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# Improving Non-Point Source Pollution Model Input Parameters Using Substance Flux Analysis

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**Abstract:** This study investigated Substance Flux Analysis (SFA) as a potential tool to obtain better estimates of phosphorus and cadmium loadings in an on-going comprehensive research effort to model the phosphorus and cadmium transport via., surface runoff to Songkhla Lake in the southern part of Thailand. The lake is a major producer for local fisheries. Because substantial portions of the drainage area are used for agriculture, non-point source pollution loading from the surrounding drainage area to the lake has become a concern, especially since surface runoff is the major transport mechanism for non-point source pollutants. Using SFA it is estimated that approximately 384,289 t of chemical fertilizer were applied throughout the basin in 2004. The major sub-watershed contributing phosphorus and cadmium was the U-Tapao and Eastern Coast Sub Basin 4 Sub-watershed. Changing the fertilizers from 8-24-24, 13-13-21 and 15-15-15 (high cadmium) by 15-15-15 (low cadmium) type led to a significant decrease in cadmium contribution to the lake.

**Key words:** Songkhla Lake basin, agricultural pollution, phosphorus transport, cadmium transport, distributed parameter models, AnnAGNPS model, TREX model

## INTRODUCTION

Material reported in this study is part of a comprehensive research effort to model the non-point source loading of phosphorus and cadmium to Songkhla Lake, Thailand, from the surrounding drainage area. A schematic of the overall study is shown in Fig. 1. The study focuses on the land used predominantly for agriculture.

Spatially distributed parameter models are commonly used for modeling non-point source pollution transport via., surface runoff (Tiemeyer *et al*., 2007; Chen and Mackay, 2004). The term lumped or distributed describes the way in which the model handles the spatial data. Lumped models use spatially averaged parameters and perform computations over the whole catchment region. However, increases in the within variation for a catchment may negatively affect the accuracy of the model predictions (Oudin *et al*., 2006). Distributed models are based on the discretization of the landscape into smaller functional land units. Typically, a uniform grid is used for computational convenience. Calculations are performed

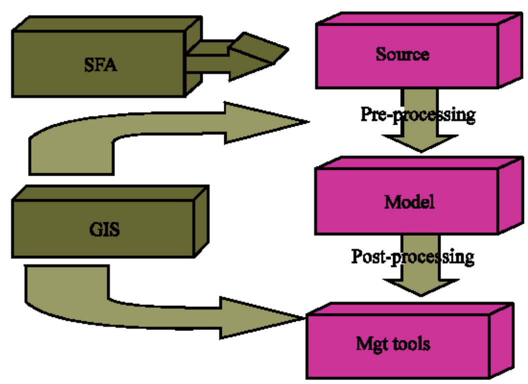


Fig. 1: Schematic of the comprehensive study

on discrete cells and then accumulated to make predictions over the whole catchment (Curtis *et al*., 2005). With advances in computer technology, distributed models have gained popularity. The disadvantage of distributed parameter models is that they require large amount of data; the advantage is that they are able to better account for local variability in land and loading

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conditions. This ability is important for making land management decisions that require a better understanding of land processes within a catchment and for applying farm scale management options.

The Annualized Agricultural Non-Point Source (AnnAGNPS) model is a widely used model for nutrient transport via., runoff in agricultural watersheds. However, the Two-dimensional Runoff and Erosion and Export (TREX) model is the only model that can handle metal transport via., runoff. Both are spatially distributed cell-based models (Yuan *et al*., 2008; Polyakov *et al*., 2007; Velleux *et al*., 2008, 2006). Therefore, these two models were considered in this study: AnnAGNPS for predicting phosphorus transport and TREX for predicting cadmium transport. Reliable results from models can be expected only when good quality input data are used. Specifically, we need accurate estimates of the phosphorus and cadmium available for transport at each cell.

Substance Flux Analysis (SFA) is a technique used for tracking and assessing inputs, stocks and outputs of a particular substance for a defined system boundary. The method establishes a mass balance of goods and selected substances (Kleijn *et al*., 2008, 2000). SFA is a widely established method that has been used to support decision making in various fields such as waste management, nutrient management and urban metabolism analysis (Doberl *et al*., 2002; Hug and Baccini, 2002; Lofts, 2007). Compared with conventional mass balance approaches, SFA is more comprehensive since it relates substance flows to processes (Lofts, 2007). By providing early recognition of environmentally relevant material flux changes, it enables the identification of potential environmental problem, helps tracing the origins of pollution problems and, therefore, can be used to support environmental policy developments (Lofts, 2007). SFA can be applied at different geographical scales and at different locations. Chen *et al.* (2008) carried out a SFA study in China and found that the technique can still be used effectively even in situations where poor data availability and quality are encountered. In data rich countries, the application of SFA for various decision support purposes is becoming increasingly common (Tangsubkul *et al*., 2005; Kwonpongsagoon *et al*., 2007a, b).

Songkhla Lake is located in southern Thailand. Intense agriculture-related activities in the lake catchments have raised concerns about the potential for surface runoff to transport significant amounts of phosphorus and cadmium into the lake. In recent years, macrophyte blooms lasting for several months have been observed in the middle of the lake. Phosphorus causes concern because it is the prime cause of eutrophication in tropical lakes (Drolc and Koncan, 2002). Cadmium was also found in the lake sediments (Sirinawin and Sompongchaiyakul, 2005). Cadmium is a highly toxic, bio-accumulative heavy metal that can cause kidney disease and prostate cancer if ingested. Cadmium is commonly associated with rock phosphates used as raw material for producing fertilizers. Prolonged use of cadmium-contaminated products can lead to unacceptably high concentrations of cadmium in agricultural soil, a situation in which cadmium can accumulate to high levels in food crops such as rice and root vegetables. Cadmium is subject to health standards in most importing nations. High concentration of cadmium, if found in crops, could lead to the rejection of those crops for human consumption or even for animal feed. Contaminated soils over large areas are difficult or impossible to remedy and eventually result in severe public health and ecological problems. Increasing agricultural activities in the catchments have the potential to increase cadmium accumulation in the lake (Sae-Eong *et al*., 2002). Though, cadmium is not of great concern under the present conditions, it could pose problems under potential future scenarios of agricultural activities in the basin. Published literature on the pollutant transport to Songkhla Lake is scarce. Recent studies are mostly published in Thai language journals. Sereewatthanachai *et al.* (2004) performed a preliminary study of phosphorus and cadmium in the agricultural soil of the catchment and stated that estimates cannot be precisely made on the annual rate of accumulation. Liu *et al.* (2004) created a statistical model by balancing the physical quantities of phosphorus flows using SFA. Chen *et al.* (2008) investigated the nutrient flows in agricultural systems in China using a partial substance flow analysis (SFA) method and an Agricultural Phosphorus Flow Analysis (AgiPhosFA) model. However, they make no attempt to compare SFA estimates with other measurements direct or indirect. None of the authors intended to use their results to improve input parameters of non-point source pollutant transport models.

The objective of this study is to investigate the potential of SFA to improve estimates of phosphorus and cadmium available on the land for transport by surface runoff into Songkhla Lake, Thailand. Data for the year 2004 were used. The use of SFA to improve estimates of input loading of phosphorus and cadmium to non-point source pollution models is the focus of this study.

## MATERIALS AND METHODS

The study was conducted in the Songkhla Lake basin (Fig. 2) located in the Southern part of Thailand during January-December, 2004.

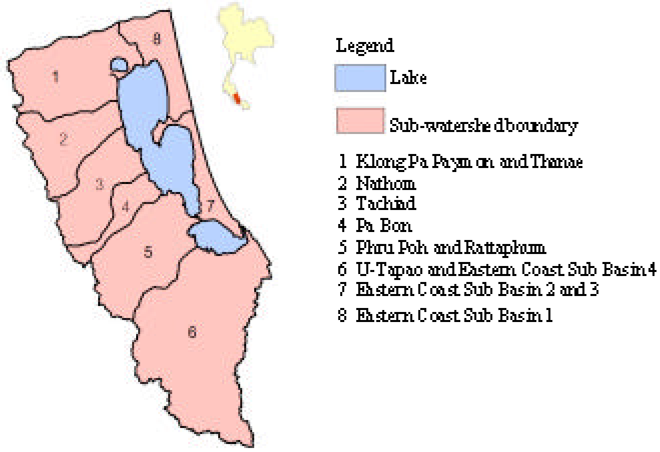


Fig. 2: Sub-watersheds of the Songkhla Lake Basin

**Models used**

**Annualized agricultural non-point source (AnnAGNPS) model:** Transport of phosphorus via runoff is one of the concerns in this study. The predominant land use in the study area is agriculture. The AnnAGNPS model is widely used for modeling nutrient transport via., runoff in agricultural watersheds. The basic modeling components in the model are hydrology, sediment, nutrient and pesticide transport. The AnnAGNPS model requires a large amount of input data: soil, land use, management and weather. The management data includes crop, non-crop, fertilizer, field management, schedule management and operation management data. The model tracks nutrients such as nitrogen and phosphorus transport, but does not track transport of metals such as cadmium (Yuan *et al*., 2008; Polyakov *et al*., 2007). One of the objectives of this study is to estimate input phosphorus amounts as accurately as possible for the AnnAGNPS model.

**Two-dimensional runoff and erosion and export (TREX) model:** Another concern in this study is the transport of cadmium via., runoff. TREX is the only spatially distributed cell-based model which can handle metal transport via., runoff (Velleux *et al*., 2008, 2006). TREX has four major submodels: (1) hydrology, (2) sediment transport, (3) chemical transport and (4) metal toxicity. The amount of cadmium available for transport is an important input to the model. Another objective of this study is to estimate input cadmium amounts as accurately as possible for the TREX model.

**Study area:** Songkhla Lake and its basin are spread over 3 provinces of Thailand: Phattalung, Songkhla and Nakhon Si Thammarat (Fig. 2). The lake covers approximately an area of 1,042 $km^2$ with a drainage area of 7,687 $km^2$. The basin spans approximately 150 km from north to south and 65 km from east to west. Songkhla is the only lake in Thailand that is a large lagoon system: fresh water from precipitation drain into the lake through streams and overland flow and mixes with saline water from the sea. The basin is bounded by two mountain ranges. The higher grounds of both the mountain ranges are covered with rainforests. Undulating plains alternating with low hills run parallel to the north-south mountain range in the basin. The area towards the east approaching the lake is a large flat plain containing mostly rice farms. North of Songkhla Lake is a large wetland that covers approximately 137 $km^2$. A large flat plain lies east of the Songkhla basin between the lake and the sea. The basin is divided into 12 sub-basins. The majority of Songkhla Lake Basin (SLB) land, 5,660 $km^2$ is used for growing rice and rubber trees (60 and 30%, respectively). Forest land occupies 1,164 $km^2$, most of which is rainforest and the remaining is mangrove forest and swamp. Other land use categories include natural water body (12.5%), residential area (2.6%), industrial, man-made water body, roads and undeveloped land. The average rainfall in the basin is 2,043 mm.

**Current status of the lake water quality:** Songkhla Lake consists of 4 parts: Thale Noi, upper Songkhla Lake, middle Songkhla Lake and lower Songkhla Lake. The latter is connected to the Gulf of Thailand at Muang District, Songkhla Province. One of 2 criteria is necessary for eutrophication of a lake: phosphate must be more than 0.05 mg $L^{-1}$ or Chlorophyll a must be more than 10 $\mu g L^{-1}$ (Drolc and Koncan, 2002; Smith *et al*., 1999). Nutrient concentrations in the upper, middle and lower Songkhla Lake indicate a higher level of phosphate at the lower Songkhla Lake, whereas Chlorophyll a is higher in the upper and middle Songkhla Lakes. The U-Tapao canal located in the lower Songkhla Lake contributes to the heavy loading of nutrients and wastewater to the lake due to the industries and dense population along the canal. Although, the general water quality in the lake is within acceptable ranges, eutrophication and nutrient levels in the lake are suspected to be higher than stated. The area of most critical concern is the upper lake system, consisting of Thale Noi, Thale Luang and Thale Sap. Cadmium was also found in the lake sediments (Sirinawin and Sompongchaiyakul, 2005). Although cadmium is not a concern under the present conditions, future agricultural activity could pose problems; therefore, methods are needed to accurately estimate the nutrients and metals transported by runoff into the lake.

**Methods:** This study investigates the potential of the SFA method to estimate the phosphorus and cadmium input loads into Songkhla Lake; data will be gathered through in-depth interviews with fertilizer importers, wholesalers, retailers and farmers and through laboratory testing of soil samples from all the three provinces in the basin. As a first step, the SFA was applied to the whole basin as a lumped system for evaluating the applicability of the method. For the purposes of this study, amounts of phosphorus and cadmium were estimated with and without applying SFA and compared. The improved estimates were subsequently used to model one selected sub-watershed.

Several methods can be used for improving the nutrient and metal input estimates, including Substance Flux Analysis (SFA) and Material Flow Analysis (MFA) developed by Baccini and Brunner (1991), Life Cycle Analysis (LCA) (Tukker, 2002) and Partial Economic equilibrium Analysis (PEA); however, method used should be able to determine the problem-causing mechanism in an operational fashion in the sense of having a low data demand and being easy to construct and run in practice. SFA was selected in this research because it uses an input-output analysis of material or substance compared to LCA, which focuses on the function of a product, not on the amount of the product. In addition, SFA tracks the processes within the system, whereas MFA treats the system as a black-box. Drolc and Koncan (2002) developed a phosphorus balance using MFA in a river basin and evaluated different scenarios for pollution reduction. Montangero and Belevi (2008) also used MFA to assess the impact of environmental sanitation systems on the phosphorus load discharged into surface water in Hanoi, Vietnam. However, the intent of both the studies was not to derive improved estimates of input to non-point source models. The PEA method also tracks the process within the system, but it was not chosen because the method also performs an economic analysis, which makes the process more complex. Therefore, in this study, SFA is used to refine the previously available estimates of loading, which ultimately improves the quality of the major input to non-point source pollution transport models. Bouman *et al.* (2000) evaluated the differences and similarities of the methods and results of the model in a practical way. Kleijn *et al.* (2008, 2000) categorized the usage of measurement tools (Table 1) based on the objectives and primary interests of their studies. Table 1 clearly shows that SFA is the preferable tool to estimate the amounts of nutrients and metals available for transport via runoff. SFA is preferred for its simplicity and for not treating the system as a black box.

**Substance flux analysis:** Substance Flux Analysis (SFA) uses an input-output analysis of substances. The first step for applying SFA is to develop a conceptual model of the system under study. The conceptual model developed for Songkhla Lake Basin is presented in Fig. 3,

Table 1: Material flow related analysis and associated issues of concern

| Issues of concern | Specific concerns related to environmental impacts, supply security, technology development With certain business, economics activities, countries, regions Associated with | | | General environment and economic concerns related to the throughput Of substances, material, manufacturing good At the level of | | |
|---|---|---|---|---|---|---|
| Objects of primary interest | Substances | Material | Manufactured goods | Business | Economic activities | Countries, regions |
| | Chemical elements or compounds e.g., Cd, Cl, Pb, Zn, Hg, N, P, C, $CO_2$, CFC | Raw material and semi-finished goods e.g., energy carriers, metal (ferrous, non-ferrous), sand and gravel, timber, plastics | e.g., batteries, cars, computers, | e.g., firms, companies, plants, medium sized and big enterprises, MNEs | e.g., production sectors, chemical industry, iron and steel industry, construction | e.g., aggregate mass of materials and related materials mix, groups of material, selected materials |
| Type of analysis | Substance flow analysis | Material system analysis | Life cycle analysis | Business level MF analysis | Input-output analysis | Economy-wide MF analysis |
| Type of measurement tool | Substance flux accounts | Individual material flow accounts | Life cycle inventories | Business material flow accounts | Physical input-output table | Economy-wide material flow accounts |

Kleijn *et al.* (2002, 2008)

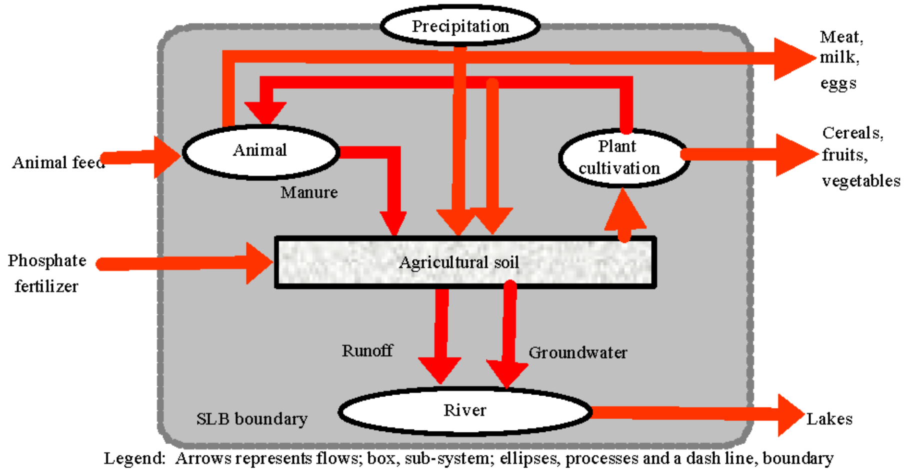


Fig. 3: Conceptual model of Songkhla Lake Basin system for SFA

which shows the subsystems, processes and flows of substances. Goods containing phosphorus and cadmium that had passed through relevant processes in the SLB over the one-year period of 2004 were examined. Accumulations of phosphorus and cadmium on agricultural soil via., phosphate fertilizer, feed for swine, manure from swine farming and precipitation was considered potentially significant. Phosphorus and cadmium stored in soil can be taken up by plants, released into the air, leached into groundwater and/or washed away by surface runoff. Even in predominantly agricultural areas, only trace amounts of phosphorus below detectable limit leach into groundwater. Similarly the levels of cadmium in lower soil layers are also below detection limit. However, runoff due to rain events can be a main carrier of phosphorus and cadmium transport from the system. The only significant pathways leading to the lake are runoff and direct precipitation on the surface of the lake.

Data from both primary and secondary sources need to be compiled to establish a database of sources and amounts of phosphorus and cadmium in the system products and processes (Table 2-4). The non-availability of different categories of data for the same periods has been a problem. For example, the concentration of cadmium in phosphate fertilizer was investigated in 2004, but the corresponding figures for the concentration in animal feed were only available for the year 2001. Moreover, neither governmental bodies nor research centers possess adequate records of the rate of increase of these substances each year. That such factors are often obstacles to the application of the SFA approach in most developing nations, compared to developed ones, is not unexpected (Baccini and Brunner, 1991; Tangsubkul *et al*., 2005). The paucity of such data is a common problem for the use of distributed parameter models, particularly in under-developed and developing countries. Mass or chemical balance approach is not practicable mainly due to huge data requirement and the need to account for complex reactions and process representations. The amount of phosphorus and cadmium

Table 2: System parameters and characteristics

| Product/processes | Consumption/quantity | Unit |
|---|---|---|
| Chemical fertilizer | | |
| - 8-24-24, 13-13-21, 15-15-15 and 16-16-16 formula | 4,965 | t year$^{-1}$ |
| Number of swine | 226,390 | Head |
| Feed for swine | 1.5 | g/head/day |
| Precipitation | 1,880 | mm year$^{-1}$ |
| Agricultural soil area | 5,691 | km$^2$ |
| Runoff | 4,896×10$^6$ | m$^3$ year$^{-1}$ |

Sereewatthanachai *et al.* (2004)

Table 3: Phosphorus in product systems and processes

| Product/processes | Content/concentration | Unit |
|---|---|---|
| Chemical fertilizer | | |
| SLC: 8-24-24, 13-13-21, 15-15-15 and 16-16-16 formula | 9.8, 6.4, 6.8 and 7.3, respectively | % |
| Feeds for swine | | |
| General | 7 | g/head/d |
| Manure from swine farming | 50-80 | % |
| Precipitation | | |
| Agricultural areas of Amphoe Hat-Yai, Songkhla | 0.03 | mg L$^{-1}$ |
| Agricultural soil Agricultural soil | | |
| Major soil in Thailand | 1-76 (available P) | mg kg$^{-1}$ |
| | 38-1,137 (total P) | mg kg$^{-1}$ |
| Peninsular Thailand | 2-3.5 (available P) | mg kg$^{-1}$ |
| | 39-238 (total P) | mg kg$^{-1}$ |
| SLC | 24-288 (total P) | mg kg$^{-1}$ |
| Plant cultivation | | |
| General | 5-10 | % |
| Runoff | | |
| Klong U-Tapao | 0.002-0.40 | mg L$^{-1}$ |
| Rajjaprabha Dam reservoir | ND-0.36 | µM |
| 0-25 m | 0.14-0.68 | µM |
| >25 m | <0.01-0.18 | mg L$^{-1}$ |
| Tapi-Pumduang basin | | |

Sereewatthanachai *et al.* (2004)

Table 4: Cadmium in product systems and processes

| Product/processes | Contents/concentration | Unit |
|---|---|---|
| Chemical fertilizer | | |
| SLC : (8-24-24, 13-13-21, 15-15-15 and 16-16-16 formula) | 1.4, 1.4, 30.1 and 1.4, respectively | mg Cd $kg^{-1}$ |
| Feeds for swine | 0.18-0.32 | ppm |
| Manure from swine farming | 0.32 | ppm |
| Precipitation | | |
| SLC | $1.63\times10^{-4}$-$2.23\times10^{-3}$ | ppm |
| Mauritius | ND<90 | μg $L^{-1}$ |
| Malaysia | <1 | μg $L^{-1}$ |
| Northern England | 0.01 | μg $L^{-1}$ |
| Agricultural soil | | |
| Other parts of the world | 0.06-1.1 | mg $kg^{-1}$ |
| SLC | <0.001-0.089 | mg $kg^{-1}$ |
| In each region of Thailand | 0.001-0.294 | mg $kg^{-1}$ |
| Runoff | | |
| Klong Kud, Klong Teuy, and Klong U-Tapao | ND(<0.0005)-0.003 | mg $L^{-1}$ |

Sereewatthanachai *et al.* (2004)

entering the system via., different entry processes and flow paths are briefly discussed below.

**Fertilizer utilization** The amount of phosphorus and cadmium entering the system through fertilizer application was calculated by first identifying the fertilizers used in each province and then calculating the amount of fertilizer applied as A*F* SC, where A is the planting area for crops (acre) and F is the fertilizer applied in each crop (kg/acre/year) and SC is the percent by weight of substance of interest in the fertilizer obtained from the laboratory analysis of each fertilizer.

**Feed for swine and manure from swine farming:** Phosphorus and cadmium entering the system is calculated by multiplying the number of swine in the area with the amount of feed consumed and the amount of phosphorus and cadmium in the feed. A study by Radcliffe *et al.* (2006) indicated that swine utilized 20-50% of phosphorus in feed and excreted the remainder in manure. The phosphorus and cadmium amounts in the manure are then calculated from the number of swine multiplied by the average manure produced $animal^{-1}$ and the amount of phosphorus and cadmium in the manure.

**Precipitation:** In general, the cadmium content in atmospheric precipitation is very low, except at locations close to smelters or other significant industrial and urban emission sources. Only 2% of the SLB area is settlement soil and the catchment does not accommodate any intensive industrial zones. Phosphorus was detected at a level of 0.03 mg $L^{-1}$ within the agricultural area. Cadmium was detected at a level of $1.63\times10^{-4}$-$2.23\times10^{-3}$ ppm within the agricultural area. The amounts of phosphorus and cadmium brought in by precipitation were calculated by multiplying the average precipitation with the area and the phosphorus and cadmium concentrations in the precipitation.

**Accumulation of phosphorus and cadmium in agricultural soil:** The soil within the SLB can be described as being of moderate to poor fertility and poorly drained. In general, the soil in peninsular Thailand was found to have relatively low phosphorus content: 2-3.5 mg $kg^{-1}$ of available phosphorus and 39-162 mg $kg^{-1}$ of total phosphorus. A slightly higher level of phosphorus, 145-238 mg $kg^{-1}$ of total phosphorus, has occasionally been found, with content decreasing with soil depth. The majority of the phosphorus in these soils (48-71%) is organic and is, therefore, not available for plant uptake. The amounts of phosphorus and cadmium in agricultural soil are calculated by multiplying the soil mass with the phosphorus and cadmium contents in the soil.

**Plant cultivation:** The source of phosphorus for plant growth is present as orthophosphate in soil. Agricultural crops generally take up only 5-10% of phosphorus applied as fertilizer in the first year, with uptake gradually decreasing in the following years (Greenwood *et al.*, 2001), 90% of phosphorus uptake originates from residual phosphorus in soil. Phosphorus from freshly applied fertilizer cannot compensate for a low soil phosphorus status, since, in general, more than 80% of the applied phosphorus becomes immobile and unavailable for plant uptake due to adsorption, precipitation, or conversion to the organic form. Plant refuse within the area is used as animal feed and as manure.

**Losses of phosphorus and cadmium through runoff:** Phosphorus and cadmium in the river were calculated by multiplying the quantity of SLB surface water runoff with the phosphorus/cadmium in the surface water runoff. Runoff in the SLB is estimated as $4.896\times10^9$ $m^3$ $year^{-1}$ (Sereewatthanachai *et al.*, 2004).

## RESULTS AND DISCUSSION

**Substance Flux Analysis (SFA):** The only study in the past to evaluate the loading of phosphorus and cadmium to the lake was very limited in scope. It used only 7 interviews and no fertilizer samples. Of the 7 interviewees, 6 were from Songkhla Province. It concluded that phosphate fertilizer application is the main source (Sereewatthanachai *et al.*, 2004). Therefore, any information or method to better estimate the input loads needs to be explored. Reliable estimates of accumulations of phosphorous and cadmium in the agricultural soil of the SLB are necessary as input for cell-based transport models to track the transport of these chemicals via., storm water runoff flowing into the lake.

This study attempted to estimate the input amounts for transport models using SFA. A total of 86 interviews covering all of the 3 provinces including farmers, fertilizer resellers, cooperatives and government officials were carried out. Thirty-five fertilizer samples were also collected from wholesalers, resellers and farmers for laboratory testing of phosphorus and cadmium amounts. The weak acid (2 M $HNO_3$) leaching method was used to extract metals from the fertilizer samples. Subsequently, an inductively coupled plasma-optical emission spectroscopy on a Perkin-Elmer ICP-OES Optima 2000 DV instrument was used to determine cadmium levels. Phosphorus is extracted from the soil using Bray 2 solution, ascorbic acid ($C_6H_8O_6$), as extractant. Table 5 indicates fertilizer utilization for each province from each source. Table 6 indicates planting area of various crops. Table 7 contains the fertilizer application rates for each crop. The resulting data on plantation area and fertilizer utilization are presented in Fig. 4 and 5, respectively. Figure 4 shows planting areas where fertilizer was applied (affected and non-affected areas). Amounts of fertilizer utilization (Kg/rai/year) in the planting area are shown in Fig. 5. The entry of phosphorus and cadmium into agricultural soil was analyzed via primary and secondary data. The results found that the entry of phosphorus and cadmium into the agricultural soil was potentially significant via., three products and one process line: (1) phosphate fertilizer, (2) feed for swine, (3) manure from swine farming and (4) precipitation. The entry points and pathways of phosphorus and cadmium entering agricultural soil are illustrated in the SFA schematic in Fig. 6. These entry points are discussed below.

**Phosphate fertilizer:** This study found that approximately 384,289 t of chemical fertilizer was applied in the SLB agricultural soil in the year 2004, whereas Sereewatthanachai *et al*. (2004) reported 55,307 t in 2002. Interview data from SLB wholesalers revealed that the fertilizer formulae (N-P-K) used in the area were 16-8-4, 15-7-8, 20-8-20, 16-20-0, 25-7-7, 15-15-15, 18-24-24 and 13-13-21. The main formulae used in paddy fields and old rubber farming were 20-8-20 and 16-20-0.

Table 5: Fertilizer utilization

| Fertilizer formula | Phatthalung (t year$^{-1}$) | | | Nakhon Si Thammarat (t year$^{-1}$) | | | Songkhla (t year$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Survey | Resellers | Co-ops | Survey | Resellers | Co-ops | Survey | Resellers | Co-ops |
| 16-8-4 | 4,402 | 4,519 | 5,000 | 7,778 | 8,224 | 9,718 | 11,270 | 11,474 | 12,945 |
| 15-7-8 | 4,402 | 4,912 | 5,708 | 7,778 | 8,005 | 9,320 | 11,270 | 11,979 | 12,206 |
| 20-8-20 | 52,829 | 53,761 | 53,945 | 93,330 | 93,622 | 94,386 | 135,236 | 135,391 | 135,861 |
| 16-20-0 | 50,623 | 51,069 | 52,209 | 68,231 | 68,977 | 69,909 | 41,498 | 41,853 | 42,926 |
| 25-7-7 | 92 | 150 | 150 | 1,716 | 2,608 | 3,868 | 766 | 1,336 | 1,558 |
| 15-15-15 | 2,996 | 3,766 | 5,096 | 19,502 | 19,958 | 21,186 | 15,605 | 15,704 | 16,735 |
| 8-24-24 | 313 | 465 | 1,915 | 2,971 | 3,392 | 4,125 | 13,059 | 13,874 | 15,248 |
| 13-13-21 | 313 | 757 | 1,360 | 2,971 | 3,173 | 3,505 | 13,059 | 13,228 | 14,600 |
| Total | 115,970 | 120,231 | 126,987 | 204,277 | 207,959 | 216,017 | 241,763 | 244,839 | 252,079 |

Table 6: Planting area of crops treated with fertilizer application in 3 provinces

| Sub-province | Phatthalung (acre) | Nakhon Si Thammarat (acre) | Songkhla (acre) |
|---|---|---|---|
| Rubber | 281,753 | 497,762 | 721,260 |
| Rice | 202,493 | 272,925 | 165,994 |
| Mangosteen | 6,704 | 30,264 | 1,605 |
| Palm oil | 732 | 13,728 | 6,130 |
| Rambutan | 3,672 | 25,888 | 1,352 |
| Durian | 2,828 | 17,860 | 5,580 |
| Longan | 7,520 | 11,379 | 5,274 |
| Pamelo | 880 | 7,247 | 2,453 |

Table 7: Fertilizer application rate for each crop

| Crop | Fertilizer formula* | Application rate (kg/acre/year) | Spatial distribution in Phatthalung | Spatial distribution in Nakhon Si Thammarat | Spatial distribution in Songkhla |
|---|---|---|---|---|---|
| Young rubber | 16-8-4 | 125 | Pabon | Tungsong | Sadaow |
| (<6 years) | 15-7-8 | | | | |
| Old rubber | 20-8-20 | 250 | Pabon | Chaaud | Sadaow |
| Rice | 16-20-0 | 250 | Muang, Kwankanoon | Haisai | Ranote, Satingpra |
| Mangosteen | 15-15-15 | 250 | Tamote | - | - |
| Palm oil | 25-7-7 | 125 | Bangkaew | Tungsong | Klonghoikong |
| Rambutan | 15-15-15 | 250 | Piboon | Tasala | |
| Durian | 15-15-15 | 250 | Piboon | Tasala | |
| Longan | 15-15-15 | 125 | Piboon | Tasala | |
| | 8-24-24 | 125 | Piboon | Tasala | |
| | 13-13-21 | 125 | Piboon | Tasala | |
| Pamelo | 15-15-15 | 250 | Kauankanoon | Hwaisai | Singhanakorn |

Interviewing of farmers and fertilizer dealers. *The formula represents the value of N-P-K concentration

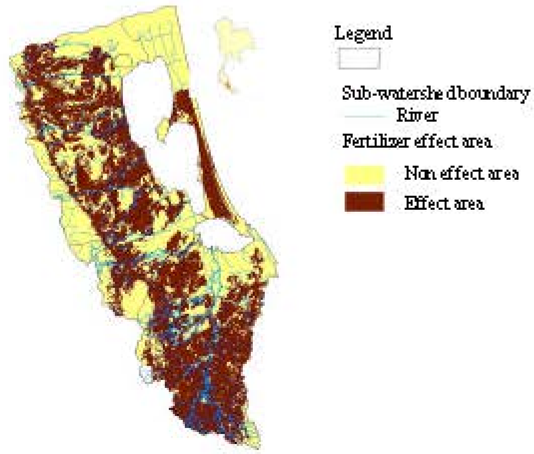


Fig. 4: Planting area

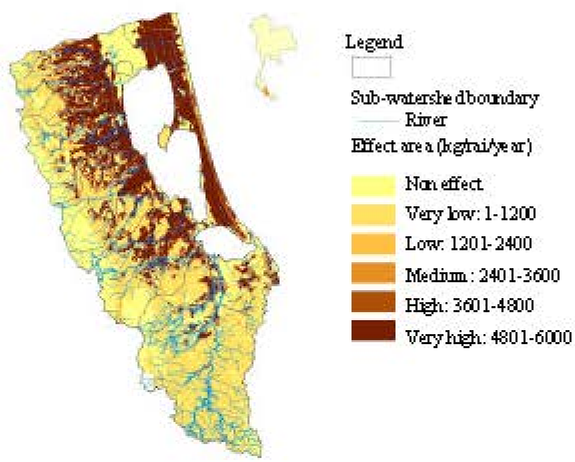


Fig. 5: Fertilizer utilization

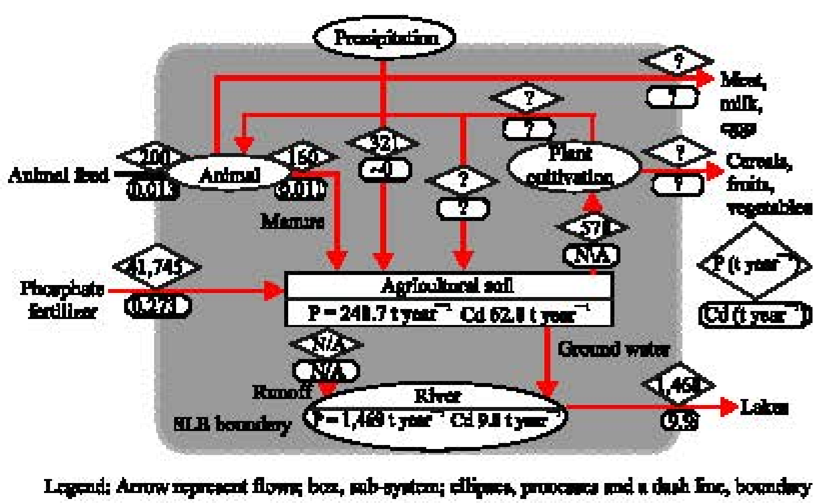


Fig. 6: SFA of phosphorus (diamond) and cadmium (rounded rectangle) in SLB (t year$^{-1}$)

Sereewatthanachai *et al.* (2004) reported 4 specific formulas (8-24-24, 13-13-21, 15-15-15 and 16-16-16) and noted that other grades of fertilizers had been used but not analyzed. This study found phosphorus contents in the investigated grades were 8.3, 6.5, 7.4, 16.8, 6.4, 13.2, 20.2, 10.1%, respectively; cadmium amounts in phosphate fertilizers ($P_2O_5$) were 1.5, 1.6, <1.4, <1.4, <1.4, <1.4, 7.19 and 1.4 mg Cd kg$^{-1}$, respectively. Sereewatthanachai *et al.* (2004) had found phosphorus amounts in the investigated grades were 9.8, 6.4, 6.8 and 7.3%, respectively; cadmium amounts in phosphate fertilizers ($P_2O_5$) were 1.4, 1.4, 30.1 and 1.4 mg Cd kg$^{-1}$, respectively. Annual data regarding the fertilizer entering the SLB agricultural soil reveal that phosphorus content was approximately 41,745 t year$^{-1}$ and cadmium content in phosphate fertilizer ($P_2O_5$) was approximately 0.273 t year$^{-1}$. These amounts suggest that fertilizer applied to SLB soil is relatively clean with respect to cadmium.

**Feed for swine and Manure from swine farming:** The present study found that feed for swine contributed 200 t year$^{-1}$ of phosphorus and 0.013 t year$^{-1}$ of cadmium into the system. Because the maximum phosphorus uptake of 80% came from feed, 160 t year$^{-1}$ was estimated to be available as manure as direct input to soil. The cadmium content in swine manure was found to be 0.32 ppm, resulting in a total input of around 0.011 t year$^{-1}$.

**Precipitation:** The range of atmospheric phosphorus input in different areas can vary widely, from 5 kg/km$^2$/year to over 100 kg/km$^2$/year. From reviews, the average precipitation in the SLB is 1,880 mm year$^{-1}$ and the phosphorus concentration in the precipitation is around 0.03 mg L$^{-1}$. Thus, the phosphorus loading from precipitation is estimated at 321 t year$^{-1}$. If a concentration of 0.01 μg L$^{-1}$ is assumed on the basis of reports, the cadmium accumulation resulting from precipitation will be approximately 0.11 t year$^{-1}$.

In summary, the SFA in this study found that approximately 384,289 t of chemical fertilizers were applied to the SLB agricultural soil in the year 2004, whereas Sereewatthanachai *et al.* (2004) reported 55,307 t in 2002. Based on the planting area for each crop, the fertilizer utilization rate for Phatthalung, Nakhon Si Thammarat and Songkhla were 115,970, 26,556 and 241,763 t year$^{-1}$, respectively. This finding was similar to the information obtained from agricultural fertilizer dealers in the provinces and private organizations such as the Bank of Agriculture and Agricultural Cooperatives (BAAC). Thus, over 41,745 t year$^{-1}$ ear of phosphorus and 0.273 kg year$^{-1}$ of cadmium from phosphate fertilizer would be more precise values.

Comparisons of input phosphorus and cadmium amounts with and without applying SFA are shown in Table 8. The SFA estimate of phosphorus load is 688% times higher and cadmium load is 26% times lower than the previously available estimates. The improved estimates were then carried into the modeling effort.

**Modeling:** For the overall study, the lake drainage area was divided into eight sub-watersheds (Fig. 2). AnnAGNPS and TREX models were developed for each sub-watershed. All of the models were calibrated for runoff and sediment loads and then SFA-estimated input loads were used to predict the amount of phosphorus and cadmium, respectively. The entire modeling results of all the sub-watersheds are not discussed here because the thrust of this paper is only to demonstrate the usefulness of SFA for obtaining improved estimates of input amounts of phosphorus and cadmium for the models. The results of the modeling showed the relative loadings of phosphorus and cadmium from different parts of the watershed. The major contributor of phosphorus and cadmium to the SLB was the U-Tapao and Eastern coast sub basin 4 sub-watershed, which was responsible for almost one-third of the total phosphorous and cadmium contributions (Table 9). Figure 7 and 8 show the

Table 8: Comparisons of soil loading for the entire SLB before and after applying SFA

| Soil loading (model parameters) | Estimate without SFA | SFA Estimate |
|---|---|---|
| Input phosphorus amount | 5,297 t year$^{-1}$ | 41,745 t year$^{-1}$ |
| Input cadmium amount | 370 kg year$^{-1}$ | 273 kg year$^{-1}$ |

Table 9: Phosphorus and cadmium results in U-Tapao and Eastern Coast Sub Basin 4 Sub-watershed

| Coordinate | | | | | | | |
|---|---|---|---|---|---|---|---|
| X | Y | P observed (mg kg$^{-1}$ dry soil) | Estimate without SFA | SFA estimate | Cd observed (μg kg$^{-1}$ dry soil) | Estimate without SFA | SFA estimate |
| 652479 | 781907 | 24.05 | 3.05 | 24.43 | 16.11 | 21.83 | 17.15 |
| 649857 | 779751 | 74.31 | 9.43 | 76.05 | 40.05 | 54.28 | 49.49 |
| 641771 | 769116 | 120.84 | 15.33 | 122.02 | 4.64 | 6.29 | 6.30 |
| 651714 | 760350 | 58.62 | 7.44 | 62.81 | 5.54 | 7.51 | 7.26 |
| 654446 | 737358 | 40.96 | 5.20 | 44.35 | 1.21 | 1.64 | 1.72 |
| 662859 | 740376 | 288.49 | 36.61 | 316.22 | 8.93 | 12.10 | 10.25 |

X and Y are coordinates in World Geodetic System of 1984 (WGS84 system). SBL is in Zone 47 in this system

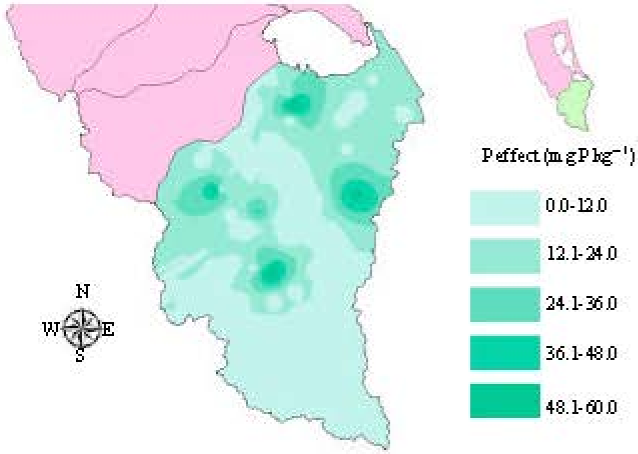


Fig. 7: Phosphorus amounts (mg P kg$^{-1}$) in U-Tapao and Eastern Coast Sub Basin 4 Sub-watershed obtained using AnnAGNPS model

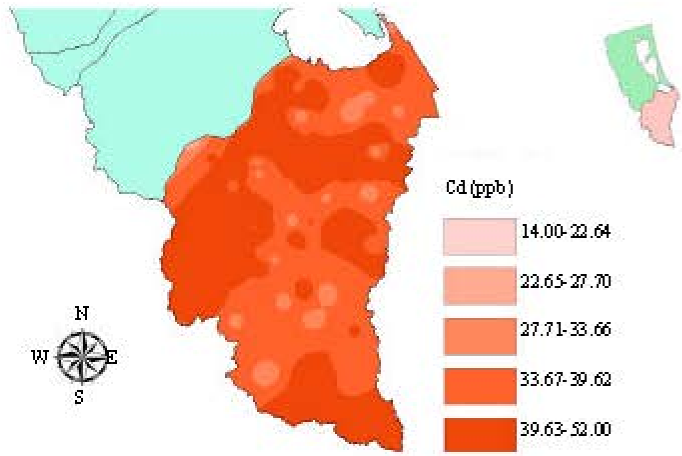


Fig. 8: Cadmium amounts (ppb) in U-Tapao and Eastern Coast Sub Basin 4 Sub-watershed obtained using TREX model

Table 10: Scenarios for analysis

| Scenario | Names | Strategies |
|---|---|---|
| 1 | Changes of fertilizer application rate | • Increase fertilizer application rate by 10%<br>• Increase fertilizer application rate by 50%<br>• Decrease fertilizer application rate by 10%<br>• Decrease fertilizer application rate by 50% |
| 2 | Changes of fertilizer formula | • Replacement of 8-24-24, 13-13-21 and 15-15-15 (high cadmium) by 15-15-15 (low cadmium) |
| 3 | Changes of crops cultivated | • Replacement of horticultural crops by rubber crop |

phosphorus and cadmium amounts in the U-Tapao and Eastern Coast No. 4 sub-watershed obtained by using the models. Results clearly show that the observed values are closer to the model-predicted estimates of phosphorus and slightly higher for cadmium with the SFA-estimated input of phosphorus and cadmium.

Three scenarios were considered and tested with the U-Tapao and Eastern Coast Sub Basin 4 sub-watershed (Table 10). The scenarios were selected to reflect changes in fertilizer formulas, fertilization application rates and cultivated crops. The scenario results and the current situations for phosphorus and cadmium loadings for the U-Tapao and Eastern Coast Sub Basin 4 sub-watershed are presented in Table 11 and 12, respectively. The results show that changing the fertilizer type from high- to low-cadmium-contaminated alone leads to a significant decrease of cadmium contribution from the watershed, especially in the U-Tapao and Eastern Coast Sub Basin 4 sub watershed where overall physical conditions (i.e., high runoff, horticultural crops, steep slope, high

Table 11: Scenario results of phosphorus in U-Tapao and Eastern Coast Sub Basin 4 Sub-watershed

| Coordinate | | Current phosphorus loading observed | Scenarios | | | | | |
|---|---|---|---|---|---|---|---|---|
| X | Y | (μg kg$^{-1}$ dry soil) | 1.1 | 1.2 | 1.3 | 1.4 | 2.1 | 3.1 |
| 652479 | 781907 | 24.43 | 28.52 | 37.61 | 21.26 | 15.65 | 15.03 | 14.43 |
| 649857 | 779751 | 76.05 | 102.10 | 124.92 | 60.31 | 36.96 | 31.69 | 27.17 |
| 641771 | 769116 | 122.02 | 156.26 | 195.99 | 100.09 | 65.97 | 58.96 | 52.69 |
| 651714 | 760350 | 62.81 | 70.39 | 94.98 | 55.96 | 42.82 | 42.30 | 41.79 |
| 654446 | 737358 | 44.35 | 58.44 | 72.21 | 35.65 | 22.52 | 19.64 | 17.12 |
| 662859 | 740376 | 316.22 | 439.52 | 528.26 | 244.15 | 140.46 | 116.51 | 96.64 |

X and Y are coordinates in World Geodetic System of 1984 (WGS84 system). SBL is in Zone 47 in this system

Table 12: Scenario results of cadmium in U-Tapao and Eastern Coast Sub Basin 4 Sub-watershed

| Coordinate | | Current cadmium loading observed | Scenarios | | | | | |
|---|---|---|---|---|---|---|---|---|
| X | Y | (mg kg$^{-1}$ dry soil) | 1.1 | 1.2 | 1.3 | 1.4 | 2.1 | 3.1 |
| 652479 | 781907 | 17.15 | 20.60 | 22.96 | 14.29 | 9.05 | 7.05 | 7.17 |
| 649857 | 779751 | 49.49 | 58.62 | 65.77 | 41.61 | 27.34 | 20.83 | 20.58 |
| 641771 | 769116 | 6.30 | 8.31 | 8.87 | 4.92 | 2.23 | 2.15 | 2.72 |
| 651714 | 760350 | 7.26 | 8.24 | 9.44 | 6.26 | 4.54 | 3.27 | 2.98 |
| 654446 | 737358 | 1.72 | 2.35 | 2.47 | 1.31 | 0.49 | 0.54 | 0.75 |
| 662859 | 740376 | 10.25 | 12.50 | 13.84 | 8.46 | 5.13 | 4.10 | 4.30 |

X and Y are coordinates in World Geodetic System of 1984 (WGS84 system). SBL is in Zone 47 in this system

organic matter, high erosion, acidity, high clay percentage and high total metal) could promote the transport of cadmium through the watershed. The scenario results demonstrate that changing the fertilizer type from high-cadmium (3 mg Cd kg$^{-1}$) to low-cadmium (1 mg Cd kg$^{-1}$) leads to 50-60% reduction in the cadmium load to the lake. However, with other scenarios, changing the types of crops grown in the area or lowering the fertilizer rate could further reduce cadmium contribution to the SLB as a whole. The results of this study could be used to develop an effective approach to minimize cadmium loadings by changing the phosphate fertilizer type. The scenario results for phosphorus from this study also indicates a potentially favorable scenario of adopting rubber cultivation instead of horticultural crops. Decision makers and/or planners can use this information for crop planning and/or agricultural extension.

## CONCLUSION

Distributed-parameter cell-based models are widely used in studies related to non-point source pollution transport problems. Though these are sophisticated models, results will be reliable only if the data input to the spatially distributed cells are of good quality and faithful to reality. The lack of a well-established database of spatially distributed data is a severe problem in many situations similar to the Songkhla Lake Basin. Methods used and approximations made in earlier studies on estimating phosphorus and cadmium loads to the Lake were often crude and could be sources of inaccuracy. Data from early studies should, therefore, be considered only as a starting point. The wide range of phosphorus and cadmium content recorded in the literature suggests the need for additional measurements specific to the SLB. The study reported in this study is an attempt to improve the input data for modeling the phosphorus and cadmium transport to the lake via., surface runoff using substance flux analysis. The parameter values are then used as input for the spatially distributed cell-based models, AnnAGNPS and TREX. The major phosphorus and cadmium contributing sub-watershed was then tested with different scenarios to identify the impact of changes in agricultural practices to phosphorus and cadmium loading. Though, SFA is used in this study to obtain estimates of the input parameters as lumped quantities, the idea is to use this approach on a cell-by-cell basis for detailed modeling. The study confirms that SFA is a viable method for improving estimates of pollutant amounts available for transport via., runoff, estimates that can be used as input to spatially distributed pollutant transport models.

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