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Impact of Biofuel Production on Hydrology (A Case Study of Klong Phlo Watershed, Eastern Thailand)

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Government of Thailand has perceived biofuel as a suitable source of alternative energy to meet the increasing energy demand and reduce imports of fossil fuel. Considerable amount of land is being converted for biofuel production. This land use change can have significant impacts on water resources in terms of both quantity and quality. Hence, this study evaluates the impact of biofuel production on the water resources and hydrology of a small watershed, Khlong Phlo in the Rayong province of eastern Thailand. Water footprint of bioenergy was estimated to identify the most water-efficient crop to produce biofuel in the watershed and Soil and Water Assessment Tool (SWAT) model was used to evaluate the impact of land use change for biofuel production on water balance and water quality. Several land use change scenarios consisting of oil palm, cassava and sugarcane expansion were evaluated. Water footprint results indicate that cassava is the most water-efficient feedstock to produce biofuel and will have less impact on water resources of the watershed as compared to sugarcane and oil palm.

Modeling results reveal that expansion of cassava and sugarcane coverage will decrease annual evapotranspiration and baseflow but increase annual surface runoff and water yield which lead to increased sediment, nitrate and total phosphorus yield from the watershed. Even though increased oil palm production showed no considerable change on the water yield, the nitrate extraction to the surface water increased. This indicates that land use change for bio-ethanol will affect both the water balance and water quality of the watershed, while biodiesel will affect the water quality only. Study results further indicate that biofuel production will have negative impact on the environment of the Khlong Phlo watershed.

Keywords: Biofuel, Hydrology, SWAT, Water footprint

Introduction

Many countries have perceived biofuel as an opportunity to cut the fossil fuels consumption, to decrease oil import, to reduce the greenhouse gas emission, and to reduce poverty of rural communities. Production of biofuel, to meet the current and future demands, can have significant implication on the water resources and hydrological process due to land use changes, agricultural intensification and introduction of new plants. Production of biofuel, to meet the current and future demands, can have significant implication on the water resources and hydrological process due

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*Coresponding Author: Songvoot Sangchan **E-mail:** svsangchan@yahoo.com to land use changes, agricultural intensification and introduction of new plants.

Biofuel crops, which require irrigation, may increase the withdrawal of fresh water hence increase the stress on the water availability and effect the water allocation. On the other hand rain fed energy crops and land use changes (e.g., existing crop land, forest land, pasture, barren land) may alter the runoff, ground water recharges, water availability and local climate by change in evapotranspiration from land.

Increase in energy demand and loss of great deal of foreign currency to fossil fuel imports has encouraged Thai Government to initiate policy to explore alternative renewable energy sources such as solar, wind, water and biofuel. Ministry of Energy has plans to increase share of renewable energy in total energy consumption from 0.5% in 2002 to 8% (3% from biofuel) by 2011. Government has planned to increase current biofuel demand (2.1 million liters/day) to 13.5 million liters/day by 2022. This projection signifies intensive biofuel production scenario for Thailand, which needs considerable amount of water and land resources. Biofuel production in Thailand is expected to cause land use changes and add stress on already limited water resources. This study looks into the implication of biofuel production on hydrology.

Objectives: The main objective of the study is to analyze the implication of biofuel production on the water resources and hydrology of the Khlong Phlo watershed in Thailand. The specific objectives are:

1) To estimate the water footprint of biofuel and biofuel energy. Water footprint result is used to select the crops to produce biofuel in the most water-efficient way.

2) To evaluate the impact of land use change for biofuel production on annual and seasonal water balance of the Khlong Phlo watershed

Methodology

The Khlong Phlo is the sub basin of Khlong Prasae basin located in the Rayong province of eastern Thailand.

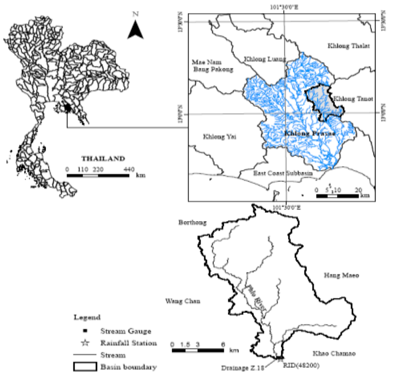


Figure 1. Khlong Phlo watershed, stream gauge andrainfall station within the watershed

The study watershed lies within 12°57’-13°10’ N and 101°35’ – 101°45’ E and encompasses a total area of 202.8 km^2 above the stream gauge station Z. 18 of the Royal Irrigation Department (RID). The watershed receives an average annual rainfall of 1,734 mm. The annual mean temperature ranges from 27 to 31°C and the relative humidity ranges from 69 to 83 percent. Agricultural land is the dominant land cover of the watershed, which comprises nearly 66 percent. Soils in this watershed are predominantly sandy clay loam and sandy loam in texture.

Calculation of water footprint of crops (WF$_C$)

The water footprint of crop, WFc (m^3/tons) is the proportion of the amount of water used to produce crop Wc (m^3/ha), to crop yield, Y (tons/ha).

$$WFc = \frac{Wc}{Y} \tag{1}$$

Volume of water used by crop is the sum of volume of evaporative water and non-evaporative water.

$$Wc = Wevaporative + Wnon - evaporative \tag{2}$$

Evaporative volume of water can be classified into green and blue water, where as the grey water volume is non-evaporative water.

$$Wevaporative = Wg + Wb \tag{3}$$

$$Wnon - evaporative = Wp \tag{4}$$

where Wg (m^3/ha) is the volume of green water, Wb (m^3/ha) is the volume of blue water and Wp (m^3/ha) is the volume of grey water.

The green and the blue water volume are based on evaporation requirement of the specific crop and soil moisture. The crop evaporation (ET [t]mm/day) is the function of reference crop evaporation (ETo [t]mm/day) at that particular time and location and crop coefficient (Kc[t]) for respective growth period.

$$ET(t) = Kc(t) X\ ETo(t) \tag{5}$$

The green water use Ug(t) is the minimum of effective rainfall Peff(t) and the crop evaporation at that time step.

$$Ug(t) = \min[ET(t), Peff(t)] \tag{6}$$

Total green water used is the cumulative of green water used for each time-step over the whole duration of crop period, l(day).

$$Wg = \sum_{t=0}^{l} Ug(t) \tag{7}$$

The blue water use Ub(t) is equal to minimum of irrigation requirement I(t), and the effective irrigation supply, Ieff(t) which is irrigation water stored as soil moisture and available for crop evaporation. In case where all the crop evaporation is met by the effective rain, the blue water requirement is zero.

$$I(t) = ET(t) - Ug(t) \tag{8}$$

$$Ub(t) = \min[I(t), Ieff(t)] \tag{9}$$

Total blue water used is the aggregate of blue water used for each time-step over the whole duration of crop period, l(day)

$$Wb = \sum_{t=0}^{l} Ub(t) \tag{10}$$

The grey water use is often not easy to quantify because the established standard can always be argued and the standard differs based on the use value of the water downstream. The grey water use Up(t) is the ratio of the weight of pollutants released into the water system Pr(t) due to crop production to the permissible limit of that pollutants Pl(t).

$$Up(t) = \max\left(\frac{\mathrm{Pr}(t)}{\mathrm{Pl}\ (t)}\right) \tag{11}$$

Total dilution required due to crop production pollution is given by:

$$Wp = \sum_{t=0}^{l} Up(t) \tag{12}$$

Calculation of water footprint of biofuel (WF_B)

The water footprint of biofuel (L of H_2O per L of biofuel) was calculated by dividing water footprint of crop (m^3/t) times 1000 by biofuel conversion rate (L/t).

Calculation of water footprint of biofuel energy (WF_{BE})

The water footprint of biofuel energy (m^3 per GJ of biofuel energy) was estimated by dividing water footprint of biofuel (L of H_2O per L of biofuel) times 1000 by energy per liter biofuel (kJ/ L). Energy per liter of biofuel is calculated by multiplying the product of Higher Heating Value (HHV) of biofuel (kJ/g) and density of biofuel (kg/L) by 1000.

Biofuel crop yield, conversion rate and energy

Cassava, sugarcane and oil palm are three biofuel crops in the study area. The crop yield data were obtained from Office of Agricultural Economics (OAE). The provincial average yield for cassava is 23.59 t/ha, while for sugarcane and oil palm it is 62.11 t/ha and 12.38 t/ha respectively. The yield value presented is the average of three production year (2010 - 2012).

Table 1. Biofuel crop yield and conversion rate

Crop	**Average yield**	**Biofuel produced**	**Conversion rate**
	t/ha		**L/t**
Cassava	23.59	Bio-ethanol	180[a]
Sugarcane	62.11		70[a]
Oil Palm	12.38	Biodiesel	221[a]

Source: [a] Department of Alternative Energy Developmemt and Efficiency, 2006

Energy of biofuel was calculated based on Higher Heating Value (HHV) and density of biofuel (Table 2) which were adopted based on literature. Per unit biodiesel can produce more energy than bio-ethanol.

Table 2. Higher heating value (HHV) and density of biofuel

Biofuel	**Higher Heating Value (HHV)[a]**	**Density[b]**
	kJ/g	**kg/L**
Bio-ethanol	29.70	0.789
Biodiesel	37.70	0.840

Source: [a]Penning de Vries (1989) and Verkerk et al. (1986); [b] www.dft.go.uk, 2010.

Land use change scenarios

In order to estimate the impact of land use change due to biofuel crop expansion on water balance components, sediment yield and nitrogen and phosphorus loss several scenarios were constructed. The model was calibrated and validated based on baseline (present) land use scenario and then run to simulated all land use change scenarios. Proposed land use change scenarios are grouped into three, namely oil palm expansion, cassava expansion and sugarcane expansion. There are four scenarios under each group and they are presented in Table 3.

Table 3. Details of the land use change scenarios in the Khlong Phlo watershed

Scenarios	**Land use**												**Conversion**
	Rubber		**Forest**		**Orchard**		**Cassava**		**Sugarcane**		**Oil Palm**		
	km^2	**%**	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**	
Baseline (Existing)	85.12	41.98	66.36	32.73	32.80	16.18	9.88	4.87	2.11	1.04	1.12	0.55	
A. Oil Palm expansion scenarios													
Scenario A1	85.12	41.98	66.36	32.73	-	-	9.88	4.87	2.11	1.04	**33.92**	**16.73**	Orchard to oil palm
Scenario A2	-	-	66.36	32.73	32.80	16.18	9.88	4.87	2.11	1.04	**86.24**	**42.53**	Rubber to oil palm
Scenario A3	-	-	66.36	32.73	-	-	9.88	4.87	2.11	1.04	**119.04**	**58.71**	Orchard and Rubber to oil palm
Scenario A4	85.12	41.98	-	-	32.80	16.18	9.88	4.87	2.11	1.04	**67.48**	**33.28**	Forest to oil palm
B. Cassava expansion scenarios													
Scenario B1	85.12	41.98	66.36	32.73	-	-	**42.68**	**21.05**	2.11	1.04	1.12	0.55	Orchard to cassava
Scenario B2	-	-	66.36	32.73	32.80	16.18	**95.00**	**46.85**	2.11	1.04	1.12	0.55	Rubber to cassava
Scenario B3	-	-	66.36	32.73	-	-	**127.80**	**63.03**	2.11	1.04	1.12	0.55	Orchard and Rubber to cassava
Scenario B4	85.12	41.98	-	-	32.80	16.18	**76.24**	**37.60**	2.11	1.04	1.12	0.55	Forest to cassava
C. Sugarcane expansion													
Scenario C1	85.12	41.98	66.36	32.73	-	-	9.88	4.87	**34.91**	**17.22**	1.12	0.55	Orchard to sugarcane
Scenario C2	-	-	66.36	32.73	32.80	16.18	9.88	4.87	**87.23**	**43.02**	1.12	0.55	Rubber to sugarcane
Scenario C3	-	-	66.36	32.73	-	-	9.88	4.87	**120.03**	**59.20**	1.12	0.55	Orchard and Rubber to sugarcane
Scenario C4	85.12	41.98			32.80	16.18	9.88	4.87	**68.47**	**33.77**	1.12	0.55	Forest to

													sugarcane

Baseflow = Lateral soil + groundwater flow;
Total water yield = Surface runoff + Baseflow – Transmission loss

Results

Water footprint of biofuel crops

Water footprint of three biofuel crops: cassava, sugarcane and oil palm in the study area is shown in Table 4.

Table 4. Green, blue, green + blue and grey water footprint of biofuel crops (WF_{CP})

Crop	**Green WF_{CP}**	**Blue WF_{CP}**	**Green + Blue WF_{CP}**	**Grey WF_{CP}**			
				m^3/t			
	m^3/t	**m^3/t**	**m^3/t**	**5 %**	**10 %**	**15 %**	**20 %**
Cassava	306	106	412	21	42	64	85
Sugarcane	142	80	223	6	12	18	24
Oil Palm	775	420	1195	42	85	127	170

Water footprint of biofuel and biofuel energy

Cassava and sugarcane produces bio-ethanol and oil palm is a source of biodiesel. The calculation of water footprint of biofuel is based on the conversion rate of respective crops.

Table 5. Water footprint of biofuel (WF_B)

Crop	**Biofuel**	**Green WF_B**	**Blue WF_B**	**Green + Blue WF_B**	**Grey WF_B**			
		L of H_2O/ L of Biofuel	**L of H_2O/ L of Biofuel**	**L of H_2O/ L of Biofuel**	**L of H_2O/ L of Biofuel**			
					5 %	**10 %**	**15 %**	**20 %**
Cassava	Bio-ethanol	1698	588	2287	118	235	353	471
Sugarcane		2032	1150	3182	86	173	259	345
Oil Palm	Biodiesel	3505	1901	5407	192	384	576	768

Water footprint of biofuel energy

The amount of water required to produce unit energy from biofuel is shown in table 6. Energy produce per liter of biofuel is based on the Higher Heating Value (HHV)

Table 6. Water footprint of biofuel energy (WF_{BE})

Crop	**Green WF_{BE}**	**Blue WF_{BE}**	**Green + Blue WF_{BE}**	**Grey WF_{BE}**			
	m^3/ GJ of Energy	**m^3/ GJ of Energy**	**m^3/ GJ of Energy**	**m^3/ GJ of Energy**			
				5 %	**10 %**	**15 %**	**20 %**
Cassava	72	25	98	5	10	15	20
Sugarcane	87	49	136	4	7	11	15
Oil Palm	111	60	171	6	12	18	24

Effect of land use change on the water balance

The summary of the annual water balance of the Khlong Phlo watershed for the baseline scenario and the twelve land use change scenarios is presented in Table 7. Under palm oil expansion scenarios, conversion of orchard area and rubber to oil palm plantation (Scenario A1, A2 respectively) decreased surface runoff by less than 1mm for both cases and baseflow by 2.21 mm and less than 1 mm respectively. Under maximum area conversion scenario (Scenario A3) both the surface runoff and baseflow decreased by less than 1% (Figure 2). In contrast forest area replacement (Scenario A4) increased surface runoff but decrease baseflow by nearly 27 mm. In all the cases the implication on total average annual water yield was insignificant (less than 1%) (Figure 2a). This is due to fact that there was no considerable change in evapotranspiration.

For both the cassava and sugarcane expansion scenarios there was significant increase in surface runoff and total water yield but decrease in baseflow (Figure 2b and 2c) and the evapotranspiration decrease with increasing hectare coverage.

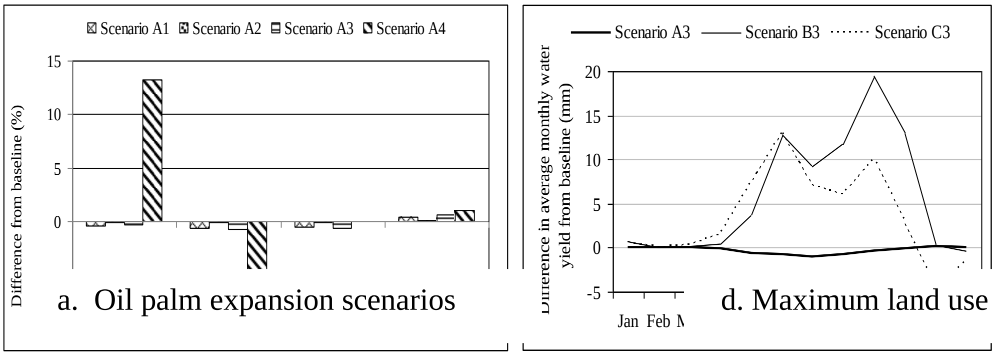
In all cases amount of surface runoff increase was high for cassava expansion scenarios while baseflow decline was high for sugarcane expansion scenarios. Increase in surface runoff will cause significant rise in sediment as well as nutrient loss and increase flooding in lower lying downstream regions.

These results simply suggest that land use change for bio-ethanol production will affect the water balance of the Khlong Phlo watershed due increased surface runoff and water yield and decreased baseflow and evapotranspiration. On the other hand the impact of land use change for biodiesel production on water balance seems insignificant except for the forest conversion case where surface runoff increased and baseflow decreased.

Table 7. Summary of the annual water balance in the Khlong Phlo watershed under baseline (current) and land use change scenarios.

	Surface runoff	**Lateral soil**	**Groundwater flow**	**Evapo-transpiration**	**Transmission loss**	**Base flow**	**Total water yield**	**Q/P**	**ET/P**
	mm	**mm**	**mm**	**mm**	**mm**	**mm**	**mm**	**%**	**%**
Baseline	206.69	102.24	288.61	835.60	1.03	390.85	596.51	34	48
A. Oil Palm expansion scenarios									
Scenario A1	205.97	102.17	286.47	839.40	1.02	388.64	593.59	34	48
Scenario A2	206.48	102.23	288.41	836.70	1.03	390.64	596.09	34	48
Scenario A3	205.99	101.75	286.35	840.80	1.10	388.10	592.99	34	48
Scenario A4	234.08	94.92	268.66	844.20	1.11	363.58	596.55	34	49
B. Cassava expansion scenarios									
Scenario B1	228.54	101.85	285.04	819.10	1.10	386.89	614.33	35	47
Scenario B2	266.06	101.35	283.95	784.30	1.23	385.30	650.13	37	45
Scenario B3	288.03	100.68	280.44	768.10	1.40	381.12	667.75	39	44
Scenario B4	278.38	92.21	267.15	804.60	1.24	359.36	636.50	37	46
C. Sugarcane expansion scenarios									
Scenario C1	227.28	101.75	278.09	829.20	1.08	379.84	606.04	35	48
Scenario C2	263.81	100.88	266.14	809.20	1.21	367.02	629.62	36	47
Scenario C3	284.62	100.06	255.74	802.70	1.36	355.80	639.06	37	46
Scenario C4	276.20	87.51	257.48	824.00	1.23	344.99	619.96	36	48

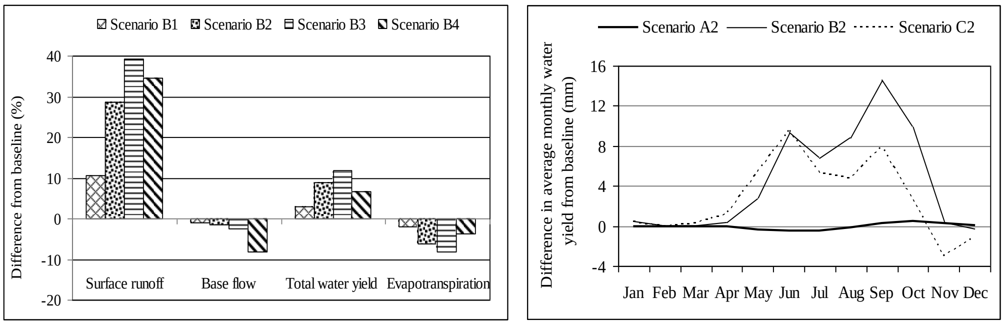
Baseflow = Lateral soil + groundwater flow
Total water yield = Surface runoff + Baseflow – Transmission loss



a. Oil palm expansion scenarios d. Maximum land use change scenarios

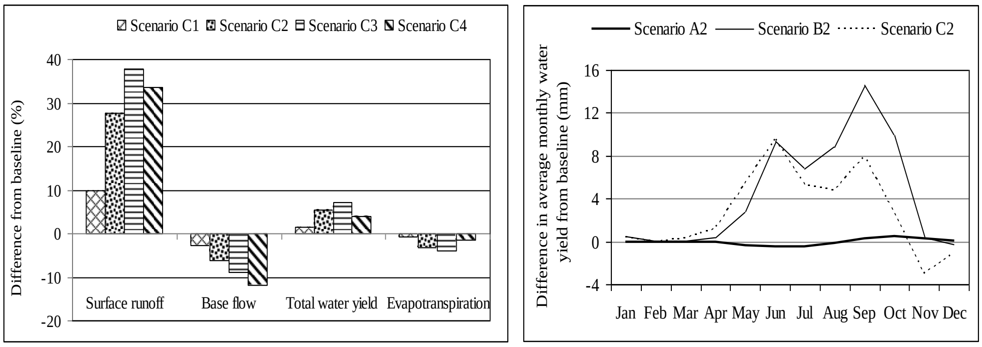
a. Oil palm expansion scenarios

d. Maximum land use change scenarios



b. Cassava expansion scenarios

e. Rubber area conversion scenarios



c Sugarcane expansion scenarios

f. Forest area conversion scenarios

Figure 2. Differences in water balance and average monthly water yield from land use

change scenarios to baseline

Effect of land use change on the water quality

Table 8 presents the summary of the annual export of nonpoint source pollutants from the Khlong Phlo watershed for the baseline scenario and the twelve land use change scenarios.

Table 8. Annual export of nonpoint source pollutants from Khlong Phlo watershed under current (baseline) land use and land use change scenarios

	NO_3-N loss	**Total P loss**	**Sediment loss**
	kg/ha	**kg/ha**	**t/ha**
Baseline	31.46	3.65	0.60
A. Oil Palm expansion scenarios			
Scenario A1	31.86	3.68	0.59
Scenario A2	37.02	3.38	0.59
Scenario A3	37.96	3.51	0.59
Scenario A4	40.25	4.71	0.68
B. Cassava expansion scenarios			
Scenario B1	32.06	4.44	0.67
Scenario B2	41.26	6.11	0.81
Scenario B3	38.48	6.51	0.89
Scenario B4	42.46	6.52	0.85
C. Sugarcane expansion scenarios			
Scenario C1	30.10	4.20	0.66
Scenario C2	34.52	4.91	0.77
Scenario C3	34.67	5.70	0.83
Scenario C4	38.43	5.82	0.82

The results clearly indicate that the conversion of land use for bio-ethanol production is likely to affect the water quality of the Khlong Phlo watershed due to increased sediment and nutrients loads into the water. Similarly the increased nitrate extraction into surface water due to land use change for biodiesel production will also affect the water quality of the study watershed. However, conversion of orchard for biodiesel production will have less impact on the water quality.

Conclusions

Water footprint of biofuel and biofuel energy reveals that cassava is the most water efficient crop to produce biofuel in the Khlong Phlo watershed. Biofuel production utilizing cassava as feedstock will have less impact on the water resources of the study watershed as compared to sugarcane and oil palm.

Land use change for bio-ethanol production utilizing cassava and sugarcane will affect the water balance of the watershed due to increased surface runoff and water yield and decreased baseflow and evapotranspiration. Land use change for biodiesel production using oil palm will not affect the water balance.

Expansion of cassava and sugarcane coverage for bio-ethanol production reveals that there will be impact on water quality of the watershed due to rise in export of sediment, nitrate and total phosphorus into the surface water. Likewise, oil palm area expansion for biodiesel production will have impact on the water quality of the Khlong Phlo watershed due to increased nitrate extraction into surface water except for conversion of orchard into oil palm which will not affect the water quality. This indicates that biofuel production will have negative impact on the environment of the Khlong Phlo watershed.

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