Water Quality Degradation and Management Strategies for Swine and Rice Farming Wastewater in the Tha Chin River Basin

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ABSTRACT

Water quality in the Tha Chin River regularly exceeds biological oxygen demand (BOD) standards of Thailand's Enhancement and Conservation of National Environmental Quality Act. This study quantified the BOD loading from rice cultivation and swine farming to the Tha Chin River using effluent data and procedures from the Pollution Control Department (PCD), geospatial land-use maps from the Land Development Department, and water quality data from the Ministry of Natural Resources and the Environment. It was determined that the BOD loading was 12 tons/day from swine farming in 2015 and 52 tons/day, on average, from rice farming between 2002 and 2011. Technology-specific, community-scale wastewater management strategies were recommended for both industries: feasibility studies revealed 66 potential sites for constructed wetland implementation and 7 subdistricts suitable for biogas network pipelines. It was determined that if these projects are implemented in conjunction, the BOD would be reduced by 6% (0.3 mg/L) in the entire river or 11% (0.5 mg/L) at the three water quality monitoring stations proximate to swine farms. These reductions would have a substantial effect on the water quality of the Tha Chin River, and governmental agencies such as the PCD should strongly consider subsidization and implementation of these projects.

1. INTRODUCTION

The Tha Chin River, a distributary of the Chao Phraya River Basin spanning the provinces of Chainat, Suphanburi, Nakhon Pathom, and Samut Sakhon, provides for over 2 million people (Simachaya, 2003a; Simachaya, 2003b). Rising concerns about the river's poor water quality since its subsequent rankings as Thailand's most polluted river from 2000-2002 has resulted in a call for action among researchers and local citizens. Awareness stimulating action has reportedly improved water quality according to the Pollution Control Department (PCD) in 2016. However, the river still repeatedly fails to meet the biological oxygen demand (BOD) standards, harming human and aquatic life through diminishing dissolved oxygen concentrations (Simachaya, 2003a; Simachaya, 2003b; Yolthantham, 2008; Rujivanarom, 2017).

Wastewater standards are enforced by PCD and the Subdistrict Administration Organization. While there have been some local improvements there has not yet been a basin-wide approach to water management. There is also a call for increased community involvement in wastewater management and basin-wide studies of Thailand's polluted river basins (Ministry of Foreign Affairs, 2016).

Swine farming is one of the most significant point source pollution sources to the Tha Chin River due to the sector's rapid industrialization over the last 15 years, with small and medium-sized swine farms raising over 40% of the swine (OECD, 2017; Nokyoo, 2016). According to the PCD, the waste-water quality standards of swine farms is 60 mg/L BOD for large (>600 Livestock Unit (LU)) swine farms and 100 mg/L for medium-sized farms (60-600 LU). Though the Ministry of Agriculture and Cooperatives maintains the same wastewater quality standards for small (<60 LU) farms, the PCD does not have a standard for small farms. These standards however, are not strictly enforced, allowing farmers of all sizes to disregard regulations without major, if any, repercussions. In 2016, 12.7% of small swine farms had no sewage treatment, and in a compliance study of 82 swine farms on the Tha Chin River, 52% of farms were "non-compliant" with wastewater standards, 53% of which discharged waste directly into the river (Suwunnamek and Suwanmaneepong, 2011; Nokyoo, 2016). This frequent non-compliance indicates a need for more incentives for swine farmers to comply with the wastewater quality standards, since farms that receive government subsidies are more likely to be compliant with the wastewater standards.

The recommended technology for treating BOD and also producing methane gas as an incentive is as follows: covered lagoons for small farms, and channel digesters with upflow anaerobic sludge blanket reactors (UASB) for medium and large farms. Community-scale anaerobic digestion projects can further the benefits of these systems. One successful example is the Prakha subdistrict in Phatthalung province in southern Thailand, where the Provincial Energy Office has implemented the country's first biogas pipeline network. This system reduces household reliance on LPG for cooking in 1,273 households while treating swine wastewater (Damrongsak and Wongsapai, 2016).

The largest nonpoint sector of BOD in Thailand is rice farming; 51% of agricultural land in Thailand is dedicated to paddies for rice cultivation, and plans to increase dedicated land by 500,000 hectares has been unveiled (Papademetriou and Dent, 2000; Bouman, 2008). Much of this expansion is predicted to occur in central Thailand, where water from the Tha Chin can be easily diverted from its natural flow for irrigational purposes. Rice is extremely water intensive, with 1,432 litters of water necessary to produce 1 kg of rice, and as 72% of rice is cultivated during the dry season, large quantities of irrigation water are necessary for successful production (Rice Knowledge Bank, 2016). In 2016, 460,800 ha of rice were cropped within 5 km of the Tha Chin River Basin, resulting in approximately 1.48 million tonnes of rice (Ricethailand, 2017). Runoff and water sourced discharge from agricultural fields are classified as wastewater effluent, which is assumed to become a riverine input if the wastewater is created 5 km or less from the river edge. BOD loading rates depend on many factors, such as soil percolation rates and rainfall. Minimizing synthetic fertilizer input is one solution to decreasing BOD loading, since BOD loading has a positive relationship to nutrient loading (EIC, 2017). However, since farmers rely on the nitrogen and phosphorus in fertilizers to meet yield demands, implementation of subsurface constructed flow wetlands can decrease fertilizer usage without jeopardizing production. These closed loop systems -typically 3 wetland cells fit with substrate and aquatic plants- maintain useful nutrients for reuse while removing harmful bacterial, heavy metals and organic matter through dense root systems (Good and Beatty, 2011). One of the three cells is typically designed for discharge into the ambient system, and this cell is fit with macrophytes that increase nutrient removal.

These discharge cells are recommended to output wastewater into free surface flow constructed wetlands in the form of freshwater marsh systems on the banks of the Tha Chin River. These marsh systems should be constructed with a variety of macrophytes to not only purify wastewater, but also provide nutrition for native organisms and reduce erosion; native species are recommended to prevent invasive speciation complications. Additionally, floating, submerged, and rooted macrophytes would ensure secure establishment to the Tha Chin River marsh system while allowing for increased surface area for microorganism attachment, thereby increasing biodiversity (see Table S1 in the supplemental information for general wetland benefits). It is recommended that provincial governments fund the construction, operation, and maintenance of these systems, as constructed wetlands are not economically feasible for the average farmer. Implementation should occur primarily in Chainat, Suphanburi, and Nakhon Pathom, which have larger areas of rice paddies near the river. In these provinces, constructed wetland systems are more cost-effective than many conventional wastewater treatment facilities and clean-up projects (see Table S2 for substrate recommenddations; Table S3 for macrophyte recommendations; S4 for wetland costs; and Table S5 for further information in the supplemental information). PCD has applied the procedure for water quality management of Heathcote (1998) including (1) identifying the uses of the basin, (2) setting appropriate water use and water quality targets, (3) determining the current water quality "state of the basin", (4) identifying specific issues and management options, and (5) developing a process for public consultation. The first three steps of this procedure have already been addressed for the Tha Chin River by PCD and Land Development Department (LDD). Thus this paper investigates and addresses the fourth step: identifying specific issues and mitigation options for swine and rice farming. To determine the issues, BOD loading is quantified from swine and rice farming. Additionally, the feasibility of two management projects is discussed: (1) construction of swine biogas digesters for reduction of pollution as a result of swine farming effluent; and (2) implementation of constructed wetlands to decrease fertilizer usage and improve wastewater effluent quality.

The results of this study can be used for on-farm, community-scale, and investor decision-making as well as for making changes to agricultural policy in Thailand. These results are applicable for swine and rice farming, but similar methodologies can be used for quantification of other point and nonpoint pollution. This study is unique because it quantifies discharges in recent years of two rapidly growing industries, one of which (swine farming) is recently industrialized and the second of which (rice paddies) is a nonpoint source of pollution that is quantified without the use of models. The framework presented for calculation of contaminant loading with limited data and without the use of models is beneficial not only for Thailand, but also for other nations with similar limitations.

2. METHODOLOGY

To provide a basis for recommendations to decrease loading, BOD loading of rice discharges and swine farming to the Tha Chin River were calculated. Critical areas in the Tha Chin River Basin including Chainat, Suphanburi, Nakhon Pathom, and Samut Sakhon provinces were analyzed.

2.1 Literature variance

The agricultural sector is the highest contributor to water pollution according to the PCD, discharging 39 m^3 of wastewater per day in 2015 (Rujivanarom, 2017; Simachaya, 2003a; Simachaya, 2003b). This is likely why BOD concentrations repeatedly exceed the Class 4 BOD standards (2-4 mg/L) throughout the river, with 58% of BOD measurements from the Ministry of Natural Resources and Environment from 2011-2015 above 4 mg/L (Ministry of Natural Resources and Environment, 2017; PCD, 1994). An average of percent BOD contributions by sector from 1997-2016 was constructed from various journals and can be seen in Table 1. Percent contributions vary due to calculation methodology ranging from models such as Mike 11 to usage of PCD guidelines, but regardless of method, wastewater from domestic usage and rice paddies shown to load the highest concentration of BOD. Additionally, the same literature found the average total BOD loading to be 129 ± 56 tons/day. Non-point sources, such as rice, have especially high variation because they are more complicated to quantify than point source pollution. Therefore, it was concluded that BOD loading from rice should be re-quantified. In addition, the recent industrialization and growth of the swine industry calls for a quantification of BOD loading for recent years. Domestic, factories, and aquaculture all have higher average BOD loading than swine, but these industries have not increased as dramatically in recent years. For example, the aquaculture industry has declined in production by 30% in the past 10 years (FAO, 2015).

2.2 Rice loading

Using 2015-2016 land-use maps from the LDD in QGIS, a 5 km buffer was created to determine the area of rice paddy fields that contribute to nonpoint source pollution to the Tha Chin River; this is the same proximity used by the PCD (LDD, 2017). It was assumed that the average area stays the same within the 2014-2017 time frame, since land use maps are not available on a yearly basis. Using this area, irrigation water usage, BOD loading from rice farming, and potential BOD reduction from constructed wetlands were calculated.

BOD loading from rice was calculated using the Event Mean Concentration method. This method incorporates monthly rainfall data and soil textures into the calculations and uses a constant for paddy field BOD concentration as shown in Equation (1); rainfall data was obtained from the Thai Meteorological Department (TMD) and geospatial soil data from the Food and Agriculture Organization of the United Nations. A worst-case scenario was calculated using the maximum BOD concentration for the second crop (November-April), since these months are in the dry season and irrigation water must be used; the BOD concentrations were provided by the PCD. The monthly average maximum daily rainfall values from 2002-2011 were used to represent the monthly maximum daily rainfall for the study years of 2014-2017 in order to gain a more accurate representation of monthly averages for rainfall amidst data gaps at measuring stations. Since there is no TMD rainfall measuring station in Samut Sakhon, an average of the four nearest measuring stations was used for the total maximum daily rainfall.

$$\text{Rice BOD Loading (kg/day)} = \frac{C \times P \times C_{vw} \times A}{10^6} \quad (1)$$

where C=concentration of BOD discharge for paddy fields (mg/L); P=average maximum daily rainfall for each month (mm/day); C_{vw}=weighted coefficient of soil surface erosion; and A=area by land use (m^2)

Table 1. Averages and standard deviations of percent contribution to BOD loading as per literature review

	Average BOD loading contribution to the Tha Chin River (%)				
	Domestic	Rice	Factories	Aquaculture	Swine
Literature values	33±20	24±22	22±13	16±9	15±7
Normalized values	30.0	21.8	20.0	14.5	13.6

Note: literature review percentages do not aggregate to 100% as references were averaged (Kulpredarat, 2017; McCrorie et al., 2016; Nokyoo, 2016; Visvanathan and Shapkota, 2006; Weeteeprasit, 1995; Inyim and Liengcharernsit, 2012; Yensong et al., 2008; PCD, 2007; Chongprasith and Praekulvanich, 2003; UN-ESCAP, 2004; Kaewkrajang, 2000; World Bank, 2001; Simachaya, 1999).

The soil textures in the study area were fine, medium, and coarse/medium. Considering that soil types vary within the provinces, each soil coefficient was weighted by area of soil textural class for the wastewater contributing paddy area as shown in Equation (2); these areas were found using QGIS. Uncertainty for this method was propagated based on differences in province total paddy field area due to a map projection conversion using upper and lower bounds for uncertainty as shown in Equation (3).

$$C_{vw} = \sum C_{vi} \times A_i \quad (2)$$

$$\Delta C_{vw} = \sum C_{vi} \Delta A_i \quad (3)$$

where C_{vi} = coefficient of soil surface erosion for soil texture; and A_i = fraction of soil type in each province.

2.3 Projected rice discharges

The 2014-2016 average percent of rice grown within 5 km of the river per province were multiplied by the Thailand 2017 rice projection estimates in order to find projected irrigation values per province (Prasertsri, 2017). These projections were used to determine BOD reductions for constructed wetland implementation.

2.4 Swine loading

BOD loading from swine farming was calculated using standard contaminant concentrations per pig type and headcounts, as shown in Equation (4); information about headcount was obtained from the PCD, and wastewater BOD concentration from the LDD. A standard river discharge rate and treatment efficiency was applied. The swine types include breeder pigs, finishing/fattener pigs, and nursery pigs; "local" pigs were assumed to be finishing/fattener pigs.

$$\text{Swine BOD Loading (kg/day)} = R \times T \frac{\sum C \times W_s \times N_s}{10^6} \quad (4)$$

where R=discharge rate (%), T = treatment rate (%), C = concentration of contaminant (mg/L); W_s = wastewater generated per swine type (L/head); and N_s = headcount per swine type.

2.5 Swine biogas network

Building on the example of the Prakha Subdistrict biogas network case study in Phatthalung Province a feasibility analysis was performed to find subdistricts for similar projects. These subdistricts were chosen using land use maps based on an area of subdistrict swine pastureland greater than 1 km^2 and within 5 km proximity to the Tha Chin River. The potential cost savings from switching to a biogas network in these target provinces were calculated, based on the price of Liquid Petroleum Gas (LPG) in Thailand, the price of inclusion in the biogas network ($1 USD/month for each household), and the 2015 swine data provided by the PCD. The conversion factors and prices were all based on the case study, and household data from the Department of Provincial Administration was used for the target subdistricts.

2.6 Rice effluent treatment

A sensitivity analysis using an average cultivation plot of rice (0.22 km^2) was calculated using polygon length scaling through ArcGIS. This size plot would result in a 98 tons yield in the wet season, calculated using average yield projections for 2017 across the four provinces the river flows through. The method to calculate rice effluent was then used to calculate the average BOD loading per day in this plot size and the inflow of water into the system. Data usage was as follows: the upper limit of rainfall, two standard deviations from the average across 2002-2011, concentration of BOD per liter was PCD data sourced, and soil coefficients were based on the most prominent soil type along the river according to FAO soil maps (fine soils). Data was translated to wastewater influent and input into the free surface, subsurface, and combination efficiency removal data collected from literature reviews of experimentation to determine system outputs for reduction guidelines.

Reduction guidelines were calculated based on four BOD scenarios: reuse cells in subsurface flow wetlands only, reuse and discharge cells in subsurface flow wetlands, free surface water wetlands only, and free surface paired with dual subsurface wetlands. Using 2017 projected BOD loading, calculated using ArcGIS area within 5 km of the river and average yield per hectare, and rice discharging methods, a percent reduction was calculated through simple algebraic ratio calculations.

3. RESULTS AND DISCUSSION

3.1 Rice loading

The PCD reports irrigation water use to be much higher during the second growing season than the major season. Within 5 km of the river, all irrigation water is assumed to be drawn directly from the Tha Chin River. Between the four provinces, the volume of water used for irrigation is highest in Chainat for 2014 and in Suphanburi for 2015-2016 and 2017 (projection), with the highest volume being the 2017 projection-calculated using hectares devoted to rice per province, provided by the Rice sector of Thailand. As water scarcity increases and drought conditions continue, the use of irrigation water will have further negative impacts on the river. Yields will likely decrease during the dry season unless the use of alternative management techniques, such as Alternate Wet and Dry, are used and genetically modified rice breeds able to withstand drought conditions begin to be cultivated (Carrijo et al., 2017).

As shown in Figure 1, the average BOD loading from rice farming to the Tha Chin River was highest during the wet season due to the higher rate of nonpoint source runoff. Suphanburi had the highest BOD loading due to a greater area of rice paddies, higher maximum daily rainfall, and soil type. The soils get finer further north, allowing for high percolation rates and less runoff. In the worst-case scenario, shown in gray in Figure 1, the dry season maximum BOD loading exceeded that of the wet season in Nakhon Pathom and Chainat provinces. This high variation is due to the high variation in BOD loading concentrations, and calls for more precise estimates of BOD loading concentrations.

3.2 Swine loading

BOD loading from swine farming was highest in Suphanburi and is directly proportional to headcount. Though the number of swine has decreased in Nakhon Pathom, it has increased enough in Suphanburi to result in a net increase. BOD loading from swine in Samut Sakhon is negligible. It was determined that fattener/finisher swine contributes to 83% of BOD loading on the Tha Chin River (as can be seen the results in Table 2).

3.3 Comparison to literature

Most of the values of swine loading BOD and rice loading BOD fall within the range of literature values, except for the major rice farming loading (Table 3) which exceeds the range. When averaged with the second rice crop, however, BOD loading from rice farming is within the literature values. The reason for the higher than literature values of BOD discharge in major rice is because of the usage of rainfall data in the quantification. The major rice season has high daily rainfall totals, and the method used for calculation utilized this rainfall data to account for high levels of runoff, thereby increasing the discharge of BOD into the river. As compared to literature values, the data quantified in this study is more accurate than previous studies due to usage of updated data, as well as the utilization of multiple methods to develop the result.

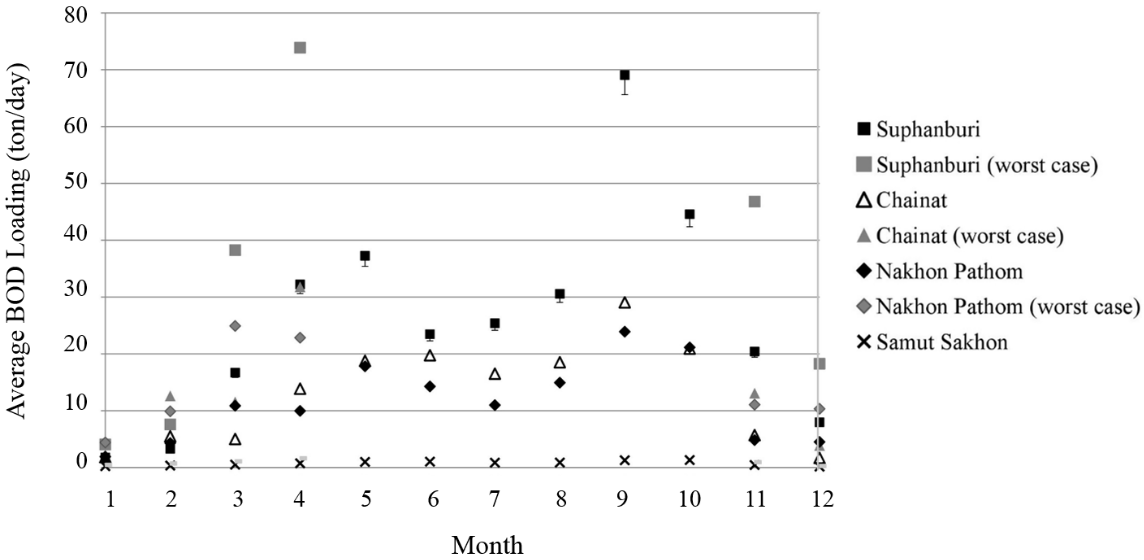

Figure 1. Results of event mean concentration method for BOD loading to the Tha Chin River from rice farming; worst-case scenario increased BOD concentration during the second rice crop is shown in gray.

Table 2. Headcount and water usage for swine farming at the Tha Chin River in year 2014 and 2015

Province	Headcount (1,000 pigs)		BOD (ton/day)	
	2014	2015	2014	2015
Suphanburi	254.0	315.2	6.08	7.36
Nakhonpathom	230.8	213.5	4.96	4.68
Samutsakhon	0.1	0.1	0.00	0.00
Tha Chin total	484.9	528.8	11.04	12.05

3.4 Limitations

Many of the limitations stem from missing values in data and data unavailability. For example, the 2002-2011 rainfall data had missing and zero values. Another limitation is that there is no rainfall measuring station for Samut Sakhon and instead an average of 4 nearby stations was used; this limitation was acceptable because of the minimal amount of rice paddies in this province. Swine headcount data for 2016 was unavailable, so BOD loading from swine farming could not be calculated for this year. In data from map projection changes for rice loading, all uncertainties were less than 1%; therefore, these values were accepted. Land use maps are only released by the LDD every eight years, though land use likely changes more frequently.

Table 3. Comparison of literature and study values

		BOD loading (ton/day)	
		Study values	Literature values
Swine		12	19±17
Rice	Major rice	77	31±42
	Second rice (normal)	26	

Note: (Kulpredarat, 2017; McCrorie et al., 2016; Nokyoo, 2016; Visvanathan and Shapkota, 2006; Weeteeprasit, 1995; Inyim and Liengcharernsit, 2012; Yensong et al., 2008; PCD, 2007; Chongprasith and Praekulvanich, 2003; UN-ESCAP, 2004; Kaewkrajang, 2000; World Bank, 2001; Simachaya, 1999)

3.5 Swine wastewater treatment

Modeled on the previously mentioned community scale biogas pipeline network project in the Prakha subdistrict, subdistricts along the Tha

Chin River with large enough areas of swine farms to make similar projects feasible were identified. The farms in the identified subdistricts, located in Nakhon Pathom and Suphanburi provinces, are within 5 km of the river and are likely to significantly contribute to BOD loading. These locations are shown in Figure 2, along with the corresponding pastureland from the land use map; it was assumed that land labeled "pastureland" in the LDD 2015/2016 Land Use Maps is land used for swine farms due to the prevalence of swine in the Tha Chin River Basin. Additionally, the potential expenses saved in each subdistrict were calculated based on actual expenses saved from the case study. Ton Tan and Sampathuan subdistricts could save \$53,000 and \$64,000 each year, respectively, from this decreased reliance on LPG (Table S6 in the supplemental information).

Using the assumption that 60% of farms in Thailand are large (Nokyoo, 2016), BOD loading from swine within selected subdistrict could be reduced by 66% using the suggested digester technology; in the context of a province, this subdistrict reduction corresponds to a 3-5% decrease in BOD loading from swine (see Table 4). If a biogas network pipeline were implemented in all of the 7 subdistricts, the new BOD concentrations at the nearby water quality monitoring stations would be reduced by, on average, 0.3 mg/L. These reductions were calculating using an average across Nakhon Pathom and Suphanburi; therefore, since the BOD loading is concentrated around the water quality stations in Table 5, the new BOD concentration at these stations is likely to be lower than calculated. Though the recommended projects at TC17 would not decrease the BOD concentration to class 4 standards ($\leq$4 mg BOD/L), these reductions would be a step towards improved water quality.

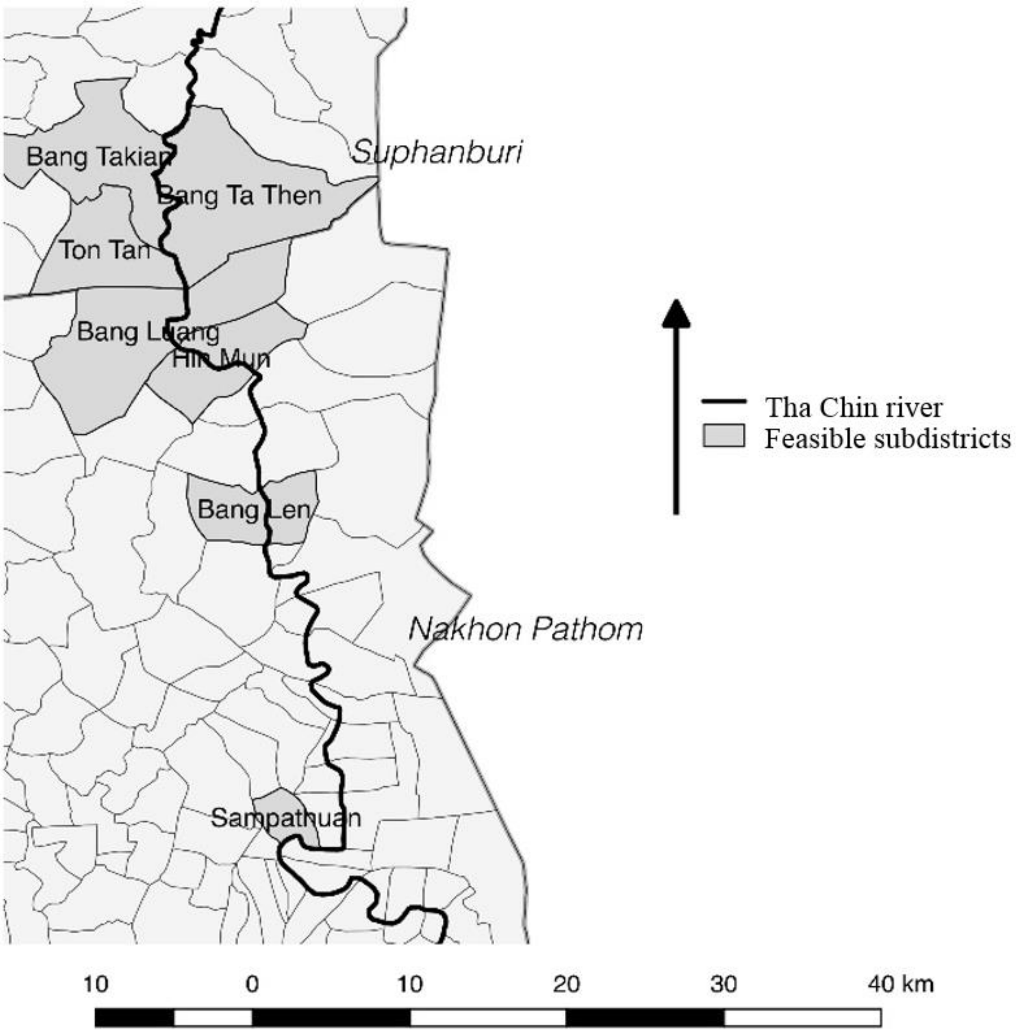

Figure 2. Feasible subdistricts for biogas pipeline networks along the Tha Chin River Basin

Table 4. Predicted reductions in BOD loading for recommended biogas network pipeline in selected subdistricts based on 2015 swine data

Sub-district	Province	BOD loading (ton/day)		% Reduction	
		Current	Recommended treatment	Sub-district	Province
Ton Tan	Suphanburi	0.55	0.19	66	5
Sampathuan	Nakhon Pathom	0.24	0.08	66	3

There is currently a demonstration biogas network project beginning in Bang Len subdistrict that was proposed by Chiang Mai University and is completely funded by the Thai Ministry of Energy (P. Aggaransi, personal communication, July 07, 2017). It is recommended that this project provide a case study to inform the other subdistricts about the potential to both reduce BOD loading and allow for biogas energy generation.

Further studies should be done on biogas networks, such as a cradle-to-grave Life Cycle Analysis on the biogas digester technology in Thailand in the context of a pipeline network, crediting avoided LPG emissions and fertilizer by-products. Addition information about government incentives is discussed in Table S7 (the supplemental information).

Table 5. BOD concentrations in the Tha Chin River for current conditions and suggested treatment

Tha Chin monitoring station	Average BOD concentration (mg/L)	
	Current	Recommended treatment
TC13	4.0	3.8
TC15	3.8	3.7
TC17	6.1	5.4

3.6 Rice Wastewater Treatment

A feasibility study utilizing the LDD's land-use maps and Google Maps satellite imagery identified 66 locations for potential implementation of constructed wetlands based on the following criteria: (1) land area greater than 1600 m^2 between the rice paddies and the river; (2) no buildings or built structures present on the land; and (3) no economic activities such as crop cultivation on the land. This study takes a broad initial look at constructed wetland feasibility, and more research into site-specific suitability and land conversion potential is necessary before plans for constructed wetlands can be created.

To quantify potential BOD reduction from constructed wetland implementation, a sensitivity analysis was conducted based on studies in Israel, China, and Sweden (Gross et al., 2007; Liu et al., 2009; Tilley et al., 2014) that provide guidelines for removal efficiency rates of each type of wetland: reuse subsurface, discharge subsurface, and free surface. This average size of rice cultivation plots around potential wetland sites (0.22 km^2) was used to approximate inflow rate of wastewater and concentration of BOD, incorporating discharge influent caused by rainfall. An upper limit (two standard deviations from the average) of the maximum daily rainfall was used to prevent overflow; this upper limit calculated to be 114 mm in 24 h. Soil coefficients for absorption were used for fine soils, the main soil texture at potential wetland sites. Wetland construction recommend-dations were based on quantified wastewater outflow: 4,380 m^3/day.

Reuse cells were analyzed following the Swiss Federal Institute of Aquatic Science and Technology, which reports efficiency rates of BOD to be 85% with sand substrate and no macrophyte species (Tilley et al., 2014). Discharge cells were adapted from a constructed wetland design in Israel, where limestone gravel was used as substrate on top of a plastic liner, and *Phragmites australis* was the recommended macrophyte (Gross et al., 2007). The BOD removal efficiency rate was determined to be 95% (Gross et al., 2007). Free surface wetland efficiency rates were found based on the average efficiency rates of constructed free surface wetlands in China, where natural substrate and diverse macrophyte species ensure wetland sustainability and stability; the BOD removal efficiency rate was 82% (Liu et al., 2009).

Based on these studies, it was determined that if both a free surface and subsurface wetland were implemented on the Tha Chin River the overall BOD removal efficiency rate would be 99%. This efficiency rate is slightly speculative and must be supported by further experimentation. Table 6 shows the approximate BOD output in each system.

Table 6. Sensitivity analysis efficiency rates and system outputs for wastewater diversion to constructed wetland types from an average rice farm

BOD	Removal efficiency (%)	System output (kg/day)
SSW: Reuse	85	1.5
SSW: Discharge	95	0.53
FSW: Used with discharge cell	82	0.1
FSW: Used alone	82	1.9

Table 7 shows the BOD loading decrease in four scenarios of constructed wetland types: if 5% of the total effluent from rice farming were discharged into constructed wetlands rather than directly into the Tha Chin River, BOD loading of rice would decrease 10-12%. The most feasible and cost effective recommendation for farmers and the Thai provincial government to implement is Scenario 2; this would decrease BOD by 18%. However, it is recommended that in areas experiencing erosion, diminished biodiversity, extreme phosphorous loading, or other compounding adverse effects that Scenario 4 be implemented. BOD only decreases by an additional 0.7% compared to Scenario 2, but total phosphorous decreases by an additional 6%. This is a result of macrophyte uptake as well as sedimentation caused by macrophyte roots, low flow velocity, and high deposition rates. Table 7 also shows the BOD concentration percent decrease in the water, as a result of the BOD loading decrease. Total contributions were based on the literature review averages of BOD loading in the Tha Chin from 1997 to 2016 and BOD loading calculations from the results of this study.

Table 7. Percent reduction in rice discharges and total BOD decrease in Tha Chin if 5% of wastewater were discharged into wetlands.

	BOD loading decrease (%)	BOD decrease (ton/day)	New average rice BOD discharge (ton/day)	Total BOD decrease (%)
Scenario 1: Reuse cells	16	10	55	3.8±3.4
Scenario 2: Reuse and discharge cells	18	12	54	4.2±3.8
Scenario 3: FSW	15	10	56	3.6±3.3
Scenario 4: FSW, reuse and discharge cells	18	12	53	4.4±4.0

Table 8 displays water quality station alterations for BOD concentration due to a 5% diversion based on actual BOD concentrations at water quality monitoring stations; BOD concentration decreases an average of 0.2 mg/L. If used in conjunction with the aforementioned swine biogas network pipeline, the BOD at all stations would decrease an average of 0.3 mg/L. At the three monitoring stations in proximity to swine farms, the BOD would decrease an average of 0.6 mg/L or 11%.

Table 8. BOD concentration changes by monitoring station based on 5% discharge diversion to wetlands

Water quality station	Current BOD concentration (mg/L)	5% Wetland discharge BOD concentration (mg/L)	
		Scenario 2	Scenario 4
TC01	5.1	4.9±0.2	4.9+0.2
TC04	4.8	4.4±0.2	4.5±.2
TC07	5.0	4.8±0.2	4.8±0.2
TC09	3.8	3.7±0.1	3.5±0.2
TC10	6.3	6.0±0.2	6.0±0.2
TC11	6.6	6.3±0.3	6.3±0.3
TC13	4.0	3.8±0.2	3.8±0.2
TC15	3.8	3.6±0.1	3.6±0.2
TC17	6.1	5.8±0.2	5.8±0.2
Average	5.0	4.8±0.2	4.8±0.2

3.7 IBP systems

In addition to biogas pipeline networks and constructed wetland systems for electricity generation and nutrient removal, integrated photo-bioelectochemical (IBP) systems, which integrate algae and bioelectrochemical systems should be considered as a potential for implementation. IBPs utilize heterotrophic bacteria as biocatalysts to oxidize organic compounds in wastewater to produce electricity. These systems are low cost with high productivity and able to be utilized as a multi-functional system: electricity generation, energy recovery, nutrient removal, and biofuel production (Luo et al., 2016; Kello and He, 2014). Experimentation on wastewater treatment in swine and industrial food wastewater has shown the systems to have up to a 63% total N and 82.3% P removal rate with a tubular Microbial Fuel Cell system (Luo et al., 2016). However, experimentation using rice and swine wastewater should be tested before implementation is considered as the composition of wastewater severely impacts the microbial communities' efficiency rates; therefore, an IBP feasibility study in Thailand is recommended.

4. CONCLUSIONS

This study concluded that BOD loading to the Tha Chin River was 12 tons/day from swine farming in 2015 and 52 tons/day, on average, from rice farming between 2002 and 2011. Since averaging geographically and seasonally eliminates important details about the nature of BOD loading, differentiating between provinces showed that BOD loading was highest from Suphanburi in both the rice and swine industries at 6.0-6.4 tons/day (50-53%) and 7.4 tons/day (61%), respectively. Additionally, a worst-case scenario for BOD loading from rice during the dry season showed a BOD loading rate of 61 tons/day. Feasibility studies were completed to identify projects that could reduce BOD loading.

For the swine industry, anaerobic digestion technology could reduce BOD loading while providing useful co-products; small swine farms utilizing anaerobic covered lagoon systems would benefit from 85% BOD treatment efficiency, and medium and large farms utilizing channel digesters with UASB would benefit from 85% and 93% BOD treatment efficiencies. The advantages of these technologies could be extended to the larger community through a biogas network pipeline, which was determined to be feasible in 7 swine-producing subdistricts along the Tha Chin River. Implementation in Ton Tan and Sampathuan subdistricts would reduce BOD loading by 2% and would save the subdistricts $53,000 and $64,000 each year, respectively, by decreasing dependence on LPG. An implementation in all 5 subdistricts surrounding TC17 monitoring station would reduce the BOD concentration at this station from 6.1 to 5.4 mg/L. Though this would not reduce the BOD concentration to class 3 standards, this is a significant reduction and it is recommended that the provincial government fund the implementation and maintenance of these pipelines.

For the rice industry, constructed wetlands would substantially reduce BOD and nutrient loading at the 66 identified potential site locations on the Tha Chin River. Subsurface flow wetlands with reuse and discharge cells would provide an 18% BOD treatment efficiency and are a cost-effective solution. In a scenario where 5% of discharge from rice farming was diverted to a subsurface wetland, the total BOD loading to the Tha Chin River would be reduced by 4%. Additionally, a combination of free surface and subsurface flow wetlands are recommended in areas of the river with high phosphorus loading. These projects are feasible if funded by the Royal Thai Government.

If both constructed wetlands and biogas network pipelines were implemented, the BOD would decrease by 0.3 mg/L on average along the whole river. At the three stations in proximity to swine farms, a combination of both projects would decrease the BOD concentration 11% from 4.6 to 4.1 mg/L. This is a significant decrease that would allow the river to be marginally above class 4 standards.

Lastly, gaps in Thailand’s rainfall data and inconsistencies within the land use maps limited the accuracy and completeness of the calculations. It is recommended that consistent data be prioritized in order to improve future research efforts. Further studies on other sources of pollution along the Tha Chin River including industry, aquaculture, domestic water use, salt-water intrusion, and other agricultural sectors should be conducted in order to recommend further community-scale projects to improve water quality. Additionally, further studies should be completed to quantify the environmental benefit of biogas pipeline and wetland construction to the Tha Chin River.

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Supplementary data are available at https://www.tci-thaijo.org/index.php/ennrj/index.