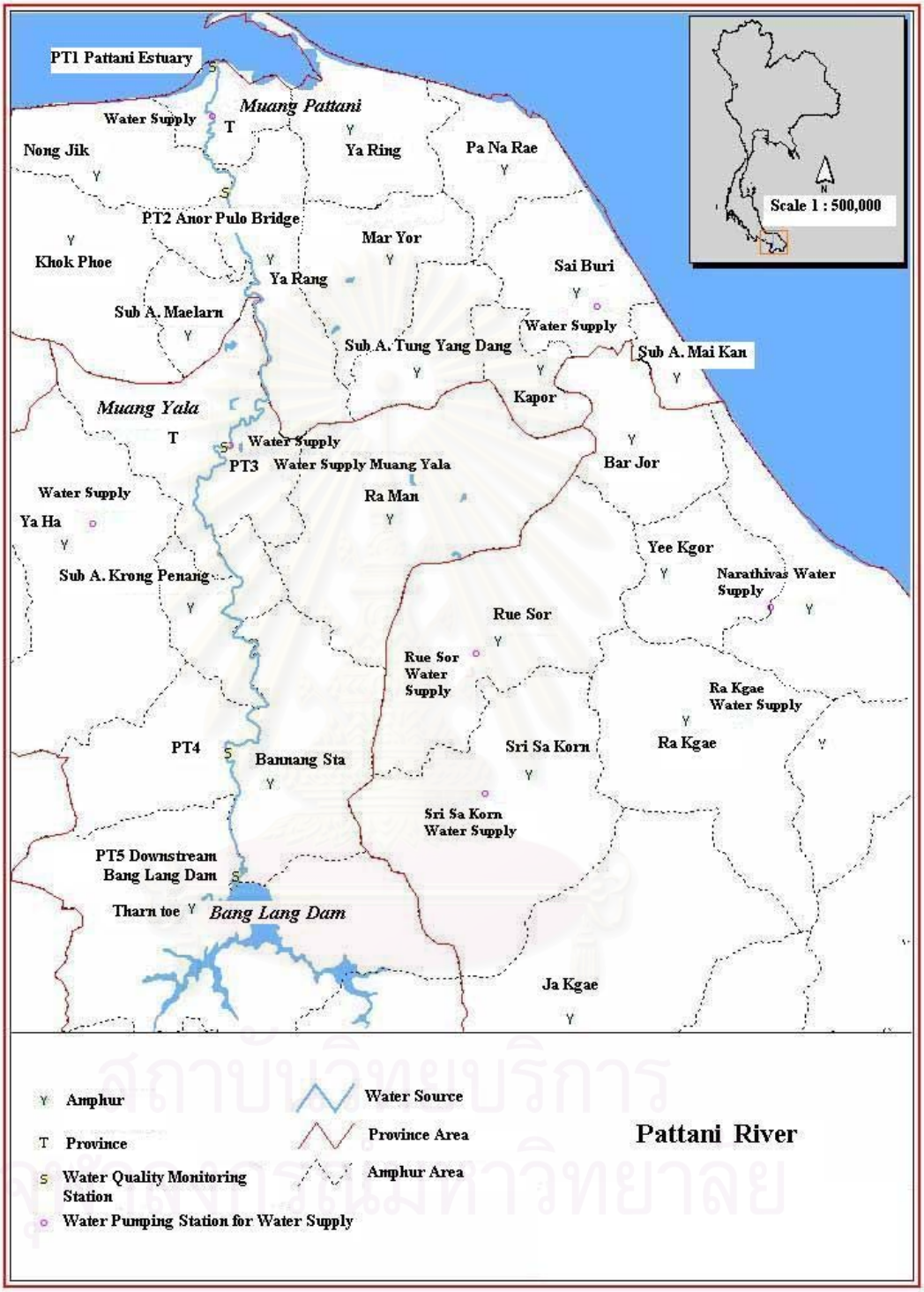


Fig. 1 Pattani River Map (Water Quality Management Bureau, Pollution Control Department, 2001)

Theoretical Background

The Water Quality Analysis Simulation Program (WASP 6.2) is an enhanced version of the original WASP, developed by Di Toro in 1983. The model helps users to interpret and predict water quality responses to natural phenomena and man-made pollution. WASP 6.2 is a dynamic compartment-modeling program for aquatic systems, including both water column and the underlying benthos. The time-varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the basic program (Wool et al., 2003).

WASP consists of two sub models, which are EUTRO and TOXI. EUTRO is used to analyze conventional pollution; for example, dissolved oxygen, biochemical oxygen demand, nutrients and Eutrophication. TOXI, which is mentioned in this study, is used to simulate toxic pollution involving organic chemicals, metals and other simple toxicants.

Loading Process:

WASP 6 allows the user to specify the loading rate for each variable. The user inputs the dataset to specify the point source loads. Loads, in kg/day will be added to the designated segments at the following rates:

$$V_i S_{Lik} = 1000 \times L_{ik}(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where:

V_i = volume of boundary segment "i" (m^3)

S_{Lik} = loading rate response of chemical "k" in segment "i" (g/m^3-day)

$L_{ik}(t)$ = loading rate of chemical "k" into segment "i" (kg/day)

Manning's Equation:

In this study, Manning's equation will be used to calculate stream velocities. It provides reasonably accurate results for a large range of natural and artificial channels. It has been widely adopted for use by engineers throughout the world (Chadwick et al., 1993).

$$v = (1/n) \times R^{2/3} \times S^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where:

v = Stream velocity (m/sec)

n = Manning's n

R = Ratio between cross-section area and perimeter (m)

S = Slope of river (m/m)

Sorption:

Sorption is the bonding of dissolved chemicals onto solid phases, such as benthic and suspended sediment. Sorption is important in controlling the environmental fate and the toxicity of heavy metals in the water. Sorption may cause the accumulation of heavy metals in the bed sediment. Sorption may retard some reactions, such as volatilization, or enhance some reactions such as acid-catalyzed hydrolysis. Sorption reactions are fast relative to other processes, and equilibrium may be assumed. For environmentally relevant concentrations (less than 10^{-5} M or one-half water solubility), equilibrium sorption is linear with dissolved chemical concentration (Wool et al., 2003) as follows:

$$C_s = K_{ps} \times C_w \quad \text{..... (3)}$$

where:

K_{ps} = Partition coefficients

C_s = Concentration in sediment (solid phase), mg/kg

C_w = Concentration in dissolved form (liquid phase), ug/l

At equilibrium, the distribution among the phases is controlled by the partition coefficients K_{ps}. The total mass of the chemical in each phase is also controlled by K_{ps} and the amount of solid phase present, so that

$$f_D = n / n + \Sigma_s K_{ps} \times M_s \quad \text{..... (4)}$$

$$f_S = K_{ps} \times M_s / n + \Sigma_s K_{ps} \times M_s \text{..... (5)}$$

where:

f_D = Dissolved fraction

f_S = Solid fraction

M_s = Total mass of chemical in each phase

n = Amount of solid phase present

These fractions are determined in time and space throughout a simulation from the partition coefficients. Given the total concentration and the phase fraction of chemical “i” in the segment “j,” the dissolved and sorbed concentrations are uniquely determined as follows:

$$C_{wij} = C_{ij} \times f_{Dij} \quad \text{..... (6)}$$

$$C_{sij} = C_{ij} \times f_{sij} \quad \text{..... (7)}$$

where:

F_{ij} = Fraction of chemical i in segment j

C_{ij} = Concentration of chemical i in segment j

Sediment Transport:

Sediment transport affects water quality directly. Sediment transport influences chemical transport and fate. Many chemicals, which sorb strongly to the sediment, undergo settling, scour and sedimentation. Sediment size fraction or solid type is simulated using TOXI program. Simulations may incorporate total solids as a single variable, or represent from one to three solids types. The character of the three solid types may represent sand, silt and clay, or organic and inorganic solids. A simple mass balance on each solid variable in each compartment is performed by WASP 6.2. The computations of mass balance are performed in the benthic compartment as well as the water column compartment. The user can vary all solid transport rates in space and time. However, there are no special process descriptions for solids transport.

Regarding the water column transport, the sediment and particulate chemicals may settle to the lower water segment. Velocities and the surface area in transport fields describe settling, deposition and scour rates in WASP 6.2. Settling velocities should be set within the range of stoke’s velocities corresponding to the suspended particle size distribution (Wool et al., 2003) as follows:

$$V_s = 8.64\, g\, (\rho_p - \rho_w)\, d^2_p / 18\, \mu \quad \text{..... (8)}$$

where:

V_s = Stokes velocity for a particle with diameter d_p and density ρ_p m/day

g = acceleration of gravity = 981 cm/sec^2

μ = absolute viscosity of water = 0.01 poise (g/cm^3-sec) at 20 °C

ρ_p = density of the solid, g/cm^3

ρ_w = density of the water, 1.0 g/cm^3

d_p = particle diameter, mm

Estimation of the River Dispersion Coefficient:

Fischer et al. (1979) suggested that the equation for estimating the dispersion coefficient in real streams is as follows:

$$Ex = 3.4 \times 10^{-5} U^2B^2 / HU^* \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Where:

Ex = Dispersion Coefficient, mi^2/day

U = mean river velocity, ft/sec

B = mean width, ft

H = mean depth, ft

U* = river shear velocity, ft/sec

The river's shear velocity is given by the following equation:

$$U^* = (gHS)^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Where:

g = 32 ft/sec^2

S = river slope in ft/ft

Input Parameters for Lead Modeling Used in WASP 6.2

Parameter	References
Segment Parameters	
- *Water column segments*	
Volume (m^3)	Calculated by using RID Info. (2004) and topographic map
Depth (m.)	Estimated from a Cross-section of river, RID Info. (2004)
Velocity (m/s)	Calculated by using Manning's Equation
Velocity multiplier and exponent	Calculations based on WASP 6 manual
Flow rate (m^3/s)	Royal Irrigation Department (2004)
Initial dissolved fraction	Calculations based on Thomann and Mueller (1987)
- *Benthic segments*	
Volume (m^3)	Calculated by using RID Info., depth and topographic map
Depth (m.)	Assumed from example model file
Velocity (m/s)	Assumed = 0
System Parameters	
Lead Loading (kg/day)	Calculations based on WASP 6 manual
Constant Parameter	
Partition coefficient to solids (l/kg)	U.S. Environmental Protection Agency (1999)
Transport Parameters	
- *Flow Parameters*	
Water column flows (m^3/sec)	Estimated from RID Info. (2004)
Settling velocity (m/sec)	Calculations based on WASP 6 manual
-Dispersion and diffusion parameters	
Dispersion coefficients (m^2/sec)	Calculations based on Thomann and Mueller (1987)
Pore water diffusion coefficients (m^2/sec)	Estimation based on www.ufaventures.com (2004)
Transverse Cross-sectional exchange area (m^2)	Calculated by a Cross-section of river, RID Info. (2004)
Vertical Cross-sectional exchange area (m^2)	Calculations using the depth and a topographic map
Transverse Mixing length (m.)	Calculations based on the WASP 6 manual
Vertical Mixing length (m.)	Assumed = Benthic segment depth

Literature Review

Lead contamination situation in the Pattani River:

During 1986 – 1997, the Office of Environmental Health of the Department of Health under the Ministry of Health monitored the contamination level of total lead in the Pattani River. For 1986 – 1992, four of the ten water sampling stations showed high lead concentrations which exceeded the permissible river and drinking water quality standard of 0.05 mg/l. The one left, which is located in Bannang Sta district, was found to exceed the standard during 1986 – 1992 and 1996 – 1997. This establishes the evidence that the contamination of lead in the Pattani River at Bannang Sta district still exist.

Tutep (1994) studied the contamination of metals in stream sediments of the Pattani River in Yala province. As, Cd, Cu, Fe, Mn, Pb and Zn adsorped on clay particles in a similar manner to that of silt, but twice as much as on sand at the station near the mining area. Then the concentrations were decreased by the increasing of distance in the downstream direction.

In 2002, the distribution of lead in the Pattani River Basin has been reported by the Pollution Control Department under the Ministry of Natural Resources and the Environment. The level of total lead and the level of lead in sediments in the streams around the abandoned tin mining area and in the river were investigated. The first sampling was carried out in March, the end of rainy season, while the second sampling was carried out in June, the end of dry season.

Regarding the investigation of lead contamination in streams around the abandoned tin mine area, lead in stream sediment was presented in very high concentrations. In the first sampling, lead in clay particles (particle size < 53 μm) of sediment samples in the stream around the Tum Ta Lu abandoned mine, was found in the range of 390 – 28,679 mg/kg dry weight. In the second sampling, lead in particle of sediments in the stream from the Na Sua and Tum Ta Lu mine was also found at high concentrations, 510.6 – 23,720.2 mg/kg dry weight. The contamination level of lead in the stream sediments was found to be 100 – 1,000 times higher than that of the river sediments. Lead contamination in water samples in Na Sua Pond at the Na Sua abandoned mine was found at highest concentration at 264.38 and 777.52 μg/L in the first and second sampling, respectively. The concentration of lead at other stations

was found to decrease in the second sampling when compared with the first sampling because the elution rate in the dry season is less than in rainy season. Moreover, lead in a water sample from the village piped water system was found at 4.8 + 0.2 µg/L, which is the same as the level guideline for lead in the drinking water standards.

According to the investigation of lead contamination in the Pattani River in Yala and Pattani provinces, from the 11 sampling stations, the amount of total lead was found to be lower than 15 µg/L at every station, except for Cha Lerm Pra Kiat Bridge where the level of suspended solid was higher than that of other stations, therefore it resulted in a higher level of lead. Lead in river sediment was mainly in the clay composition of the sediment. The results from both samplings showed a good agreement to the high concentration of lead that was found at the station in Bannang Sta district, where the Pattani River originated and connects with the streams from abandoned tin mines. The concentration of lead in sediment was found to decrease as the distance increased from mining area. However, the concentration of lead was found to increase at the Pattani River mouth. The increase in the lead concentration might have resulted from the use of lead oxide in boat repairing that occurs at the dock yard.

Application of the WASP model in water quality analysis and simulation:

Vuksanovic et al. (1995) studied the transport of polychlorinated biphenyls (PCB) in the Scheldt Estuary using the Water Quality Simulation Program (WASP). WASP was applied to simulate the present spatial distribution of 12 selected PCB isomers. The simulations were performed under average hydrodynamic and suspended sediment transport regimes. Calculated evolution profiles of the dissolved and sorbed concentration in the water column indicated a high accumulation of PCB in the turbidity maximum zone. The simulated distributions of the sorbed PCB, suspended sediment and salinity agreed with the observations.

Wu et al. (1996) investigated the effects of reservoir operations on water quality which they simulated using the Water Quality Simulation Program. WASP was employed to predict the water quality under several sedimentation conditions and operation policies. Several reservoir operation rules were simulated to address the possibility of maintaining water quality through proper operation. The watershed of the Ta-chi reservoir in Taiwan was chosen as a case study.

Wang et al. (1999) applied WASP to simulate and evaluate the relationships between external nutrient loading and the water quality of Tampa Bay, U.S.A. Tampa Bay was phosphorus enriched and nitrogen limited for algal growth. The model estimated the impact of the nutrient loads on water clarity, a pivotal water quality parameter for sea grass meadows. The model also estimated the impacts over long time periods and on a large scale. Model results were compared with monthly measurements and yearly averaged estimates for 1985 – 1994.

Umgiesser et al. (2003) developed the Finite Element Ecological Model (FEEM) by fully coupling a primitive equation finite element hydrodynamic model (FEM) with an ecological model derived from EUTRO, the submodel contained in the Water Quality Simulation Program. The integrated model has been applied to the Venice Lagoon. The idealized forces such as tide have been used together with actual field data, river discharge and nutrient loadings to run simulations over a one year period.

Kim et al. (2004) modified WASP to simulate the presence of mercury and evaluate the effects of remedial actions, which are the dredging and capping on mercury speciation and transport in Onondaga lake. Model predictions for the water column generally agreed with the measured values reported in literature. Natural attenuation showed no positive impact from these remediation effects.

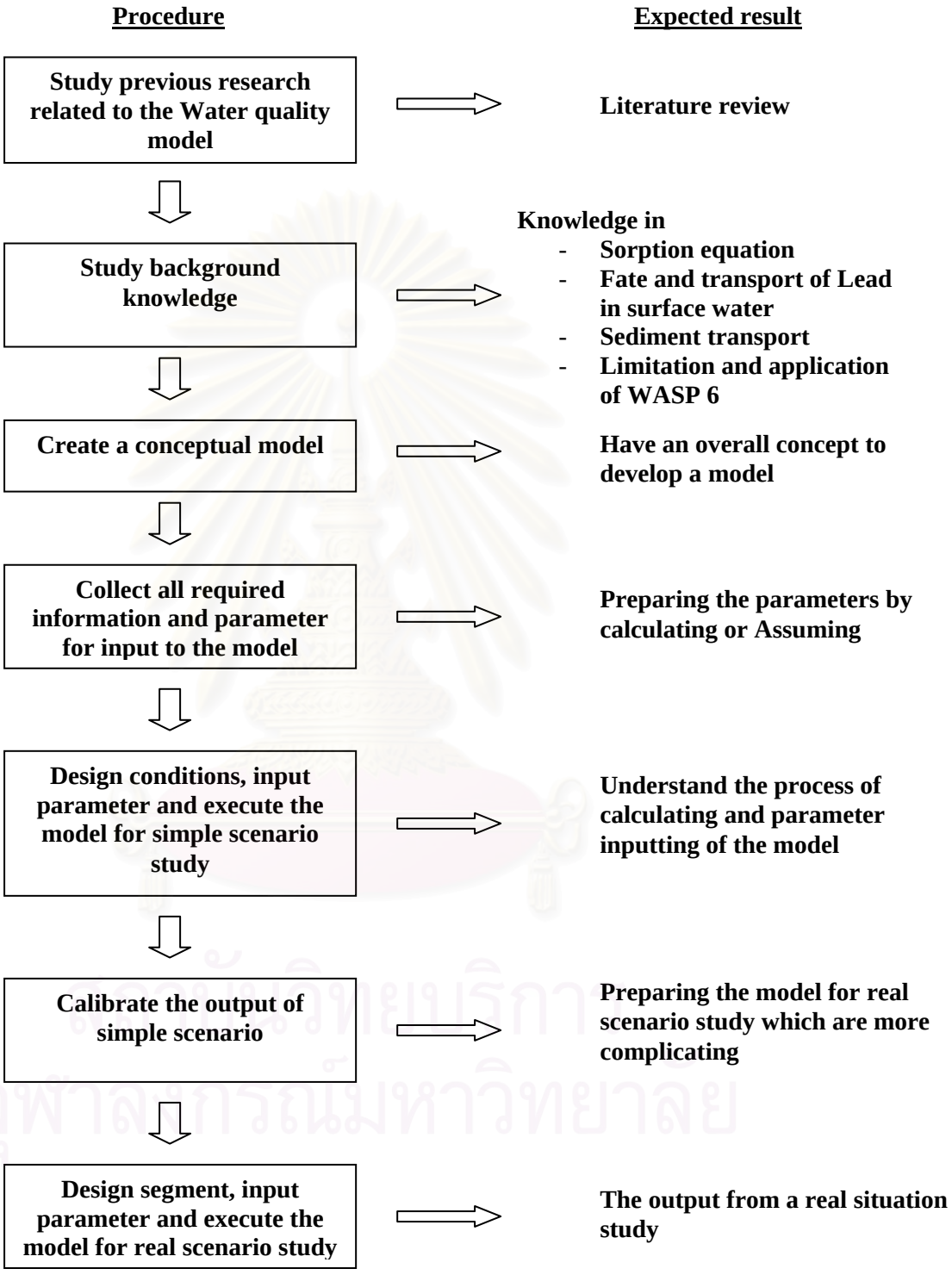
Scope of the study

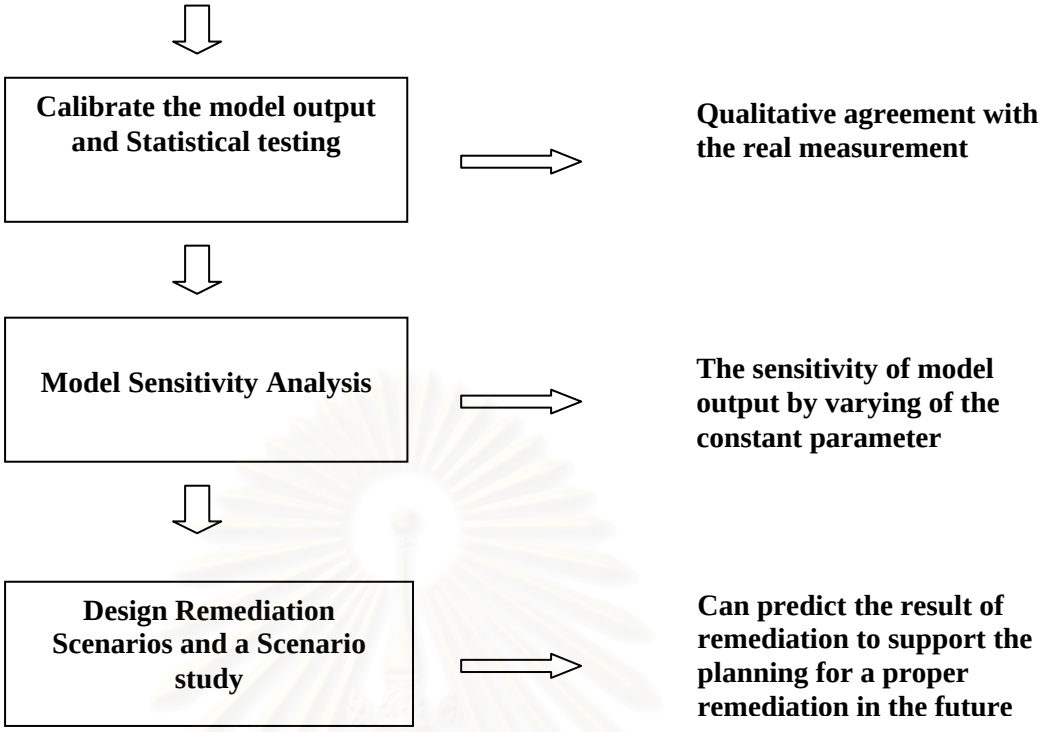
The study focuses on an investigation of the ability of the Water Quality Analysis Simulation Program (WASP) version 6.2 for predicting the concentration of lead in the Pattani River over a long time period. Therefore, some parameter could be adjusted for enhancing the output from the model.

The output of the model will be calibrated by comparing its results with the previous measurements taken by the Department of Health from 1990 – 2000 and the Pollution Control Department in 2002.

After calibration, the model will be applied to simulate a scenario of reducing the level of total lead in the river for the planning of a proper management strategy for remediation in the future.

Methodology





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