Effects of soil erosion on water quality and water uses in the upper Phong watershed

S. Sthiannopkao*, S. Takizawa* and W. Wirojanagud**

*The University of Tokyo, Department of Urban Engineering, Graduate School of Engineering, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656 Japan (E-mail: *suthisuthi@hotmail.com*)

**Faculty of Engineering, Khon Kaen University, Khon Kaen, 40002, Thailand

Water Science & Technology **Vol 53 No 2 pp 45–52**

Abstract The main objective of this paper is to simulate the effects of soil erosion on river water quality and on agricultural production as a result of the transformation of forestlands in the catchment of the upstream Phong River. Suspended solids carry down attached nutrients and agricultural chemicals causing water pollution in the downstream. There are four different types of land use in this simulation, namely forestlands, flatland and highland sugarcane plantation areas, and paddy fields. The highest mean annual amount of soil erosion is from paddy fields (585,700 tons/year), followed by highland (73,800 tons/year) and flatland (63,950 tons/year) sugarcane plantation areas and forestlands (41,800 tons/year), respectively. However, as most of paddy fields are located in a low land and are wet type cultivations, the soil erosion occurred has less impact on river water quality and its production compared to the soil erosion from the steeper slopes of highland plantation areas. Under the resource-based agriculture, the sugarcane production is mainly increased by expanding the plantation areas leading to a significant loss of topsoil and a considerable reduction of agricultural production. Soil erosion contributes to an increase in the average annual suspended solids concentration by 72 mg/l.

Keywords Land use change; soil erosion; sugarcane production; system dynamic model; water quality

Introduction

The Phong watershed is an important watershed of the upper northeast region of Thailand. The Phong River is a tributary of the Chi River system, which flows into the Mekong River. The Phong watershed covers 1.5 million ha, extending to the five main provinces of Chaiyaphum, Khon Kaen, Loei, Nong Bua Lumphu, and Petchaboon. There are four main rivers in the upstream watershed area, namely the Phrom, the Choen, the Pa Niang, and the upstream Phong. These rivers run into the Ubolratana Dam, located in the middle section of the watershed. The downstream Pong River is divided into two river sections, namely sections from the Ubonratana Dam to the Nong Wai irrigation weir and from the wier to Mahasarakam dam, respectively.

The upper Phong watershed shares 79.59% of the total watershed area and is composed of 27.33% forest, 64.05% agriculture (mainly rain-fed paddy fields and plantations producing crops such as cassava, corn and sugarcane), and 8.62% other uses. The majority of the agricultural land has been transformed from forestland in the last few decades. This land transformation, together with farming practices without soil conservation, causes soil erosion and increased amounts of suspended solids in rivers, which silt up reservoirs, raise the riverbeds and affect water quality and water uses due to elevated turbidity levels in the rainy season. In addition, suspended solids carry down attached nutrients and agricultural chemicals, which causes water pollution in the downstream.

According to the Bank of Thailand (2004), use of natural resources for economic development in the northeast Thailand is extravagant. Soil, water, and forest resources are depleting at staggering rates. More than 1.6 million ha of forest were destroyed

doi: 10.2166/wst.2006.037

during the past 20 years, from approximately 4 million ha in 1975 to only 2.24 million ha in 1995. 0.32 million ha was encroached and turned to paddy and 0.64 million ha was turned into crop fields. Transformation of land use from the forest areas into agricultural areas for the past 30 years within the Phong watershed has left only 10–15% of the total watershed as natural forest and caused many problems such as flooding, soil erosion and sedimentation, soil salinization, and water quality deterioration (KKU, 2003). This is in accordance with Babel *et al.* (2004) stating that in the past four decades, deforestation in Thailand has been very rapid and the forestland has been converted into agricultural land, which has increased erosion from these watersheds. Soil erosion from agricultural areas results in loss of not only productive soil, but also plant nutrients, and organic and inorganic matter causing reduction in soil fertility. Sediment, a product of soil erosion, becomes a pollutant in rivers. According to the land development department, Thailand, some 33% of the 51.3 million hectares of the total geographical area is moderately to severely eroded. Suspended sediments from all the watersheds in Thailand are estimated to be 27 million tons annually. Cropland expansion through exploitation of forested hilly regions in the North and the utilization of the marginal uplands in the East and Northeast have been major contributors.

Among the four main rivers located in the upper Phong watershed area, the upstream Phong River is facing the most severe soil erosion due to the transformation of forestlands into agricultural areas. The effects of forestlands transformation into sugarcane plantation areas in the upstream Phong River are simulated in this study. Plantation of sugarcane in the highland of the upstream Phong River is encouraged by the Thai Government because of suitable climate, altitude, soil conditions, price stability and sugar mills situated nearby. There are three sugar mills located within the Phong watershed with a total processing capacity of 480,000 tons of sugarcane/day (KKU, 2003). This is in accordance with Sneddon (2002) reporting that the Thai state had long targeted the northeast as a region amenable to agro-industrial development.

As the phenomena occurring in the Phong watershed are multifaceted, interrelated and difficult to understand, a system dynamic model is proposed here as a research tool. According to Forrester (1961), system dynamics is a theory of system structure and a set of tools for representing complex systems and analyzing their dynamic behavior. Simonovic (2002) states that perhaps the most important aim of system dynamics is to elucidate the endogenous structure of the system under study, to see how the different elements of the system actually relate to one another, and to experiment with changing relations within the system when different decisions are included.

Methods

First, the current situation of land use and its effects on soil erosion and on water quality in the upper Phong watershed was identified by studying reports on the Phong Watershed Management conducted by the Khon Kaen University (KKU). Second, the causal loop diagram was drawn according to the outcome obtained in the first step. Finally, a system dynamic model was constructed using the STELLA program to simulate the soil erosion effects on water quality and on agricultural production in the upstream Phong River as a result of the forestland transformation. The following assumptions were made for the modeling based on the data obtained from Khon Kaen University (2003): 30 cm topsoil depth, average monthly rainfall of 100 mm during the rainy season, i.e. June to September, and no forestland rehabilitation. The rate of soil erosion was calculated based on the Universal Soil Loss Equation (MSU, 2004). The simulation was run for a 30-year period. The simulation model is composed of four sub-models, namely the soil erosion, the land use transformation, the water quality, and the agricultural production.

Results and discussion

Identifying problems in the upper Phong watershed

The conversion of forestlands into agricultural areas has caused a severe problem of soil erosion. According to the Office of Agricultural Economics (2004), among five main provinces located within the Phong watershed, four provinces, i.e. Chaiyaphum, Nong Bua Lumphu, Khon Kaen and Petchaboon, clearly show the increasing trends of agricultural lands during the period of 1994–2002 at mean annual rates of 0.77, 3.28, 4.71, and 10.66%, respectively. On the contrary all of the forest areas in the provinces of Chaiyaphum, Nong Bua Lumphu, Khon Kaen, Petchaboon and Loei had decreased during the period of 1988–1999 at mean annual rates of 0.84, 1.00, 2.34, 3.21, and 2.07%, respectively. Khon Kaen University (2003) monitored suspended solids in the main rivers of upper Phong watershed and estimated amounts of transported suspended solids in the rivers of Phrom, Choen, upstream Phong, and Pa Niang as 0.06, 0.32, 1.04, 0.19 tons/ha/year, respectively. According to KKU (2003), the highest amount of suspended solids was found in the upstream Phong River (1.04 tons/ha/year) because of the lesser forest coverage compared to the higher forest coverage in other rivers.

Promotion of agriculture is often considered as the only tool to eradicate rural poverty and boost exports to get foreign currency in many developing countries, including Thailand. The national policy of exporting agricultural produce is the main driving force for the intensive use of land resources in Thailand. Thailand is a main exporter of both rice and sugar. According to Food Market Exchange (2004), Thailand was the world's largest rice exporting country between 1995–1998. Although at the end of the year 1998 Thailand's export market share has declined by 4.2% from its original share in 1995, Thailand is projected to keep the largest market share at approximately 26–28% of the world rice production.

Besides rice, Thailand is the world's sixth largest sugar producer and the twelfth largest consumer. According to Food Market Exchange (2004), there are 107,000 small farmers growing sugarcane in Thailand. Mills do not grow cane themselves, but have contract farming with growers. In recent years, growth in sugar production has come largely from area expansion in the north and northeast of the country. The Thai sugar industry has done extremely well in the past decades, thanks to high cane prices, greater stability and confidence in the industry, successful government initiatives in mill relocation and expansion and favorable weather. Moreover, Thailand is presently one of the five largest global sugar exporters, with relatively small domestic demands for sugar and low shipping costs, especially to growing regional markets. The government policy of maintaining high domestic sugar prices has supported increased production, dampened growth in use and increased exportable surpluses. Thai sugar production in 1999/2000 was 5.72 million tons, an increase of 6% from the previous year. Domestic consumption was 1.6 million tons, a decrease by 8.3% from 1.8 million tons in the previous year, leaving plenty of sugar to be exported. In fact, Thailand does not import sugar, but exports about 3.3–3.4 million tons per year, being ranked as the world's fourth largest exporter.

Based on these reports and observations a causal loop was developed as shown in Figure 1. Forestland transformation into agricultural fields increases the rate of soil erosion, which leads to a higher concentration of suspended solids in rivers and a faster rate of siltation in reservoirs. When topsoil is lost due to soil erosion, the agricultural production, especially sugarcane production in this study, is diminished. The sugar stock kept at sugar mills is determined by the difference between agricultural (sugarcane) production and consumption, which comprises domestic consumption and exports. When the sugar stock exceeds a certain sugar stock goal, then the sugar mills will try to reduce the production next year. On the contrary, if the sugar stock depletes then the sugar mills will encourage

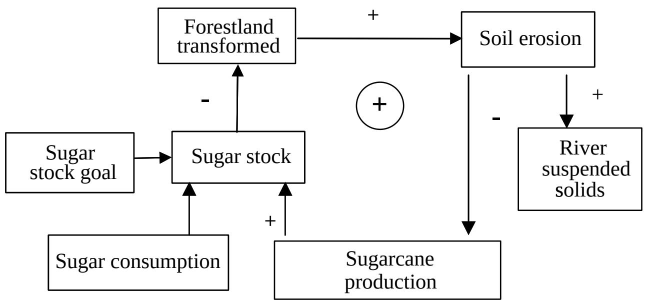

Figure 1 A causal loop diagram of soil erosion effects as a result of forestlands transformation

expansion of the sugarcane production, very often by transforming forestlands into sugarcane fields.

Simulation results

Effects of soil erosion on sugarcane production. As shown in Figure 2, the goal of sugar stock is set at 1,217,000 tons/year, which is 30% of the total mean annual sugarcane productions in the provinces of Loei, Nong Bua Lumphu and Khon Kaen. Therefore, sugarcane production is yearly adjusted to make the sugar stock reach this target as far as possible. Due to one-year delay in production adjustment, sugar stock fluctuates slightly every year. As the forestland conversion rate is determined by the pressure for increase in sugarcane production, this rate also fluctuates year by year. Although, the results shown in Figure 2 fluctuate yearly, the data are summarized in three decades of the simulation period to see the long-term changes (Table 1). The mean annual rates of change displayed in Table 1 are obtained by taking an average of the percent changes from previous years for each parameter. Due to the decreasing flatland sugarcane production at mean annual rates of 1.20%, 1.95%, and 11.01% in the 1st, 2nd, and 3rd decades of the simulation period, respectively, caused by topsoil loss, together with traditional nature-based agriculture, the sugarcane production can be increased only by converting forestlands into highland sugarcane plantations. The land conversion is

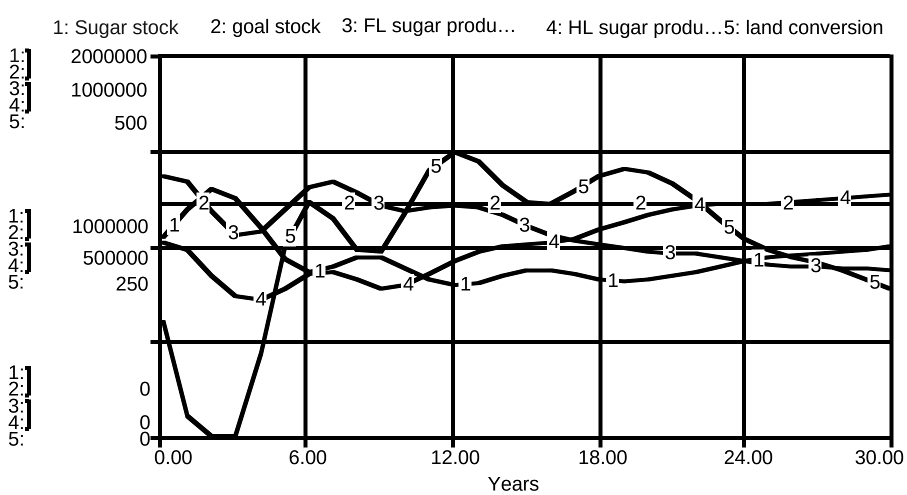

Figure 2 Sugarcane production (tons/year), sugar stock (tons) and land conversion (ha/year) (FL = flatland, HL = highland)

Table 1 Mean annual rates of changes in different simulated parameters (% per year)

Parameters	Year periods		
	1–10	11–20	21–30
Soil erosion–forest (tons/year)	−1.37	−3.61	−4.29
Soil erosion–highland sugarcane plantation (tons/year)	−7.95	−1.95	−11.69
Soil erosion–flatland sugarcane plantation (tons/year)	0	0	−24.99
Soil erosion–paddy (tons/year)	0	0	0
Total soil erosion (tons/year)	−1.55	−1.37	−0.83
Topsoil–forest (cm)	−2.80	−3.90	−6.49
Topsoil–highland sugarcane plantation (cm)	−37.87	0	0
Topsoil–flatland sugarcane plantation (cm)	−6.60	−26.72	0
Topsoil–paddy fields (cm)	−1.17	−5.61	−7.37
Forestland (ha)	−1.37	−3.61	−4.29
Highland sugarcane plantation area (ha)	1.90	3.07	1.92
Land conversion rate	9.85	2.00	−15.04
Sugar stock (tons)	−1.30	−0.67	1.96
Flatland sugarcane production (tons/year)	−1.20	−1.95	−11.01
Highland sugarcane production (tons/year)	−2.11	3.93	−9.22
Paddy production (tons/year)	−0.49	−0.45	−0.46

increasing at mean annual rates of 9.85% and 2.00% during the first and second decades leading to an increase of highland sugarcane production at a mean annual rate of 3.93% in the second decade of simulation. However, as the topsoil of the highland is easily eroded because of the steeper slope, this causes the decrease of highland sugarcane production in the third decade at a mean annual rate of 9.22%. Consequently, the sugar stock is affected by the decrease of sugarcane production in both flatlands and highlands. The mean annual sugar stock is decreased at rates of 1.30% and 0.67% during the first and second periods of simulation, respectively (Figure 2).

Effects of soil erosion on the topsoil depth and on water quality. As shown in Table 1 and Figure 3, the mean annual soil erosion from the forestland is gradually decreasing every year by 1.37%, 3.61% and 4.29% in the first, second and third decades, respectively. The main reason is that more forestlands are transformed into highland

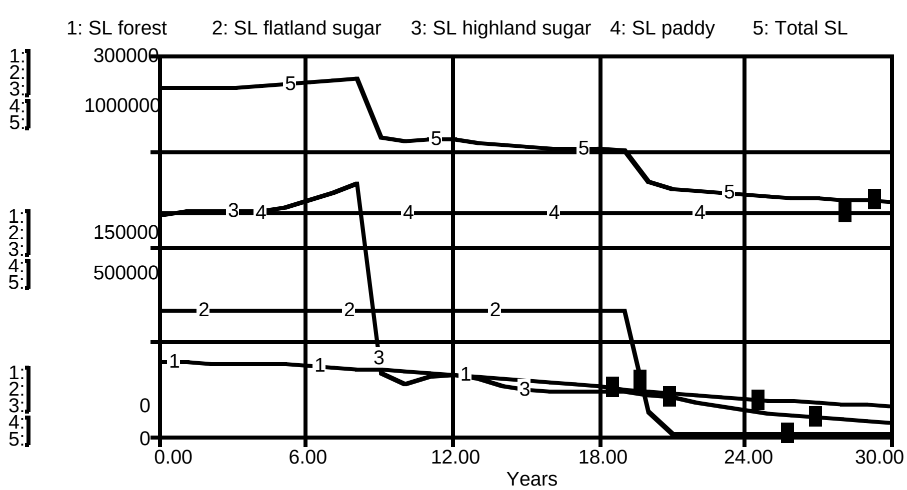

Figure 3 Amounts of soil erosion (tons/year) from different land uses (SL: soil loss)

sugarcane plantation areas at annual rates of 1.90%, 3.07%, and 1.92% in each decade of the 30-year simulation period, respectively. Consequently, the 30 cm topsoil depth from highland sugarcane plantation areas sharply decreases at a mean annual rate of 37.87% in the first decade leading to a complete topsoil loss in the second and third decades. However, the mean annual rates of soil erosion of the highland sugarcane plantations decrease at 7.95%, 1.95% and 11.69% during the first, second and third decades, respectively. This clearly indicates continuing conversions of forestlands to highland sugarcane plantation areas.

Table 1 and Figure 3 show that, in the first and second decades, the mean annual soil loss of flatland sugarcane plantation areas is stable and then it decreases during the third decades annually by 24.99%. This is because the 30 cm topsoil is continuously eroded during the first and second decades annually by 6.60% and 26.72% respectively and is totally depleted during the third decade of simulation. However, in the case of paddy fields, the annual rate of soil erosion is stable during a 30-year simulation period. This is because lowland paddy fields are wet type cultivations. Water storage in a field at the water level ranging from 5–10 cm helps to protect soil being transported far away from its original sources. In the case of deep-water rice plantations, the water level kept in the fields ranges from 50 cm to more than 300 cm.

As shown in Table 1 and Figure 3, the total soil erosion decreases annually by 1.55%, 1.37% and 0.83% during the first, second and third decades of simulation, respectively. This is because of the significant depleting of topsoil in the flatland and highland sugar plantation areas during the second and third decades. Hazarika and Honda (2001) estimated the rate of soil erosion in 1992 and 1996 using remote sensing data and GIS. According to their study the maximum rate of soil loss in the northern Thailand reached 25 mm/year; and the average rates of soil loss decreased from 1.24 mm/year in 1992 to 0.94 mm/year in 1996. The mean amounts of soil erosion from forestlands, highland and flatland plantation areas and paddy fields during a 30-year simulation period are 41,800, 73,800, 63,950, and 585,700 tons/year, respectively. The mean amount of soil erosion from paddy fields is the highest because of the largest areas of land cultivated (281,848 ha).

Figure 4 shows that, assuming 30% of eroded soil reaches the river, suspended solids in the upper Phong River increase by mean annual concentrations of 84.76, 71.26, and

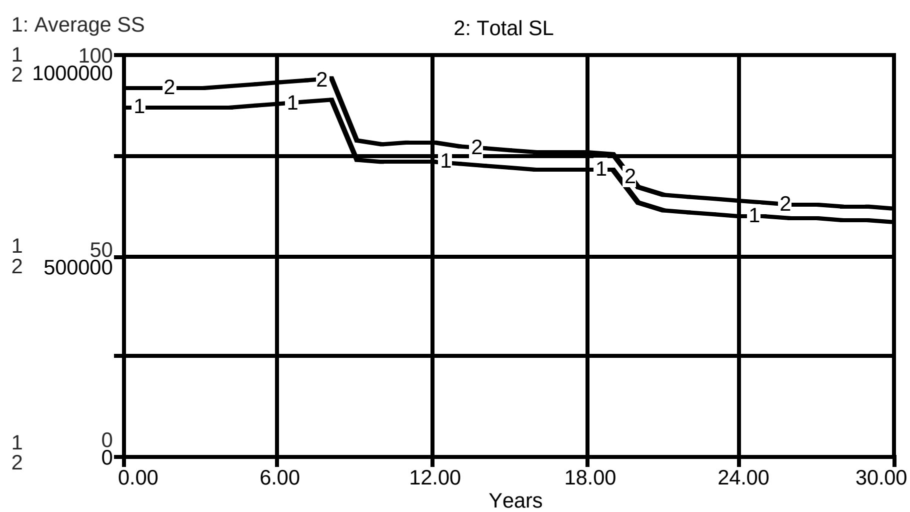

Figure 4 Suspended solid concentrations (mg/l) in the upstream Phong River

59.43 mg/l during the first, second and third decades of simulation, respectively. Soil erosion occurs in the upstream Phong River so that the suspended solids concentration in a river gradually decreases due to the depletion of topsoil in the next three decades. This result is obtained by assuming the topsoil depth as 30 cm. We may obtain different results if the topsoil depth is deeper or shallower than 30 cm. In addition, the soil erosion rate and suspended solids concentration are calculated as annual rates; depletion of topsoil may change the run-off rate and run-off pattern so that the fluctuations of suspended solids concentration in a river may be higher in the future than the present level.

Management application of the model produced. The simulation model presented in this study shows how sugar industry and soil erosion are interconnected. Export-driven economy prospers sometimes at the cost of the domestic environment. This simulation model can be used as one of the effective tools for environmental management, especially at the watershed level. It can easily be modified to examine the effectiveness of, e.g., the land conservation program on reduction of soil erosion and loss of agricultural production. The relationships and feedback built among sub-models of land use transformation, soil erosion, water quality, and agricultural production are comprehensively linked so as to see the effects of running different environmental policies on these different sub-models. With this model alternative policies can be compared and the result of simulation can be used to demonstrate the consequences of different policy options to the stakeholders.

Conclusions

The national policy of export-driven agriculture is a main driving force for the intensive land use in Thailand. In the upper Phong Watershed, the agricultural sector contributes to about 50% of the local economy, which is greater than two other sectors of manufacturing and wholesale. Together with suitable soil property, favorable climate and the establishment of the Sugarcane Association, sugarcane has become one of the preferred cash crops in the region. In addition, there are three sugar mills located within the Phong Watershed with a total processing capacity of 480,000 tons of sugarcane/day. A system dynamic model was developed and used to simulate soil erosion, deforestation and also loss of agricultural production. The increased forestlands conversion into sugarcane plantation areas accelerated the rate of soil erosion in the highland and the topsoil of the farmlands became completely eroded during the third decade of the simulation period. Soil erosion in the upstream Phong River was estimated to increase the suspended solids in a river by the annual concentration of 72 mg/l during the 30-year simulation period. In addition, soil erosion led to the decrease in sugarcane production of both flatlands and highlands mainly because of the decrease of topsoil set at 30 cm in this simulation. The system dynamic model developed in this study can be a useful tool to compare different policy options, and thus to come up with the best management practice.

References

Babel, M.S., Mujithaba, M., Najim, M. and Loof, R. (2004). Assessment of agricultural nonpoint source model for a watershed in tropical environment. *Journal of Environmental Engineering*, **3**(9), 1032–1041.

Bank of Thailand (2004). The northeast economy: Isaan region and social, economic, and environmental development. www.bot.or.th.

Foodmarketexchange (2004). Thai sugar. www.marketexchange.com.

Foodmarketexchange (2004). Thai rice. www.marketexchange.com.

Forrester, J.W. (1961). *Industrial dynamics*. MIT Press, Cambridge, Massachusetts.

Hazarika, M.K. and Honda, K. (2001). Estimation of soil erosion using remote sensing and GIS, Its valuation and Economic Implications on Agricultural Production. In *Sustaining the Global Farm*, Stott, D.E. (ed.), pp. 1090–1093.

Khon Kaen University (KKU) (2003). *Environment management of the Phong watershed*.

Michigan State University (2004). On-line soil erosion assessment tool. www.iwr.msu.edu.

Office of Agricultural Economics (2004). Agricultural Statistics of Thailand. www.oae.go.th.

Simonovic, S. (2002). World water dynamics: global modeling of water resources. *Environmental Management* **66**, 249–267.

Sneddon, C. (2002). Water conflicts and river basins: The contradictions of co-management and scale in Northeast Thailand. *Society & Natural Resources*, **15**(8), 725–741.