WATER QUALITY MODELING AND LOAD ALLOCATION IN LAM TAKHONG WATERSHED

Chau Ngoc Tran

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แบบจำลองคุณภาพน้ำและการประเมินภาระของเสียในลุ่มน้ำลำตะคอง

นางสาวเจ่า ง็อบ เจ่า

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มหาวิทยาลัยเทคโนโลยีสุรนารี
ปีการศึกษา 2562

WATER QUALITY MODELING AND LOAD ALLOCATION IN LAM TAKHONG WATERSHED

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

Thesis Examining Committee

S. Dararatana

(Dr. Somchai Dararatana)

Chairperson

P. Yossapol.

(Dr. Chatpet Yossapol)

Member (Thesis Advisor)

Netnapid

(Assoc. Prof. Dr. Netnapid Tantemsapya)

Member

(Assoc. Prof. Dr. Nares Chuersuwan)

Member

ปรียาพร โกษา

(Asst. Prof. Dr. Preeyaphorn Kosa)

Member

(Dr. Apichon Watcharenwong)

Member

(Assoc. Prof. Flt. Lt. Dr. Kontorn Chamniprasart)
Vice Rector for Academic Affairs
and Internationalization

Pornsiri Jongkol

(Assoc. Prof. Dr. Pornsiri Jongkol)
Dean of Institute of Engineering

เจ่า งื่อบ เจ่า : แบบจำลองคุณภาพน้ำและการประเมินภาระของเสียในลุ่มน้ำลำตะคอง
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ดร.ฉัตรเพชร ยศพล, 206 หน้า.

ในห้วงทศวรรษที่ผ่านมามีปรากฏการณ์พร่องออกซิเจนในลำตะคองหลายครั้งโดยเฉพาะอย่างยิ่งในฤดูแล้ง ส่งผลให้คุณภาพน้ำในลำตะคองไม่เหมาะสมต่อการนำมาใช้เป็นน้ำดิบในการผลิตน้ำประปาในเขตเมืองนครราชสีมา แหล่งกำเนิดมลพิษทางน้ำประกอบไปด้วยทั้งแหล่งกำเนิดแบบมีที่ตั้งชัดเจนกับแหล่งกำเนิดแบบไม่มีที่ตั้งชัดเจนซึ่งปล่อยมลพิษทั้งสารอินทรีย์และธาตุอาหารลงสู่ลำตะคอง งานวิจัยนี้ได้ใช้แบบจำลอง SWAT ควบคู่กับแบบจำลอง QUAL2K ในการประเมินผลกระทบของการปล่อยมลพิษจากแหล่งกำเนิดทั้ง 2 แบบ ซึ่งได้มีการปรับเทียบข้อมูลนำเข้าและทดสอบความถูกต้องในแบบจำลอง QUAL2K โดยใช้ข้อมูลคุณภาพน้ำในลำตะคองที่ตรวจวัดในปี พ.ศ. 2562 และได้ประยุกต์ใช้แบบจำลอง QUAL2K สำหรับทำนายค่า DO และ BOD ในช่วงที่มีโอกาสเกิดปรากฏการณ์วิกฤตเพื่อเปรียบเทียบกับเกณฑ์มาตรฐานคุณภาพน้ำผิวดินประเภทที่ 3 (ซึ่งกำหนดว่าต้องมีค่า DO ไม่น้อยกว่า 4 mg/L และมีค่า BOD น้อยกว่า 2 mg/L)

แบบจำลองมีขอบเขตศึกษาของลำน้ำเป็นระยะทาง 122 กิโลเมตรนับจากเขื่อนลำตะคองไปจนถึงจุดบรรจบของลำตะคองกับแม่น้ำมูลที่อำเภอเฉลิมพระเกียรติ ซึ่งการทำแบบจำลองนั้นตั้งเป้าหมายหลักที่มลพิษที่ส่งผลให้มีสภาวะพร่อง DO ในลำน้ำในแต่ละช่วงของลำน้ำ และได้กำหนดสถานการณ์หลายสถานการณ์ในการลดการปล่อยภาระ BOD จากระบบบำบัดน้ำเสียรวมของเมืองนครราชสีมาและจากชุมชนริมลำน้ำทั้งในฤดูแล้งและฤดูน้ำหลากเพื่อศึกษาลักษณะการเปลี่ยนแปลงของค่า DO และ BOD

ผลของการทำแบบจำลอง QUAL2K พบว่าค่า DO และ BOD ในลำตะคองช่วงตั้งแต่เขื่อนลำตะคองมาจนถึงกิโลเมตรที่ 102 นั้นอยู่ในเกณฑ์ดี (อยู่ในมาตรฐานคุณภาพน้ำผิวดินประเภทที่ 2) และจากนั้นค่า DO จะลดต่ำลงไปจนถึงกิโลเมตรที่ 115 ที่มีค่า DO ต่ำสุดโดยอยู่ในเกณฑ์คุณภาพน้ำผิวดินประเภทที่ 4 ในขณะที่ค่า BOD นั้นมีค่าเทียบกับเท่ากับเกณฑ์คุณภาพผิวดินประเภทที่ 4 ในช่วงตั้งแต่กิโลเมตรที่ 104 ไปจนถึง 112.5

การเปลี่ยนแปลงการใช้ที่ดินในปี พ.ศ. 2570 นั้นไม่ได้ส่งผลต่อคุณภาพน้ำในลำตะคองโดยพิจารณาจากค่า DO และ BOD อย่างไรก็ตามผลจากการทำแบบจำลองบ่งชี้ว่าระบบบำบัดน้ำเสียรวมเป็นแหล่งกำเนิดมลพิษหลักที่ส่งผลต่อคุณภาพน้ำในลำตะคอง ซึ่งการลดภาระมลพิษทางน้ำจากระบบบำบัดน้ำเสียจะส่งผลให้คุณภาพน้ำในลำตะคองดีขึ้น

แบบจำลอง QUAL2K นั้นสามารถทำนายคุณภาพน้ำในลำน้ำทั้งในสภาพปัจจุบันและในอนาคต และสามารถช่วยผู้ที่มีหน้าที่บริหารแหล่งน้ำในการกำหนดนโยบายทางเลือกในการจัดการคุณภาพน้ำในลำตะคอง แบบจำลองนี้ยังเป็นประโยชน์ในการช่วยระบุถึงข้อมูลที่จำเป็นสำหรับการนำเข้าในแบบจำลอง อันจะเป็นประโยชน์ในการวางแผนการรวบรวมข้อมูลสำหรับหน่วยงานที่เกี่ยวข้อง นอกจากนี้แบบจำลองนี้ยังสามารถบูรณการร่วมกับแบบจำลองในระดับลุ่มน้ำที่จะจำลองภาระของเสียแบบไม่มีที่ตั้งชัดเจนได้อีกด้วย ดังงานวิจัยนี้ที่ได้พบกว่าการบูรณาการระหว่างแบบจำลอง SWAT และ QUAL2K นั้นนับว่ามีประโยชน์ในการวางแผนการจัดการแหล่งน้ำในพื้นที่ศึกษา

สาขาวิชา <u>วิศวกรรมสิ่งแวดล้อม</u>
ปีการศึกษา 2562

ลายมือชื่อนักศึกษา chau Ngoc Tran
ลายมือชื่ออาจารย์ที่ปรึกษา

CHAU NGOC TRAN : WATER QUALITY MODELING AND LOAD
ALLOCATION IN LAM TAKHONG WATERSHED. THESIS
ADVISOR : DR. CHATPET YOSSAPOL, Ph.D., 206 PP.

SWAT/QUAL2K/WATER QUALITY/ LAM TAKHONG RIVER/SIMULATION

Dissolved oxygen in Lam Takhong River gradually reaches zero value during the dry season on several occasions in the past decade causing the unsuitable quality for use as the raw water for Nakhon Ratchasima Town. Discharges of point sources and diffuse sources containing pollutants with organics and nutrients are the major cause of water quality deterioration in the river. To find the sources of impact on the water quality in the river, integrating SWAT model and QUAL2K model was constructed and simulated. The QUAL2K model was calibrated and validated using the water quality data in 2019 for the Lam Takhong River. The QUAL2K model was applied to simulate DO and BOD concentration during the critical period to compare to the designated surface water quality criteria third class in Thailand (minimum DO at or above 4 mg/L; maximum BOD_5 (below 2.0 mg/L).

The study reach of the river flows 122 km from Lam Takhong Dam to the Mun River at Chaloem Phra Kiat district through the urban central area. Several segments of the river have been alarmed for many constituents with the dissolved oxygen (DO) impairment is the focus of the study. The scenarios of BOD load reduction from WWTP and urban area were conducted in both the dry and wet season to assess the change of DO and BOD_5 concentration.

The result of the QUAL2Kw model indicated that DO and BOD upstream to 102 km location of the Lam Takhong River is always good (class 2 of standard), while the class of DO decreased from 102 km toward downstream (115 km) where it recorded a class 4. While, BOD was at class 4 from 104 km to 112.5 km. Location had the minimum DO value is the same location had the maximum BOD value at 105.88 km from upstream. The highest DO value is always located in headwater of Lam Takhong River, while the lowest BOD value is at from 49 to 54 km from upstream of Lam Takhong River. Land use change does not affect on the water quality in 2027 including DO and BOD concentration in the Lam Takhong River. However, the simulated scenarios proved that WWTP is the main pollutant source in the Lam Takhong River, so the BOD reduction release into the river from WWTPs is a good way to improve water quality in the Lam Takhong River.

The QUAL2K model is suitable for simulating the current and future river water quality and help water resources managers to issue the appropriate policy options for the Lam Takhong River. The model is also beneficial in showing what information needs to be collected in order to simulate the water quality in the river for planning purposes and can be integrated with a watershed model to simulate diffuse sources discharge into the river. Therefore, the integration of the SWAT and Qual2K model has been shown to be a useful tool for water resources management in the study area.

School of Environmental Engineering — Student's Signature Chau Ngoc Tran

Academic Year 2019 — Advisor's Signature

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Chau Ngoc Tran

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LIST OF ABBREVIATIONS

AGRL	Agriculture
ALPHA_BF	Baseflow Alpha Factor
BMP	Best Management Practice
BOD	Biochemical oxygen demand
CH_N2	Manning's "n" value for the main channel
CH_K2	Effective hydraulic conductivity in main channel alluvium
CN2	SCS runoff curve number for moisture condition II
CN	Curve Number
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems
DEM	Digital Elevation Model
DO	Dissolved oxygen
ESCO	Soil evaporation compensation factor
FCTR	Factory
FRSE	Evergreen Forest
FRSL	Deciduous Forest
GIS	Geographic Information System
GRASS	Geographic Resource Analysis Support System
GW_DELAY	Groundwater delay time
GW_REVAP	Groundwater "revap" coefficient

GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur
HRU	Hydrologic Response Units
HSG	Hydrology Soil Group
HSPF	Hydrological Simulation Program-Fortran
LDD	Land Development Department
MISC	Miscellaneous
NO3-N	Nitrate-Nitrogen
NPS	Non-point source
NSE	Nash-Sutcliffe model efficiency coefficient
ORCD	Orchard
PBIAS	Percent bias
PCD	Pollution Control Department
PS	Point source
R^2	Coefficient of determination
RCHRG_DP	Deep aquifer percolation fraction
RCN	Concentration of nitrogen in rainfall
SURLAG	Surface runoff lag coefficient
SWAT	Soil and Water Assessment Tool
TP	Total Phosphorus
TMDL	Total maximum daily load
URBN	Urbanization
WATR	Water

WETN	Wetland
WWTPs	Wastewater treatment plants

CHAPTER I

INTRODUCTION

1.1 Background and problem statement

Water pollution is the contamination of water bodies that environmental degradation occurs when pollutants are directly or indirectly discharged into water resources without treatment to remove polluted compounds.

The state of water quality across 65 significant surface water sources nationwide measured in 2016 showed that the percentage of water quality in the proportion was 34% in good quality, 46% fair quality, and 20% of poor quality. Water quality in 2016 is compared to 2015 and found that the water quality in 2016 had improved, with the 41 percent of surface water sources as fair quality increasing to 46%, and 25% poor quality decreasing to 20% (PCD, 2016).

For the surface water quality monitoring results in the Northeastern region, it was found that the highest percentage of parameters did not comply with the surface water quality standard class three on the ammonia (NH_3-N), and heavy metal (HM) concentration (1.5% of all monitoring surface water areas) such as Zinc (Zn), Manganese (Mn), Mercury (Hg), Cadmium (Cd) and Arsenic (As) (Figure 1.1). The main causes of the problem are the urban community, livestock farming, aquaculture activities, and soil erosion from agricultural activities such as rice tapioca, sugar cane cultivation, etc.

The water quality of Lam Takhong River at 20 stations from 2008 to 2009 was in class three of surface water standard in Thailand (PCD, 2016), except NH3-N, P, and

BOD. The highest of NH3-N (12.6 mg/L), Phosphate 2.7 mg/L, and BOD (8.7 mg/L) were respectively found at Royal Thai Army Bridge, Nakhon Ratchasima, exceeded class four of standard in these areas. (Suwannarat et al. 2014)

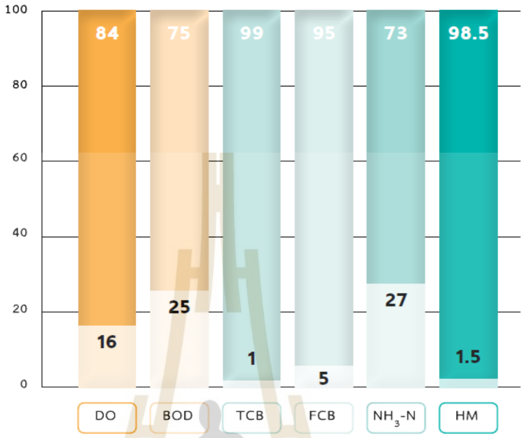


Figure 1.1 Surface water quality monitoring results in the Northeastern Region (Pollution Control Department (PCD), 2016)

The lower Lam Takhong river, has been a part of the Mun river watershed in critical condition, Lam Takhong River has the role of drainage, recreation, and environmental conservations that Netnapa et al. (2015) applied the Soil and Water Assessment Tool (SWAT) model for the evaluation of streamflow, sediment, nitrate nitrogen, and total phosphorus in this river basin. The simulation identified nine subbasins and classified as high loading rate of TP. Besides, the author mentioned that the result of SWAT model could be used to manage water resources and plan soil conservation in Lam Takhong River basin.

Previous studies in Lam Takhong basin have not estimated total maximum daily loading (TMDL) of sediment, nutrient, and fecal indicator bacteria or any reduction of

NPS pollution in the critical area. In addition, there are no studies that forecast the water quality change from the prediction of land use change in the area.

In this study, the SWAT model can realistically represent the spatial variability of watershed characteristics, is used to study critical areas, TMDL scenarios in Lam Takhong river basin by combining with Qual2k model. SWAT and Qual2k model are selected for this study because they are included channel routine with detail appropriate for river watershed management (Staley et al. 2006). The results could be a useful methodology for managing water resources and planning of land use in Lam Takhong river basin.

1.2 Motivation of the study

In this study, the integration of the SWAT model and the Qual2K model is used to assess the water quality of the Lam Takhong river. SWAT is employed in the initial stages of this study. They mainly assisted in achieving the flow simulation in the Lam Takhong River and from subbasin into the river, while the Qual2K model is applied to simulate and assess the river's quality status. SWAT and Qual2k are capable to provide a good representation for the Lam Takhong basin. Besides, land use will change day by day in the future and this will effect on water quality.

The research outputs may be useful to support pollution control, management, and planning in Lam Takhong basin. The benefits of the results are as follows:

i) Finding a highly reliable model to simulate the runoff and water quality.

ii) The water quality management, control, and planning load allocation in Lam Takhong river basin.

iii) Application for other basins with similar conditions.

1.3 Research questions

From the motivation of the study, the following research questions arise:

i) Is the SWAT model suitable for flow calculation and can the Qual2k model be used to simulate water quality in Lam Takhong river?

ii) Which pollutant source is a major source affecting water quality and has land use change likely influence the water quality of Lam Takhong river?

iii) How is TMDL allocated in the Lam Takhong river for the present and in the future?

iv) How is the pollutant loading reduction conducted in the Lam Takhong river to meet the water quality standards in Thailand?

1.4 Research objectives

The specific objectives of the study are the following.

Objective 1. To build SWAT model for flow evaluations in the river, and from subbasins; conduct the calibration, validation, and forecasting of current and future flow in Lam Takhong River.

Objective 2. To calibrate and validate water quality in Lam Takhong River by QUAL2K model, carrying out water quality simulated scenarios in the river for the existing and future situation following temporal and spatial variations.

Objective 3. To determine a major source affecting water quality and how land use change influences the water quality of Lam Takhong river.

Objective 4. To calculate TMDL allocation in the Lam Takhong river for the present and the future, and determine how to reduce the pollutant load and can attain water quality standard targets.

1.5 Scope and limitation of the study

1.5.1 Study area

This research is conducted in Lam Takhong basin in Northeastern region of Thailand, the river length is 220 km from Sangampang Range in Khao Yai National Park covering nine districts of three provinces including six in Nakhon Ratchasima province namely Pak Chong, Sikhio, Sung Noen, Kham Thale So, Mueang Nakhon Ratchasima and Chaloem Phra Kiat.

Lam Takhong watershed has an area of 3,518 km^2 with covering six districts and more 880,000 population resides. It is a part of the Mun river watershed, which is a sub-basin of the great Mekong river. The Lam Takhong watershed can be delineated into 75 sub-basins as calculat using the digital elevation map from the Land Development Department.

This study uses the SWAT model to assess pollution loading which can impact surface water quality in Lam Takhong watershed, in Nakhon Ratchasima province. ArcGIS10.1 software integrated with the SWAT model is selected for this study due to a wide variety and with proper testing (Arnold and Fohrer, 2005). Besides, combination of SWAT and Qual2k have been indicated that this is an effective tool to assess water quality and non-point source pollution (Arnold et al., 2013).

1.5.2 Study period

The weather data used to build the SWAT model is from 2002 to 2017 provided by the Thai Meteorology Department. The SWAT model is calibrated from 2005 to 2012 by the observed streamflow at M89 (Pak Chong district) and M164 (Muang district) stations from the Hydrology and Water Management Center for Lower

Northeastern Region, Nakhon Ratchasima, Thailand, while the validation is carried out from 2013 to 2017.

Besides, water quality data are collected from Regional Environment Office 11 in 2019 to simulated water quality by the Qual2K model. SWAT mainly performed in the flow simulation in the Lam Takhong River and from subbasins into the river, while the Qual2K model was applied to simulate and assess the river’s quality status in the present and the future.

CHAPTER II

LITERATURE REVIEW

2.1 Water quality problem of the study

Water pollution comes from two different sources; point and nonpoint sources. Point source (PS) of pollution from which pollutants are discharged, such as a pipe, ditch, ship, or factory (Hill, 1997). Nonpoint source (NPS) pollution is often termed diffuse pollution and refers to those inputs and impacts which occur over a wide area and are not easily attributed to a single source. They are often associated with particular land uses, as opposed to individual point source discharges (EPA, 2017).

Since point source pollutants are associated with point locations, therefore, they are characteristical; more readily identifiable and measurable. On the other hand, nonpoint source pollutants are difficult or impossible to trace to a source, certainly uncontrollable meteorological events and existing geographic or geomorphologic conditions, and long-term, chronic effects on human health and soil-aquatic degradation (Loague and Corwin, 2005).

Non-point source pollution is often more difficult to control than point source pollution. In urban areas, the provision of sewerage systems and adequate street cleaning are important measures, while in farming and forestry areas, soil conservation practices and the controlled application of pesticides and fertilizers are necessary if pollution of waterways is to be avoided.

In Thailand, water pollution is largely associated with urbanization, industrialization, and agricultural activities. The main pollutants for surface water quality problems are sediments, nutrients, and chemical substances (Rajaraman & Ullman, 2011; Office of Natural Resources, Environmental Policy and Planning, 2012).

Lam Takhong River watershed is one of the critical watersheds of Thailand. It is a part of the Mun river watershed, in the Northeastern region which has the role of drainage, recreation, and environmental conservations. There are than 880,000 residents within Lam Takhong River watershed.

Lam Takhong River watershed has an area of 3,269 km^2 covering six districts in Nakhon Ratchasima province. At Ban Kong Rae, Kham Thale So district, Lam Takhong River is divided as Lam Boriboon, with 35 kilometers in length.

Lam Takhong River basin was covered with extended large forests in the past. At present, most areas have been invaded, deforested, and converted into communities, farmland, orchards, deserted areas, and others (Lam Takhong Watershed Research Station, 2010). The dominant land use is agricultural land of 55.73% (Land Development Department, 2008). Water quality degradation is constantly deteriorating, especially in urbanization areas and intensive farming (Regional Environment Office 11, 2010).

Pollution Control Department (2008) reported that Lam Takhong River had good water quality in 2007. Upper Lam Takhong was classified into class two (Good) but the water quality in Lower Lam Takhong is in class four (deterioration).

Regional Environment Office 11 (2010) showed that water quality was improved from 2 stations (13.33%) in 2005 to 13 stations (86.67%) in 2008. However, the water quality of Ban Yong Yang, Pha Nao subdistrict, and Watsamukky community, Muang district, Nakhon Ratchasima province have been constantly deteriorating.

Uaychimplee (2008) studied Lam Takhong's wastewater in an urban setting using BOD, total phosphate, and coliform bacteria indexes showing that water quality in the urban would degrade to level five. Tatujiranggul (2008) evaluated the Lam Takhong River in Nakhon Ratchasima municipality using the Contingent Valuation Method (CVM) and Contingent Ranking Method (CRM). The results demonstrated that the value of Lam Takhong River in Nakhon Ratchasima municipality using the CVM was 9,009,684.48 bath/year. Using the CRM, the river's value as wastewater treatment, recreation and source of consumption were 28.0, 70.0, and 147,0 million bath/year, respectively.

Suwanwaree and Suwannarat (2010) used the 13 years (1996-2008) data combined with October 2008 to August 2009 study of Lam Takhong River and tributaries to summarise that water quality after Nakhon Ratchasima municipality was Meso-eutrophic. They suggested that additional wastewater treatments and water quality monitoring networks were needed to ensure a good livelihood for people living in the area.

2.2 Total maximum daily load (TMDL)

2.2.1 TMDL background

TMDL, or total maximum daily load, is a regulatory term in the U.S. Clean Water Act (CWA), describing a value of the maximum amount of a pollutant that a body of water can receive while still meeting water quality standards. Alternatively, TMDL is an allocation of that water pollutant deemed acceptable to the subject receiving waters.

TMDL is a tool for implementing state water quality standards which based on the relationship between pollution sources and in-stream water quality conditions. TMDL establishes the allowable loadings or other quantifiable parameters for a waterbody and thereby provides the basis for states to establish water quality-based controls. These controls should provide the pollution reduction necessary for a water body to meet water quality standards (EPA, 1991). The allowable amount takes into account all sources of pollutant in a watershed, including point sources and non-point sources, and requires a portion to be set aside as a margin of safety (EPA, 2017).

TMDL has been used extensively by the United States Environmental Protection Agency (EPA) and state environmental agencies to improve the quality of impaire waters by establishing maximum pollution limits for point sources wastewater dischargers. EPA published regulations in 1992 establishing TMDL procedures. The application of TMDL has broadened significantly in the last decades to include many watershed-scale efforts. This process incorporates both point source and nonpoint source pollutants within a watershed.

However, TMDL does not specify how pollutant loads are to be reduced within a stream or watershed. TMDL method only determines the total amount of a specific pollutant that a watershed or stream can assimilate without causing impairment or violate water quality standards. TMDL does not specify by what means a particular pollutant load is to be reduced. Rather, TMDL allocates the maximum contribution a source category (urban stormwater, agriculture, or industrial, for example) can contribute to the total load.

2.2.2 Water quality targets

The purpose of water quality targets is to protect or restore beneficial uses and protect human health. These targets may include state/federal numerical water quality standards or narrative standards, i.e. within the range of "natural" conditions. Establishing targets to restore beneficial uses is challenging and sometimes controversial. For example, the restoration of a fishery may require reducing temperatures, nutrients, sediments, and improving habitat.

Load allocations

Load allocations are equally challenging as setting targets. Load allocations provide a framework for determining the relative share of natural sources and human sources of pollution.

TMDL Planning process

Beneficial use determinations must have sufficient credible water quality data for TMDL planning. Throughout the U.S., data are often lacking adequate spatial or temporal coverage to reliably establish the sources and magnitude of water quality degradation. TMDL planning in large watersheds is a process that typically involves the following steps:

- Watershed characterization understanding the basic physical, environmental, and human elements of the watershed.
- Impairment status analyzing existing data to determine if waters fully support beneficial uses
- Data gaps and monitoring report identification of any additional data needs and monitoring recommendations

- Source assessment identification of sources of pollutants, and the magnitude of sources.
- Load allocation determination of natural pollutant load, and load from human activities (i.e. diffuse nonpoint sources and point discharges).
- Set establishment of water quality targets intended to restore or maintain beneficial uses.
- TMDL implementation plan a watershed management strategy to attain established targets.

2.2.3 Loading capacity

Calculating the TMDL for any given body of water involves the combination of factors that contribute to the problem of nutrient concentrated runoff. Bodies of water are tested for contaminants based on their intended use. Each body of water is tested similarly but designated with a different TMDL. Drinking water reservoirs are designated differently from areas for public swimming and water bodies intended for fishing are designated differently from water located in wildlife conservation areas. The size of the water body also is taken into consideration when TMDL calculating is undertaken. The larger the body of water, the greater the amounts of contaminants can be present and still maintain a Margin of Safety.

The Margin of Safety (MOS) is numeric estimate included in the TMDL calculation, sometimes 10% of the TMDL, intended to allow a safety buffer between the calculated TMDL and the actual load that will allow the water body to meet it's beneficial to use (since the natural world is complex and several variables may alter future conditions). TMDL is the end product of all point and nonpoint source pollutants of a single contaminant. Pollutants that originate from a point source are given allowable levels of contaminants to be discharged; this is the Waste Load Allocation (WLA). Nonpoint source pollutants are also calculated into the TMDL equation with Load Allocation (LA).

The calculation of a TMDL is as follows:

$$\mathrm{TMDL} = \mathrm{LC} = \sum \mathrm{WLA} + \sum \mathrm{LA} + \mathrm{MOS}$$

Where,

LC Loading capacity or the greatest loading a waterbody can receive without exceeding water quality standards;

WLA Wasteload allocation or the portion of the TMDL allocated to existing or future point sources;

LA Load allocation or the portion of the TMDL allocated to existing or future nonpoint sources and natural background;

MOS Margin of safety or accounting of uncertainty about the relationship between pollutant loads and receiving water quality (EPA's TMDL).

A TMDL specifies the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards and allocates pollutant loadings among point and nonpoint pollutant sources. A TMDL is the sum of the individual waste load allocations (WLAs) for point sources and load allocations (LAs) for nonpoint sources and natural background with a margin of safety.

2.2.4 TMDL reduction

EPA had conducted the goal of the Clean Water Act (CWA) as it requires that states establish an impairment list for waters and develop TMDLs for these waters. A TMDL includes a calculation of the maximum amount of a pollutant that can be present in a waterbody and still meet water quality standards.

As part of the CWA, states must establish water quality standards (WQS) for waters within their borders. Such standards designate the use of the particular waterbody, establish water quality criteria to protect the waterbody, and adopt requirements to protect and maintain healthy waters.

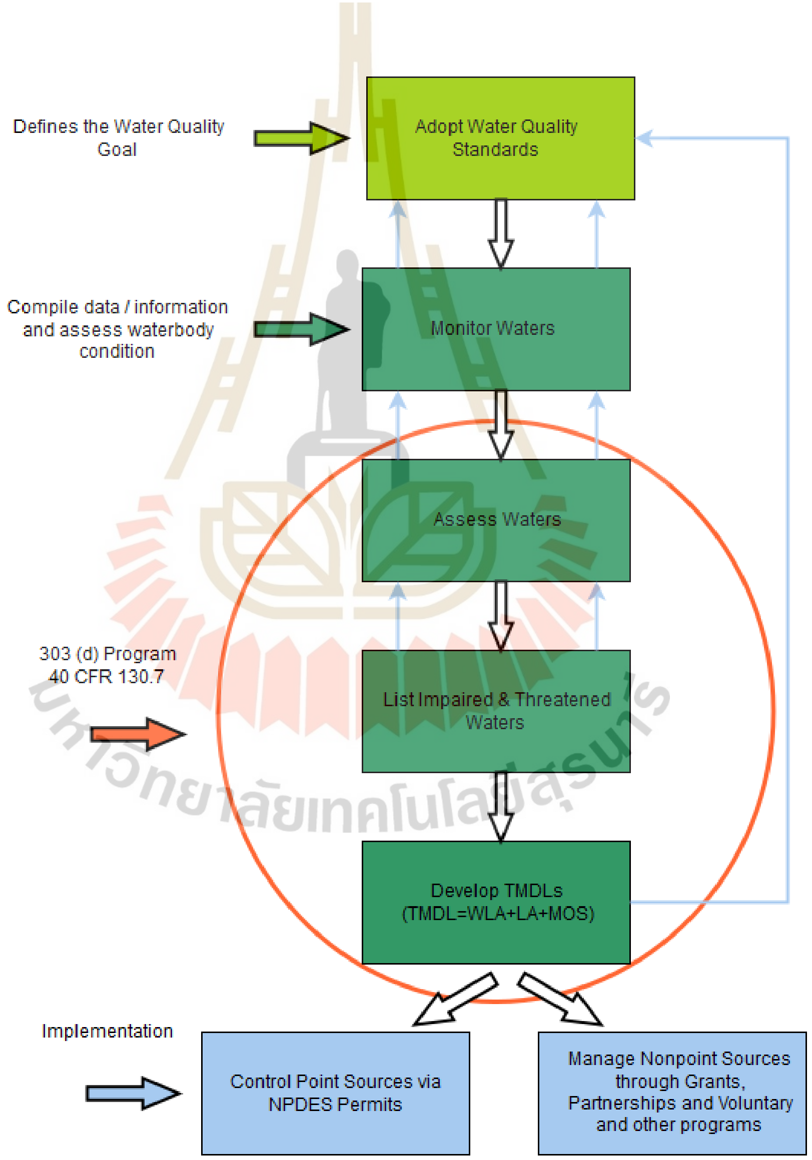


Figure 2.1 Water Quality-Based Approach of the Clean Water Act

(Section 303(d) of the Clean Water Act, EPA)

Figure 2.1 outlines the steps in the Water Quality-Based Approach of the Clean Water Act. Under Section 303(d) of the Act, states are required to evaluate all available water quality-related data and information to develop a list of waters that do not meet established WQS (impaired) and those that currently meet WQS but may exceed it in the next reporting cycle. States then must develop a TMDL for every pollutant/waterbody combination on the list. An essential component of a TMDL is the calculation of the maximum amount of a pollutant that can occur in a waterbody and meets WQS. The TMDL the state allocates this loading capacity among the various point sources and nonpoint sources (Section 303(d) of the Clean Water Act, EPA).

To determine allowable pollutant loads to remove from the impaired waters, TMDL development followed a process:

Development of models: information about land use, agricultural operations, wastewater plant discharges, and other variables are incorporated into a watershed model, which is used to estimate the total amount of sediment and nutrient pollution reaching the watershed. The model divides the watershed into segments, each containing segment specific data on rainfall, evaporation rates, nonpoint pollution sources, streamflow, and other pertinent details.

Assess water quality standards: the results of the watershed model tests which contain information on how, and to what degree, BMPs (Best Management Practices) affect the amount of pollution that reaches the watershed are used in the water quality model to calculate whether water quality standards are met. If the standards are not met, then jurisdictions would resubmit WIPs (Watershed Implementation Plans) with a more stringent set of BMPs, and the models would be rerun to assess whether these BMPs would result in pollutant reductions necessary to meet water quality standards (Chesapeake Bay, 2011).

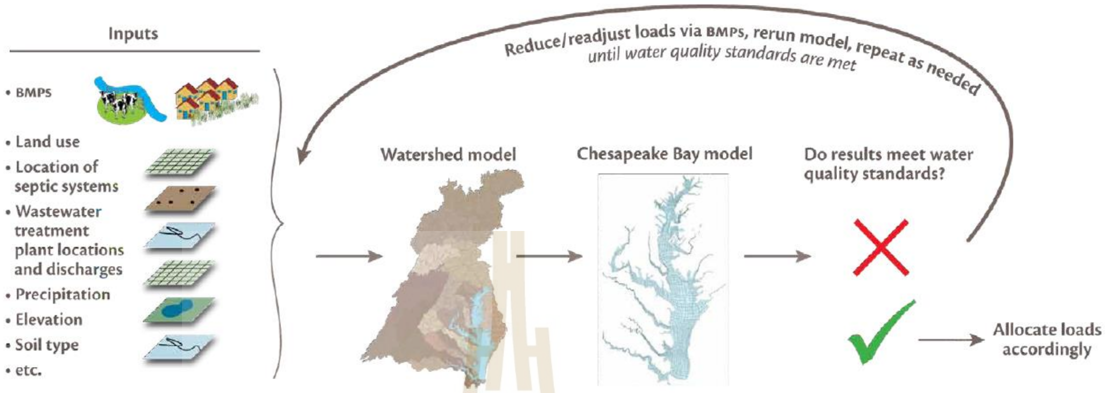


Figure 2.2 Simplified schematic of how pollution reduction goals were determined for the TMDL using environmental models

2.3 Water quality modeling tool

2.3.1 Signature of water quality models

Water quality models can be effective tools to simulate and predict pollutant transport in the water environment and they can contribute to saving the cost of labors and materials for a large number of analysis experiments. Moreover, they can also simulate in a special environment, which other general methods can not be conducted. Therefore, water quality models have become an important tool to identify pollutants in a water environment. The results from pollution scenarios using numerical models are important components of environmental impact assessment. Therefore, the environmental effects have to be simulated, predicted, and assessed before the construction projects are implemented. Moreover, they not only provide a database for environmental management agencies to authorize the projects but also provide technical supports for water environmental protection agencies (Bai et al. 2012).

More water quality models have been developed with various algorithms together with the development of model theory and computer technology. Nowadays, types of water quality model software have been improved for different topography, water bodies, and pollutants at different space and time scales. However, the modeling results have differences due to their different theories and algorithms, this affects different environment management decisions.

The developing countries have not been established a model standardization system, water quality models have limited applications to environmental management due to lack of references and comparisons to different modeling results. Thus, it is necessary to better understand the availability and precisions of different water quality models in the model standardization to apply effectively (Politano et. al 2008). This can contribute to better environmental management policies and authorizing reasonable environmental projects.

2.3.2 Development of water quality models

Surface water quality models have developed for a long period from Streeter and Phelps built the first water quality model to control river pollution in Ohio. Surface water quality models have made significant progress from a single factor to multifactor of water quality, from the point source model to nonpoint sources, from steady-state model to dynamic model, and from zero-dimensional model to three-dimensional models. These models are classified based on water body types, model-establishing methods, water quality coefficient, water quality components, model property, spatial dimension, and reaction kinetics. However, each surface water quality model has its constraint conditions. Generally, surface water quality models have undergone many stages.

From 1925, the water quality models focused on the interactions among different components of water quality in river systems as affected by living and industrial point source pollution. As hydrodynamic transport, sediment oxygen demand, and algal photosynthesis and respiration were considered as input data, and the nonpoint source pollution was just considered as the background load.

From 1965, water quality models were classified as six linear systems and made rapid progress based on further studies on multidimensional coefficient estimation of BOD-DO models. The two-dimensional model was applied to water quality simulation of lakes and gulfs. These models included the N and P cycling system, phytoplankton, and zooplankton system and focused on the relationships between biological growing rate and nutrients, sunlight and temperature, and phytoplankton and the growing rate of zooplankton (Yih and Davidson, 1976).

After 1975, the number of state variables in the models increased greatly, and the three-dimensional models were developed. The hydrodynamic model and the influences of sediments were introduced to water quality models under different input conditions. Besides, the water quality management policies were improved due to nonpoint source pollution simulation at a watershed scale. The typical models including QUAL models, MIKE11 model, and WASP models were developed.

Nonpoint source pollution has been reduced due to strong control in developed countries. Except for the typical models such as QUAL2K model, WASP 6 model, QUASAR model, SWAT model, and MIKE 21 and MIKE 31 models (Table 2.1), and other models have also been developed to simulate complicated water environmental conditions. More recently, Fan et al. (2009) integrated the QUAL2K water quality model and HEC-RAS model to simulate the impact of tidal effects on water quality simulation. More recently, Huy Hoang Bui et al. integrated SWAT and QUAL2K model for simulate water quality in the Cau River basin in Vietnam.

The USEPA developed a multipurpose environmental analysis system (BASINS), which makes it possible to assess quickly large amounts of point and nonpoint source. Among the previously mentioned surface water quality models, these models including QUASAR model, WASP model, CE-QUALW2 model, BASINS model, MIKE model, and EFDC model were widely applied worldwide.

Table 2.1 Main surface water quality models and their versions and characteristics.

Models	Model version	Characteristics	Notes
QUAL models (USEPA, 1970)	- QUAL I, QUAL II - QUAL2E, QUAL2E UNCAS - QUAL 2K	Steady-state or dynamic models.	Dendritic river and non-point source pollution
WASP models USEPA, 1983)	- WASP1-7 models	1D, 2D, 3D models	WQ simulation in rivers, lakes, estuaries, coastal wetlands
MIKE models (DHI, 1993, 1996)	- MIKE11 - MIKE 21 - MIKE 31	1D, 2D, 3D models	Water quality simulation in rivers, estuaries, and wetlands
BASINS models (USEPA, 1996)	BASINS 1, BASINS 2, BASINS 3, BASINS 4	Water quality analysis at a watershed scale	Integrated point and nonpoint source pollution
QUASAR model (Whitehead, 1997)	- QUASAR model	1D, dynamic model including PC QUA-SAR, HERMES, and QUESTOR modes	Dissolved oxygen simulation in larger rivers
EFDC model (VIMS, 1997)	- EFDC model	- Virginia Institute of Marine Science developed this model	Water quality simulation in rivers, lakes, reservoirs, estuaries, wetlands

Generally, most developed countries have developed better and advanced surface water quality models. Some surface water quality models have also been established in some universities or institutes in China over the past years, but these models were still not widely utilized like MIKE models, EFDC model, and WASP models. (Wang et al. 2013; Sumita and Kaur, 2017).

2.3.3 Types of existing water quality models

Some well-known and widely used mathematical models for water quality in rivers and watersheds are listed in Table 2.2, with the indication of the institutions in which they have been developed. These institutions can provide sufficient details about the model structure; in the table, there are also the general description, the principles, and some applications of these models (Benedini and Tsakiris 2013).

Table 2.2 Principal water quality models for rivers and streams

Country	Institution	Year	Model name	Purpose
USA	USCE	1982	CE-QUAL	Substance transport and transformation
Netherlands	DH	1985	DELWAQ	Pollution transport
USA	USEPA	1987	QUAL2E	Pollution transport
France-UK	LNH-CEH	1991	TELEMAC	Water flow and pollution transport
Switzerland	EAWAG	1994	AQUASIM	Substance transport and transformation
UK	CEH	1997	PC-QUASAR	Water flow and pollution transport
Denmark	DHI	1999	MIKE	Water quality and sediment transport
UK	Newcastle University	2008	TOPCAT-NP	Simulation of flow and nutrient transport
Germany	IGB	2009	MONERIS	Regionally differentiated quantification of nutrient emissions into a river system
UK	EA	2010	SIMCAT	Fate and transport of solutes

The water quality problems and the role of mathematical models are now one of the main subjects of scientific research, and consequently, new remarkable contributions can be expected in the qualified journals.

2.3.3.1 Modelling diffuse pollution and watershed models

Diffuse water pollution arises from many sources such as runoff from fields, seepage of nutrients from the soil into groundwater, or atmospheric deposition. Diffuse water pollution is mainly related to the way land and soil are managed and can affect all surface waters and groundwater. Groundwater is affected by leaching of pollutants from the soil while surface waters are affected by rainfall that washes over and off the land.

To model diffuse pollution from non-point sources, models are used to calculate pollutant loads from the runoff to the river system. To quantify the effect of these pollutant loads on river water quality, watershed models should be coupled with river water quality models in which pollutant loads from catchment models are used as boundary conditions.

The HSPF, SWMM, SHETRAN, BASIN, MIKE SHE, and SWAT have tools in handling diffuse water pollution models. They have been selected as appropriate models for water management from diffuse pollution. Nasr et al. (2007) compared SWAT and HSPF that HSPF was better inflow simulation and SWAT was in total phosphorus simulation. Table 2.3 shows several models that can be used with water quality modeling.

Watershed water quality model is a mathematical translation of the biological and Physico-chemical processes in rivers. In most water quality modeling applications, following components usually are modeled:

- Oxygen balance
- Eutrophication
- Pollution by heavy metals
- Pollution by pesticides
- Nutrient processes

Table 2.3 Water quality models for the basin scale

Model name	**Origin**	**Purpose /Substances modeled**
HSPF	SWM; 1966	Pesticides and nutrients transport
BASIN	EPA; 1996	Sediment and nitrogen transport
MIKE SHE	DHI; 1993	Eutrophication control/pollutant transport, nitrogen transport
SHETRAN	Univ. of Newcastle; 1996	Pollutant control/sediment and nitrogen transport
SWAT	USDA; 1993	Eutrophication and pesticide control/sediment, nutrients, pesticides

Many softwares can be used to model water quality in the watershed. Several water quality models are SWAT (USDA,1993), HSPF (SWM, 1966), BASIN (EPA, 1996), MIKE SHE (DHI, 1993), and SHETRAN (UN, 1996). The characteristics of watershed models are shown in Table 2.4.

Table 2.4 Summary of Watershed Simulation Capabilities (Shoemaker et al. 2005)

Model	Type		Level of Complexity			Timestep				Hydrology		Water Quality						
	Grid-based	Stream routing included	Export coefficients	Loading functions	Physically based	Sub-daily	Daily	Monthly	Annual	Surface	Surface and groundwater	User-defined	Sediment	Nutrients	Toxics/pesticides	Metals	BOD	Bacteria
HSPF	-	●	-	-	●	●	-	-	-	-	●	●	●	●	●	●	●	●
Basin	-	●	●	●	●	●	●	-	-	●	●	●	●	●	●	●	●	●
MIKE SHE	-	●	-	-	●	●	-	-	-	-	●	-	-	-	-	-	-	-
SHETRAN	-	●	-	-	●	●	●	-	-	-	●	-	●	-	-	-	-	-
SWAT	-	●	-	-	●	-	●	-	-	-	●	-	●	●	●	●	-	-

2.3.3.2 Integrated modeling

Only little research has been made to fully integrate distributed watershed models with river water quality models. The integration can be done at different levels: external linking through file exchange and internal linking through internal computer memory. And external linking often requires programming to reformat input/output files of the models linked because there is no standardized format for these files.

Internal linking through internal memory is implemented in several forms. The tight integration is known by MIKE-SHE software in which the distributed watershed model SHE is fully integrated towards the dynamic river model MIKE 11 (Butts and Graham, 2006).

The second form is developing modular structures within a certain framework, for example, the Java based Modular Modelling System (Leavesley et al., 2005).

Another alternative is integrating software into a single framework. For example, in the US, The Framework for Risk Analysis in Multimedia Environmental Systems – Multimedia, Multipathway, and Multireceptor Risk Assessment (FRAMES-3MRA) developed by the U.S.EPA is an important software model for risk assessment of hazardous waste management facilities (Babendreier and Castleton, 2008).

The SWAT (hydrological) model code was developed into an OpenMI-compliant version and linked with the SOBEK (hydrodynamic) model to extend SWAT's simulation of basin-scale streamflow and sediment transport in the blue Nile river basin (G. D. Betrie et al. 2011). The SWAT model simulated the streamflow and soil erosion upstream catchment, while the SOBEK model routed the streamflow and sediment downstream to the basin outlet.

2.3.3.3 TMDL support modeling

The development and application of mathematical water quality models can be very useful in almost every aspect of the TMDL process. These types of models provide insights that help inform the decision-making process. Models are often used to support the development of TMDLs - typically to estimate source loading and evaluate loading capacities that will meet water quality standards. The technical requirements of a TMDL stipulate that analysis should demonstrate the allocation of point and nonpoint source loads that would result in meeting water quality standards. The point and nonpoint sources must be evaluated as separate sources so that they can be simulated under various loading scenarios.

For nonpoint sources, TMDL guidance identifies that allocation can be made to individual sources, categories, or subcategories of sources. In cases of limited data, load allocation can be expressed as gross allotments, allowing for larger-scale grouping of the nonpoint source.

In the development of a TMDL, load allocations might also be identified that affect sources upstream of listed water depending on the transport properties of the pollutant. The need to look at sources upstream of the listed water necessitates a “watershed-based” approach to TMDLs. Although TMDLs are developed for specifically listed waters and their associated watersheds, the TMDL analyses are sometimes developed in “bundles” to address groups of listed waters that are located within a larger collective watershed.

The phased approach provides for further pollution reduction without waiting for new data collection and analysis. The margin of safety developed for the TMDL under the phased approach should reflect the adequacy of data and the degree of uncertainty about the relationship between load allocations and receiving water quality (Shoemaker et al. 2005).

The TMDL endpoints, considers the ability of models to predict the magnitude, frequency, and duration of the typical endpoints (Table 2.5). Prediction of endpoints is essential for evaluating loading capacity in TMDLs and watershed simulation modeling. For example, a wide range of models—simple models that provide only annual loads or complex models that perform sub-hourly simulation—can evaluate annual phosphorus loading. Evaluation of a dissolved oxygen endpoint might require a model to evaluate hourly dissolved oxygen fluctuations.

The model's ability to simulate typical TMDL target pollutants and expressions. Characterizes the models depending on the timestep of the simulation for the target steady-state, storm event, annual, daily, or hourly.

2.3.4 Comparisons of water quality models

Model capabilities, watershed representation, procedures to calculate rainfall excess, runoff, surface flow, reach runoff, reservoir flow, overland sediment, channel sediment, and chemical in each of these models are summarized in Table 2.6.

Table 2.5 TMDL Endpoints Supported Model

MODEL	TP load	TP concentration	TN load	TN concentration	Nitrate concentration	Ammonia concentration	TN : TP mass ratio	Dissolved oxygen	Chlorophyll a	Algal density (mg/m2)	Net TSS load	TSS concentration	Sediment concentration	Sediment load	Sulfate concentration	Metals concentrations	Pesticides concentrations	Herbicides concentrations	Toxics concentrations1	Pathogen count (e.g., fecal coliform)	Temperature	Methylmercury tissue concentration	Metals sediment concentration	Mercury sediment concentration	Synthetic organic chemicals sediment concentration
BASINS	•	•	•	•	•	•	•	•	•	⊕	•	•	•	•	-	•	•	•	•	•	•	-	-	-	⊕
DELFT3D	•	•	•	•	•	•	•	•	•	•	•	•	•	•	-	-	-	-	-	-	•	-	-	-	-
HSPF	•	•	•	•	•	•	•	•	•	-	•	•	•	•	-	•	•	•	•	•	•	-	•	-	•
MIKE11	•	•	•	•	•	•	•	•	•	•	•	•	•	•	-	•	-	-	-	•	•	-	•	•	•
SWAT	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	-	-	⊕	⊕	⊕	-	⊕	⊕	⊕	-	⊕	⊕	-	-	-	-

- Not supported ⊕ Daily • Hourly (or less)

Table 2.6 Summary of NPS pollution models (Mike et al., 2005; EPA (the United States Environmental Protection Agency), 2017)

Description	HSPF	MIKE SHE	MIKE11	BASIN	SWAT
Model components/ capabilities	Runoff and water quality constituents on pervious and impervious land area, movement of water and constituents in stream channels, and mixed reservoirs.	Interception-ET, overland and channel flow, unsaturated zone, saturated zone, an exchange between aquifer and rivers, and dispersion of solutes, dual-porosity, irrigation, and user interface with pre- and post-processing, GIS.	Flood analysis, real-time flood or forecasting, dam break analysis optimization ecological and water quality assessments and forecasting, sediment transport, in rivers and estuaries wetland restoration, integrated river.	Watershed management, development of TMDLs, coastal zone management, nonpoint source programs, water quality modeling, watershed delineation, land use classification.	Hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, agricultural management, channel and reservoir routing, water transfer, user interface, and ArcViewGIS platform.
Temporal scale	Long term; variable constant steps (hourly).	Long term and storm event; variable steps numerical stability.	Long term, hourly steps.	Long term, hourly steps.	Long term; daily steps.
Watershed representation	Pervious and impervious land areas, stream channels, and mixed reservoirs; 1-D simulations.	2-D rectangular/square overland grids, 1-D channels, 1-D unsaturated, and 3-D saturated flow layers.	1D river modeling, Reservoir, canal gate, rivers, and wetlands	Subbasins, channel, watershed.	Subbasins grouped based on climate, hru (with the same cover, soil, management), ponds, groundwater, main channel.

Table 2.6 Summary of NPS pollution models (cont'd)

Description	**HSPF**	**MIKE SHE**	**MIKE11**	**BASIN**	**SWAT**
Water balance	Water budget considering interception, ET, and infiltration with the empirically based areal distribution.	Interception and ET loss and vertical flow solving Richards equation using implicit numerical method.	Precipitation, runoff, a two-layer water balance method for infiltration losses.	Hourly water budget.	Daily water budget; precipitation, runoff, ET, percolation, and return flow from subsurface and groundwater flow.
Runoff on Overland	Empirical outflow depth to detention storage relation and flow using Chezy- Manning equation.	2-D diffusive wave equations are solved by an implicit finite-difference scheme.	Using a simplified, semi-distributed method or a 2D diffusive wave method.	Runoff volume using curve number	Runoff volume using curve number and flow peak using modified Rational formula or SCS TR-55 method.
Runoff in Channel	All inflows are assumed to enter one upstream point, and outflow is a function of reach volume or user-supplied demand.	1-D diffusive wave equations solved by an implicit finite-difference scheme.	Stratified multilayered river flow (salinity or temperature in two-layered or multilayered stratified water bodies)	Variable storage coefficient method and flow equation adjusted f transmission losses, evaporation, diversions, and return flow.	Routing based on variable storage coefficient method and flow using Manning's equation adjusted for transmission losses, evaporation, diversions, return flow.
Chemical simulation	Soil and water temperatures, DO, nitrate, ammonia, organic N, phosphate, organic P, pesticides, and tracer chemicals chloride.	Dissolved conservative solutes in the surface, soil, and groundwaters by solving numerically the advection-dispersion equation.	Biochemical and chemical oxygen demands transport, dissolved oxygen, and total suspended solids.	Sediment and nitrogen transport, different agricultural chemical yields from watersheds.	Nitrate-N based on water volume and average concentration, daily organic N, crop N and P, and pesticides.

2.3.4.1 BASINS model

Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) is a multipurpose environmental analysis system designed to help regional, state, and local agencies perform watershed and water quality-based studies. It was developed by the U.S. EPA to assist in watershed management and TMDL development by integrating environmental data, analysis tools, watershed, and water quality models.

BASINS includes tools and utilities for assessing watershed conditions to help users understand water quality issues and pollution sources in a watershed, assess monitoring programs, identify data gaps, and develop watershed-water quality modeling strategies. Further, BASINS includes tools designed to assist in summarizing key watershed information in a format suitable for preparing Watershed Characterization Reports (tables that inventory and characterize both point and nonpoint sources at the watershed and subwatershed scales).

A geographic information system (GIS) provides the integrating framework for BASINS. Through the use of GIS, BASINS has the flexibility to display and integrate a wide range of information (e.g., land use, point source discharges, and water supply withdrawals) at a scale chosen by the user.

BASINS makes watershed and water quality studies easier by bringing together key data and analytical components in one tool. BASINS allows users to efficiently access national environmental information, incorporate local site-specific data, apply assessment and planning tools, and run a variety of proven, robust nonpoint loading and water quality models.

BASINS is a useful tool for those interested in watershed management, development of total maximum daily loads (TMDLs), coastal zone management, nonpoint source programs, water quality modeling, and National Pollutant Discharge Elimination System (NDPES) permitting.

2.3.4.2 MIKE11 model

MIKE 11 can be used to investigate river bank overflow and watershed hydrology. There are several modules.

- FF - FLOOD FORECASTING

Modeling of real-time flood forecasting, including state updating and data assimilation features.

- ST/GST - NONCOHESIVE SEDIMENT

Transport, erosion, and deposition of uniform and graded noncohesive sediments, including morphological changes of river bed bathymetry.

- AD - ADVECTION-DISPERSION

Transport and spreading of conservative pollutants and constituents, including a linear decay option (includes heat modeling).

- ACS - COHESIVE SEDIMENT

Cohesive sediment modeling applying an advanced three-layer bed description with quasi-2D erosion dynamics as well as for settling and deposition dynamics.

- ECO LAB - ECOLOGICAL MODELLING

ECO Lab is applied for all water quality related applications with MIKE 11, using predefined or user defined water quality model templates.

2.3.4.3 MIKE-SHE

MIKE-SHE is a physically based and fully distributed hydrological watershed model. The model simulates the flow of water and solutes in the watershed by solving the governing equations of overland and channel flow, unsaturated and saturated flow by finite difference methods. The model can also perform numerical solutions for the 3D Boussinesq equation for saturated flow, 1D Richard equation for the unsaturated zone, 2D Saint Venant equation for overland flow and is integrated with MIKE 11 to model the exchange flow and transport between the river and the saturated zone.

The variation in watershed characteristics (e.g. land use, soil, geology, topography) and driving variables (e.g climatic input data) are represented in a network of grids in the horizontal direction. Each grid is then subdivided into many layers in the vertical direction to describe variations in the soil profile and the groundwater aquifer system.

Thompson *et al.* (2004) applied this integrated model for a lowland wet grassland, the Elmley Marshes, in southeast England. The model performed well in hydrodynamic modeling. However, little is known about modeling water quality in wetlands using this model.

2.3.4.4 SOBEK

SOBEK has been developed by Delft Hydraulics in partnership with the National Dutch Institute of Inland Water Management and Wastewater Treatment (RIZA), and the major Dutch consulting companies. SOBEK has three basic product lines including SOBEK-Rural, SOBEK-Urban, and SOBEK-river.

SOBEK-Rural gives regional water managers a high-quality tool for modeling irrigation systems, drainage systems, natural streams in lowlands, and hilly areas. Applications are typically related to optimizing agricultural production flood control, irrigation, canal automation, reservoir operation, and water quality control. SOBEK-Rural can also answer questions about increased pollution loads in response to growing urbanization.

To model the flow and water quality of the river in this study, 1DFLOW and 1DWAQ of SOBEK-Rural are used.

The water quality processes are classed under the following sections:

- Processes related to transport and tracers,
- Oxygen and BOD,
- Suspended and bottom sediment,
- Micro-pollutants,
- Eutrophication and nutrients,
- Bacteria,
- Water temperature,
- Chemical processes,
- Additional "general" processes.

2.3.4.5 HSPF (Hydrological Simulation Program – FORTRAN)

HSPF is a culminating evolution of the Stanford Watershed Model (SWM; Crawford and Linsley 1966), watershed scale Agricultural Runoff Model (ARM; Donigian et al. 1977), Nonpoint Source Loading Model (NPS; Donigian and Crawford 1976) and Sediment and Radionuclides Transport (SERATRA; Onishi and Wise 1979). HSPF is currently in version 12.2 (Bicknell et al. 2005). To improve the efficiency of using HSPF, WinHSPF was designed as an interactive Windows interface to HSPF. User control input (UCI) files are used for data exchange among WinHSPF, BASINS, and GIS (Yang and Wang 2010).

Of all models discussed, HSPF has the most complex mechanisms for the simulation of subsurface water quality processes in both the saturated and unsaturated zones. HSPF is one of the most detailed, operational models of agricultural runoff and erosion by simulating land surface and soil profile chemical/biological processes that determine the fate and transport of pesticides and nutrients; and by considering of all streamflow components (i.e., surface runoff, interflow, and baseflow) and their pollutant contributions.

Although HSPF has its limitations, so far it comparatively better meets the demands of DWP modeling studies than other models.

2.3.4.6 The Soil and Water Assessment Tool (SWAT) model

SWAT is a river basin, or watershed, scale model and is a physically-based, time-continuous model (Neitsch et al., 2002) developed by USDA Agricultural Research Service (ARS). SWAT was developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land use, and management conditions over long periods (Neitsch et al. 2011). Outputs provided by SWAT include stream-flow and in-stream loading or concentration estimates of sediment, organic nitrogen, nitrate, organic phosphorus, soluble phosphorus, and pesticides (Gassman et al. 2007).

In SWAT, the hydrological cycle is the driving force behind whatever happens in the watershed. The simulation of the hydrology of a watershed can be separated into two major divisions. The first division is the land phase of the hydrologic cycle which controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin. The second one is the water or routing phase of the hydrologic cycle which can be defined as the movement of water, sediments, etc. through the channel network of the watershed to the outlet (Neitsch *et al.*, 2002). The transformation processes of water quality components are modeled in the routing phase with the QUAL2E model concept.

The SWAT model is a very useful tool to calculate the pollution loads from diffuse sources. A lot of studies have been carried out to use SWAT to calculate nutrient loads and suggest measures to improve water quality by running SWAT models with different management scenarios. Huang *et al.* (2009) obtained reasonable results for streamflow and nutrient loadings, however, the simulated nitrogen and water soluble phosphorus is generally higher than measured value due to the wetland processes in riparian zones (Yang et al., 2009). SWAT is able to represent the general trend of water quality changes resulting from different management scenarios, thus evaluate the effect of management practices alternative on the watershed level (Ullrich and Volk, 2009; Volk et al., 2009). Kang et al. (2007) applied SWAT for TMDL programs to a small watershed containing rice paddy fields. Bouraoui and Grizzetti (2008) used SWAT to identify the major processes and pathways controlling nutrient losses from agriculture activities. Salvetti et al. (2008) also used SWAT as a tool for the rain-driven diffuse load.

2.3.5 Selection of the study

The primary goal of model selection is the definition of the problem to be addressed, and the determination of the potential models that could be used to simulate the desired processes. Besides, it is necessary to consider data availability, the accuracy of the output required, the cost of models, and limitation during model selection. Using the simplest model that will satisfy the research objectives.

For the mentioned reasons, the SWAT model and Qual2k were selected for this study because of the following reasons.

- They are screening-level models and include channel degradation routine with detail appropriate for watershed management (Staley et al. 2006) and their applicability to decision-making in the area (Capello et al., 2008).
- They have proven to be an effective tool for assessing water quality due to non-point source pollution problems, those dominated by agricultural activities (Arnold and Fohrer 2005).
- SWAT has been used to assess the impacts of land use change and practices on soil and water at a sub-watershed scale (Loi, 2010; Zhang et al., 2016).
- They are user-friendly in handing input data, and the ArcGIS interface that it can realistically represent the spatial variability of watershed characteristics.
- They make satisfactory river flow predictions in poorly monitored watersheds (Kim and Kaluarachchi 2014).

- They are capable of an application for mountainous catchment and lake (Birhanu et al., 2007).
- They can simulate and predict the flow, sediment, and nutrient loads, which are close to measured values (Pongpetch et al., 2015).
- They are also suited for investigating the long-term impacts of climate variability on surface water resources (Jin et al., 2016).
- Lastly, they can be used to calculate the pollution loads from diffuse sources and applied SWAT for TMDL programs (Kang et al. 2007).

2.4 SWAT Model (Soil and Water Assessment Tool)

2.4.1 The land phase of the hydrological cycle

The land phase of the hydrological cycle in SWAT simulates the loading of water, sediment, nutrients, and pesticides from each subbasin to the main channel. Therefore, it can be used to simulate the pollution loading from diffuse sources such as agriculture.

2.4.1.1 Water balance

The hydrological cycle is based upon the water balance (Equation 2.1 and Figure 2.3)

$$SW_t = SW_0 + \sum_{i}^{t} (R_i - Q_{surf,i} - E_{a,i} - w_{seep,i} - Q_{gw,i}) \qquad (2.1)$$

Where,

SW_t the final soil water content (mm H_2O)

SW_0 the initial water content on day i (mm H_2O)

t the time (days)

R_i	the amount of precipitation on day i (mm)
$Q_{surf,i}$	the amount of surface runoff on day i (mm)
$E_{a,i}$	the amount of evapotranspiration on day i (mm)
$W_{seep,i}$	the amount of percolation on day i (mm)
$Q_{gw,i}$	the amount of base flow on day i (mm)

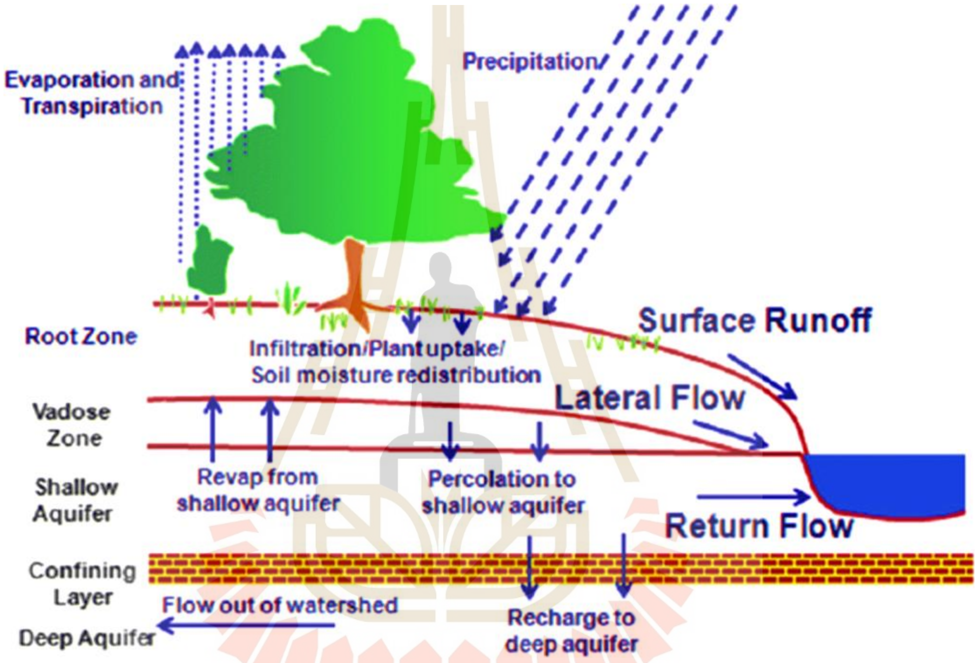


Figure 2.3 Schematization representation of the hydrological cycle in SWAT (Neitsch et al., 2002)

As precipitation descends, it is intercepted by plant cover and then evaporated or fall to the soil surface. Water falling to the soil surface will infiltrate into the soil profile or form surface runoff which is considered as a relatively quick flow to the stream channel. Infiltrated water will be uptaken by plant and then evapotranspired, evaporate through soil holes, form lateral flow in the subsurface layer or continue to percolate to the shallow aquifer. Water reaching shallow aquifer can move back to the shallow aquifer through the capillary rise and uptake of deep-rooted plants or form groundwater flow that contributes to the stream or continue to infiltrate to the deep (confined) aquifer. Water can also move to another watershed in the deep aquifer.

2.4.1.2 Nutrient balance

- **Nitrogen**

SWAT monitors five different pools of nitrogen in the soil (Figure 2.4). Two inorganic forms of nitrogen are NH_4^+ and NO_3^- and three organic forms of nitrogen are fresh organic N which is associated with crop residue and microbial biomass, active and stale organic N associated with the soil humus.

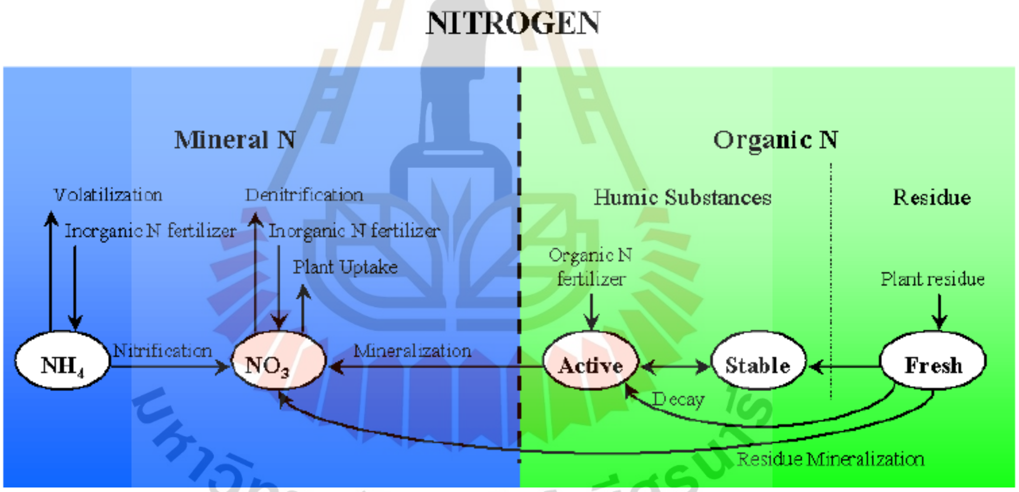


Figure 2.4 SWAT nitrogen pools and nitrogen processes in land phase (Neitsch et at., 2002)

Nitrogen can be added to the soil by fertilizer, manure or residue application, fixation by symbiotic or non-symbiotic bacteria, and nitrogen in rainfall. Nitrogen is removed from the soil by plant uptake or by water fluxes include surface runoff, lateral flow, and percolation to the groundwater. The amount of nitrate percolating to the groundwater will contribute to the river through groundwater flow or transported with water back to the unsaturated zone through capillary rise (evaporation process), a part of it is reduced by a biological or chemical reaction which is modeled in SWAT through the parameter called half-life constant for in .gw input file, the remaining is kept in the saturated aquifer.

❖ **Phosphorus**

SWAT monitors six different pools of phosphorus in the soil (Figure 2.5). Three pools are inorganic forms of phosphorus while the other three pools are organic forms of phosphorus. Fresh organic P is associated with crop residue and microbial biomass while the active and stable organic P pools are associated with the soil humus. The organic phosphorus associated with hummus is partitioned into two pools to account for the variation in the availability of humic substances to mineralization. Soil inorganic P is divided into solution, active, and stable pools. The solution pool is in rapid equilibrium (several days or weeks) with the active pool. The active pool is in slow equilibrium with the stable pool (Neitsch et al., 2011). Figure 2.5 shows six phosphorus pools and their processes in the land phase.

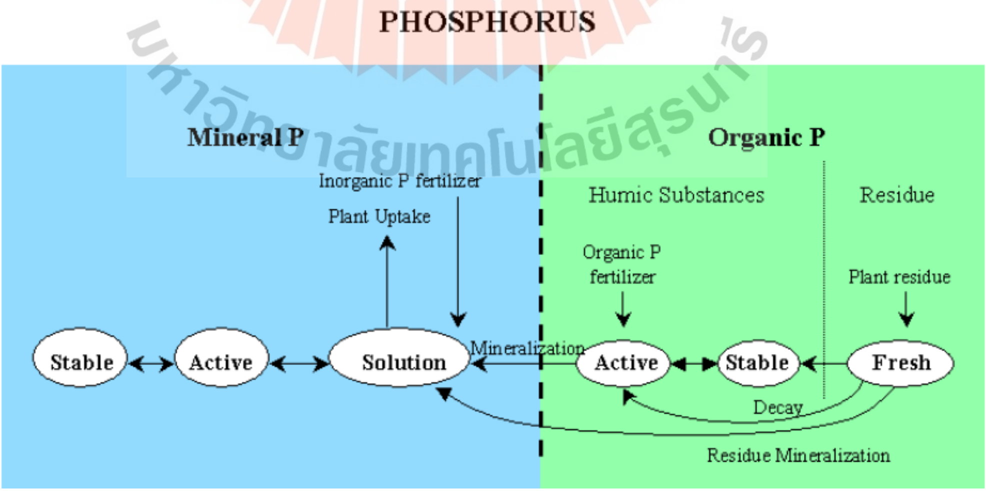


Figure 2.5 SWAT phosphorus pools and phosphorus processes in land phase

(Neitsch et al. 2002)

Phosphorus can be added to the soil by fertilizer, manure, or residue application. Plant use of phosphorus is estimated using the supply and demand approach described in the section on plant growth. In addition to plant use, soluble phosphorus and organic phosphorus may be removed from the soil via a mass flow of water. Because phosphorus is not very soluble, the loss of phosphorus dissolved in the surface water is based on the concept of partitioning phosphorus into the solution and sediment phases as described by Knisel (1980). The amount of soluble phosphorus removed in runoff is predicted using labile concentrations in the top 10 mm of the soil, the runoff volume, and the partitioning factor. Sediment transport of phosphorous is simulated with a loading function for organic N transport (Neitsch et al., 2011).

2.4.2 Routing phase of the hydrological cycle

Originally, flow is routed through the canal using the variable storage routing method or the Muskingum routing system. These methods are variations of the kinematic wave model.

- ***Variable Storage method***

In the variable storage method, outflow depends on the stored volume in the reach and the inflow and a calculated storage coefficient (SC).

$$V_{out,2} = SC \cdot (V_{in} + V_{stored,1}) \tag{2.2}$$

where SC is the storage coefficient that depends on the travel time (TT) and the time step (Δt), V_{in} is the average inflow at the beginning and the end of the time step (m^3), $V_{out,2}$ is the outflow at the end of the time step (m^3), $V_{stored,1}$ is the storage volume at the beginning of the time step (m^3).

$$SC = \frac{2 \cdot \Delta t}{2 \cdot TT + \Delta t} \tag{2.3}$$

$$TT = \frac{V_{stored}}{q_{out}} = \frac{V_{stored,1}}{q_{out,1}} = \frac{V_{stored,2}}{q_{out,2}} \tag{2.4}$$

where TT is the travel time (s), V_{stored} is the storage volume (m^3) and q_{out} is the discharge rate (m^3/s)

- ***Calculation of the travel time in the channel***

To relate the river depth, the hydraulic radius R_{ch} and the wetted perimeter p to the reach volume or the cross-section area, it is assumed that the channel sides have a 2:1 run to rise ratio ($z_{ch} = 2$).

When the volume of water in the reach exceeds the maximum amount that can be held by the channel, the excess water spreads across the flood plain.

The travel time in the channel is calculated using the manning equation:

$$TT = \frac{n \cdot R_{ch}^{-2/3} \cdot slp_{ch}^{-1/2}}{L_{ch} \cdot 3.6} \tag{2.5}$$

- ***Transmission losses***

During periods when a stream receives no groundwater contributions, it is possible for water to be lost from the channel via transmission through the side and bottom of the channel. Transmission losses are estimated with the equation.

$$tloss = K_{ch} \cdot TT \cdot P_{ch} \cdot L_{ch} \tag{2.6}$$

where *tloss* are the channel transmission losses (m^3 H_2O), K_{ch} is the effective hydraulic conductivity of the channel alluvium (mm/hr), *TT* is the flow travel time (hr), *Pch* is the wetted perimeter (m), and L_{ch} is the channel length (km). Transmission losses from the main channel are assumed to enter bank storage or the deep aquifer.

- ***Evaporation losses***

Evaporation losses from the reach are calculated:

$$E_{ch} = coef_{ev} \cdot E_0 \cdot L_{ch} \cdot W\ TT/24 \qquad (2.7)$$

where E_{ch} is the evaporation from the reach for the day (m^3), $coef_{ev}$ is an evaporation coefficient, E_0 is potential evaporation (m^3), L_{ch} is the channel length (km), *W* is the channel width at water level (m), and TT is the travel time (hr)

- ***Water balance***

Water storage in the reach at the end of the time step is calculated:

$$V_{stored,2} = V_{stored,1} + V_{in} - V_{out} - tloss - E_{ch} + div + V_{bnk} \qquad (2.8)$$

where $V_{stored,2}$ is the volume of water in the reach at the end of the time step (m^3), $V_{stored,1}$ is the volume of water in the reach at the beginning of the time step (m^3), V_{in} is the volume of water flowing into the reach during the time step (m^3), V_{out} is the volume of water flowing out of the reach during the time step (m^3), *tloss* is the volume of water lost from the reach via transmission through the bed (m^3), E_{ch} is the evaporation from the reach for the day (m^3), *div* is the volume of water added or removed from the reach for the day through diversions m^3), and V_{bnk} is the volume of water added to the reach as return flow from bank storage (m^3).

The outflow V_{out} can be calculated either by the Muskingum or the Variable Storage method.

2.4.3 Modeling parameterization

Parameterization is the process of assigning values to model parameters in a specific study area. Parameterization includes calibration, validation, and model performance evaluation (ASABE, 2017).

- Calibration can be part of the parameterization process and consists of adjusting input parameter values and initial or boundary conditions within reasonable ranges until the simulated results closely match observed data. Calibration is generally reserved for those parameters that are not easily measurable or are intrinsically heterogeneous or uncertain (Daggupati et al. 2015).
- Validation is the process of demonstrating that a given site-specific model is capable of making sufficiently accurate simulations. Validation involves running a model using parameters that were determined during the calibration process and comparing the predictions to observed data not used in the calibration.
- Validation is the process of verifying that a calibrated model reproduces measured observations for conditions different than were used for the model calibration.

In general, a good model calibration and validation should involve: (1) observed data that include wet, average, and dry years; (2) multiple evaluation techniques; (3) calibrating all constituents to be evaluated; and (4) verification that other important model outputs are reasonable (Arnold et al. 2012). The calibration and validation process in SWAT have three steps following

- The first step is the determination of the most sensitive parameters for a given watershed or subwatershed. Sensitivity analysis is the process of determining the rate of change in model output concerning changes in model inputs. Two types of sensitivity analysis are generally performed: (1) local, by changing values one at a time, and (2) global, by allowing all parameter values to change. Both procedures provide insight into the sensitivity of the parameters and are necessary steps in model calibration.

- The second step is the calibration process. Calibration is an effort to better parameterize a model to a given set of local conditions, thereby reducing the prediction uncertainty. Model calibration is performed by carefully selecting values for model input parameters by comparing model predictions for a given set of assumed conditions with observed data for the same conditions.

- The final step is validation for the component of interest (streamflow, sediment yields, etc.).

Calibration and validation are typically performed by splitting the available observed data into two datasets: one for calibration, and the other for validation. Data are most frequently split by periods, carefully ensuring that the climate data used for both calibration and validation are not substantially different. SWAT users have also used calibrated parameters from a watershed with approximately similar climatic, soils, and land use conditions for validation in their study watershed, or vice versa.

The metrics and methods used to compare observed data to model predictions are also important. Multiple graphical and statistical methods could be used, such as time-series plots, Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970), and percent bias. Most published SWAT applications report both graphical and statistical hydrologic calibration results, especially for streamflow, and hydrologic validation results are also reported for a large percentage of the studies. By far, the most widely used statistics reported for calibration and validation are r^2 and NSE.

- The r^2 statistic can range from 0 to 1 (where 0 indicates no correlation and 1 represents perfect correlation), and it provides an estimate of how well the variance of observed values are replicated by the model predictions.
- NSE values can range between $-\infty$ to 1. The NSE value of 1 indicates a perfect fit between the simulated and observed data. NSE values ≤ 0 indicate that the observed data mean is a more accurate predictor than the simulated output (Krause, Boyle, and Bäse 2005).

2.4.3.1 Model calibration

Calibration is the process of adjusting selected input parameter values and initial conditions to obtain simulated values that match measured observations with the desired accuracy. Typically, calibration has the following systematic calibration approaches (1) manual calibration, (2) automatic calibration, or (3) a combination of both.

2.4.3.2 Model validation

Model validation is the process of rerunning the simulation, using a different time-series data set as the input for input data, without changing any parameter values which may have been adjusting during calibration (Chekol et al., 2007). Validation verifies a calibrated model reproduces measured observations for conditions different from what were used for the model calibration.

2.4.3.3 Model performance evaluation

Evaluation is the process of using graphical, quantitative, and/or statistical techniques, along with performance ratings and model intended to use to judge the quality of model predictions (Harmel et al. 2014). Model performance measures are critical for evaluating how well simulated values represent measured data. The utilization of multiple performance measures includes graphical techniques and quantitative indicators, and both comprehensive evaluation of model performance.

2.5 QUAL2K Model

2.5.1 History of the model

The QUAL2K model is a river and stream water quality model that is intended to represent a modernized version of the QUAL2E model. Version 1 was released in 2003. The most recent version of 2.12 was released in 2012 (Chapra et al. 2012). The QUAL2K code is distributed by the USEPA (2018c).

The QUAL2K model is a powerful model based on many of the same assumptions as QUAL2E, such as a one-dimensional system with steady-state, non-uniform flows and hydraulics while allowing simulation of diel variations in water quality. Enhancements over QUAL2E include algorithms for slow and fast carbonaceous biochemical oxygen demand, periphyton, and detritus in addition to sediment diagenesis, pH, and alkalinity. The model inputs and outputs are in the form of user-friendly Excel spreadsheets, with underlying VBA routines to write and read files for use in a FORTRAN executable code.

QUAL2K (or Q2K) is a waterway and stream water quality model that is planned to represent a modernized variant of the QUAL2E (or Q2E) model. The

Enhanced Stream Water Quality Model (QUAL2K) is a thorough and flexible one-dimensional stream water quality model. It reenacts the significant responses of nutrient cycles, algal generation, benthic and carbonaceous demand, air reaeration, and their consequences for the dissolved oxygen balance. Furthermore, the program incorporates a heat balance for the calculation of temperature and mass balance for moderate minerals, coliform microorganisms, and non-conservative constituents, for example, radioactive substances.

The model is proposed as a water quality planning instrument for creating total maximum daily loads (TMDLs) and can likewise be utilized as a part of conjunction with field examining for recognizing the magnitude and quality attributes of point and nonpoint sources. QUAL2K has been created for steady stream and steady waste load conditions and is thus a "steady-state model" even though temperature and green algae functions can differ on a diurnal basis. (Pelletier et al., 2006)

2.5.2 Model inputs

QUAL2K requires some level of demonstrating refinement and mastery. The user must supply in excess of 100 individual information sources, some of which require extensive judgment to estimate. The information can be assembled into three classifications: a stream/waterway framework, global factors, and forcing functions. The first group, input information for the stream/waterway framework, portrays the stream framework into a configuration the model can read. The general variable gathering portrays the general simulation factors. (Chapra and Pelletier 2008)

2.5.3 Model outputs

QUAL2K produces three sorts of tables-hydrodynamics, reaction coefficient, and water quality-in the output document. The outputs can be effectively imported into other applications, for example, spreadsheets for investigation and furthermore incorporates some graphic analysis of the model outcomes. State factors can be plotted at characterized distances along the reaches. Also, the user can include field observations for dissolved oxygen with a minimum, average and maximum values. The model uses those values to plot the observed information versus the predicted ones. If there should be an occurrence of dynamic simulations, the model produces temperature and algae esteems on the characterized time step.

2.5.4 Model application

QUAL2K is appropriate for waste load allocation studies and other planning exercises. Waste load allocations are performed for states of a steady low stream and most extreme allowed effluent discharge rate. QUAL2K is proposed particularly for the relentless stream flow, consistent effluent release conditions indicated in the water quality guidelines for waste load distribution. Accordingly, QUAL2K has been generally utilized by specialists and administrative organizations and is considered as the standard for water quality models. for example, units, water quality constituents, and some physical attributes of the basin. Besides, the compelling capacities are clients indicated inputs that drive the system being modeled by Pandurang G.S. (2006).

2.6 Integrated SWAT model and SWAT model applications

The historical development of SWAT involves the creation of various Geographic Information System and other tools to support the input of topographic, land use, soil, and other digital data into SWAT. The first GIS interface program developed for SWAT was SWAT/GRASS, which incorporates the Topographic

Parameterization Tool (TOPAZ) and other tools to generate inputs and provide output mapping support for both SWAT and SWAT-G GIS (Haverkamp et al., 2005).

Arc-SWAT was also used to assess impacts of land use change & practices on soil & water at a sub-watershed scale using swat model combine GIS data in La Nga sub-watershed Vietnam (Loi, 2010). Briak et al. (2016) assessed sediment yield in Kalaya gauged watershed in Northern Morocco using GIS and SWAT model. As a result, the global evaluated soil erosion rate in the study area varied from 20 to 120ton/ha/year. It was summarized that the entire knowledge of the hydrologic processes happens in the watershed and the consciousness about an acceptable meaning range of the parameters is crucial when developing the reliable hydrologic model.

2.6.1 SWAT model applications in the US and other countries

Applications of SWAT have expanded worldwide over the past decade. Many of the applications have been driven by the needs of various government agencies, particularly in the U.S. and the European Union, that require direct assessments of anthropogenic, climate change, and other influences on a wide range of water resources or exploratory assessments of model capabilities for potential future applications (Gassman et al. 2007).

SWAT has also been used extensively in Europe, including projects supported by various European Commission (EC) agencies. Several models including SWAT were used to quantify the impacts of climate change within the Climate Hydrochemistry and Economics of Surfacewater Systems (CHESS) project. SWAT, BASINS, and a variety of other modeling tools will be used to help determine the pollutant sources and potential solutions for many of these forthcoming TMDLs (Benham et al., 2006; Borah et al., 2006).

Diffuse pollution, especially from agricultural activities, has become a major concern due to past and present efforts in wastewater treatment for industries and households. Compared to point sources, diffuse pollution is more difficult to be controlled since it is characterized by numerous and dispersed sources and the difficulties in tracing its pathways (Yang and Wang, 2010).

River basin-scale models, which are capable of estimating pollutant loads from diffuse sources in a basin to the receiving river system, are necessary components of sustainable environmental management for better implementation of the EU Water Framework Directive. Daniel et al. (2011) describe several well-known and operational modeling tools that can handle non-point source pollution at the river basin scale. Two of the more widely used of these modeling packages are the Soil and Water Assessment Tool (SWAT) model (Gassman et al., 2007) and the MIKE SHE model (Refsgaard et al., 2010), which was developed from the earlier SHE (Système Hydrologique Européen or European Hydrological System) model.

A significant number of studies have been carried out to use SWAT to calculate nutrient loads, such as those reviewed in Gassman et al. (2007), and Tuppad et al. (2011). Numerous SWAT studies also suggest measures for improving water quality based on different management scenarios (Yang et al., 2011).

SWAT is also able to simulate flow and nutrient fluxes through subsurface tile drains by the subsurface tile drainage component added by Arnold and Fohrer (2005) which was then modified by Green et al. (2006). Numerous studies have since been published that describe applications of the SWAT subsurface tile drainage routine, including several that report successful replication of measured streamflow and nitrate levels such as Schilling and Wolter (2009) for the Des Moines River basin in Northcentral Iowa, and Lam et al. (2011) for the Kielstau basin in northern Germany.

Runoff studies by using the SWAT model

Bouraoui et al. (2005) evaluated the performance of the hydrological model SWAT in the Medjerda River, the major Tunisian river, originates in the semi-arid Atlas Mountains of eastern Algeria. They found that the efficiencies for the calibrated monthly flow for the three sub-basins for September 1988 to August 1992 period ranged from 0.31 to 0.65. Arabi et al. (2006) applied the SWAT model in Allen County, northeastern Indiana. They found that R^2 = 0.92 and NSE = 0.84 in Dreisbach watershed, and R^2 = 0.86 and NSE = 0.73 in Smith Fry watershed for monthly flows prediction. The validation results showed that R^2 = 0.66 and NSE = 0.61. Coffey et al. (2004) evaluated the SWAT model at University of Kentucky, and they illustrated monthly SWAT model predictions and observed data had of R^2 = 0.70 and NSE = 0.41. Cheng et al. (2007) studied non-point source pollution in livestock breeding areas of the Heihe River basin in the Yellow River.

The results showed R^2 values for the daily surface runoff was found to be 0.94 in calibration and 0.89 during validation. This result indicated a good agreement between observed and simulated values, so the SWAT model was capable of predicting daily runoff.

2.6.2 SWAT model applications in Thailand

Thanasiriyakul (2003) used SWAT/GIS modeling to assess tributaries relativity at Upper Mae Tuen basin in Chiang Mai province. Relative difference illustrated the significant value of total flow, surface runoff, and baseflow between Ban Luang and Omkoi basin. The digital elevation model had been demonstrated on a sufficient geoinformatics system as a 360^{o} digital terrain model mountainous area and possible flood animation of the basin area.

Vesurai (2005) studied the impacts of land use changes on runoff in the Upper Nan basin by using the SWAT hydrologic model. The results demonstrated that the impacts on runoff could be clearly detected when land use changes, and hence the SWAT model can be used for the planning and management of water resources of the river basin.

Prachayasittikul (2006) applied the SWAT model to simulate managing water resources in the Songkhla Lake Basin. The results showed that the yearly average surface water supply from 1975 to 2004 was 6,051.16 x10^{6} m^{3}. In 2004, the water shortage for irrigation projects was 281.64 x 10^{6} m^{3} or 28% of the water demand for the irrigation.

Vathananukij (2006) simulated majorly caused water-related normal to an extreme event, was attempted to structure and verified the geoinformatics public domain SWAT model at the Chaophraya River basin. The results showed that this appropriate model calibrations and verifications, admissible ensued on above 90% of correlation efficiency and affirmable best arbitrated on large scale-mild slope potentiality together with un-implied in both continual rainfall investigation and a sufficient number of stations.

Keawmuangmoon (2009) assessed water use efficiency for agriculture in Mae Tha Watershed, Lamphun province by using the SWAT model. Agricultural water use efficiency index for each subbasin showed that a subbasin (No.26) has the highest efficiency (95.97%). Considering the proportion of agricultural areas to subbasin areas found that about 64.44% was occupied by the agricultural area in this subbasin. While another subbasin (No.20) has the lowest efficiency (-223.07%) since most of the subbasin area was occupied by agricultural area (97.98%) which used a large amount of water.

Punyawattano (2010) applied SWAT2000/GIS modeling for spatial dispersion evaluation of nutrients from the Utapao River Basin to Songkhla Lake. The results showed that The R2 and NSE of mineral nitrogen were 0.1 and -2.74. Moreover, the R^2 and NSE of total phosphorus were 0.04 and -23.07. Therefore, modeling was not suitable for the evaluation of nutrient from Utapao River Basin to Songkhla Lake cause of the secondary water quality data had not enough quality for adjusting the data.

Phomcha et al. (2011) studied the suitability of the SWAT model for simulating monthly streamflow in Lam Sonthi Watershed, the Pasak Watershed, which is located in the central part of Thailand. The results showed that R^2 and NSE values were raised above 0.7, and the deviation of runoff volumes (D) was also acceptably accurate. This led to the conclusion that the SWAT model can reliably predict monthly streamflows on any other agricultural watershed in tropical climates with conditions similar to the watershed studied.

Suwanlertcharoen (2011) applied SWAT model to evaluate runoff and suspended sediment at Thoungnaklang and Failuang weirs, Uttraradit province. The results showed that the highest runoff and sediment occurred in August which resulted in from rainfall in the watershed area. The total average of soil loss in the Mae Phun watershed was 5.436 t/ha/y.

Intaruksa (2012) studied the effect of land use changes on surface runoff in the Mae Jang basin by using GIS and SWAT model. The scenarios results demonstrated that land use changes were responsible for an increase in the annual surface runoff which increasing of agricultural area and decreasing of forest area.

A large number of research has been conducted for the watershed in Thailand at varying scales and models. SWAT is one of the models that is used as the most popular. Many of those, SWAT is applied to simulate streamflow, runoff, sediment, and the water use demand. Besides, the researcher studied the impacts of land use change on runoff and evaluate nutrient in the river. However, the limitation of previous studies is TMDL has not approached and calculated for watershed by using appropriate water quality models.

2.7 QUAL2K Model applications

Sarda (2013) presented an approach for water quality modeling of the Godavari River in India. 15 km stretch was taken for the purpose of analysis. It was divided into two reaches depending on the point of inflows. The water quality data considered included temperature, EC, Organic Phosphorous (Org P), DO, phytoplankton, Slow Carbenacous Biochemical Oxygen Demand (CBODslow), Fast Carbonaceous Biochemical Oxygen Demand (CBODfast), pathogens, Org. N, Alkalinity, pH. The model was run and calibrated for the data of 2000-2008. The model represented the field data quite well with some exceptions. Senstivity analysis predicted that the model was sensitive to TN, CBOD, depth coefficient.

Reareation model was selected through internal calculations by Gupta et al. (2013). Euler‘s method was used for the solution of integration. In addition, the model was calibrated for the data of three months and was run for a population of 100 with 50 generations. Besides, the model was validated using the results from the data from

October to December. The discripency in the validated and observed data was found to be up to 10%.

The modeling of the Dissolved Oxygen was conducted on the Periyar river in South India. surface water temperature, and DO for a period of 28 years ie from 1980-2008 was obtained from the departments by Lakshmi E (2014). For QUAL2K modeling the river was divided into 7 reaches. Temperature and DO were modeled using QUAL2K. Data obtained from sampling and secondary data were used for modeling. Calibration data of 2008 and 2013 also predicted that the data for all the reaches are in good agreement with the results of the model.

Zhang et al. (2015) conducted a study on the Taihulake and Hongqui river in China, scenarios consisted of a series of three water treatment technologies in different configurations, from upstream to downstream. The results showed that the optimal scenario comprised a bio-contact oxidation system upstream, followed by an ecological floating bed, and a vertical moveable eco-bed downstream. The reduction rates achieved by this scenario for BOD, NH3–N, Total Nitrogen (TN), and TP were 49.50%, 32.81%, 35.94%, and 45.27%, respectively. The method applied in this study can prevent the implementation of water quality improvement programs that would not achieve the desired goals.

Kalburgi et al. (2015) used QUAL2K to develop the BOD-DO model of Ghataprabha river in Karnatka in India. A 50 km stretch was selected for the study. ArcGis technique is used to obtain hydro-geometric data of the river for input to model QUAL2K. Six different locations were monitored for calibration and validation. The calibrated model was validated to predict water quality using a different set of data under different conditions. The results showed that the predicted results were well in agreement with the observed results.

Idris et al. (2016) conducted a study on Yamuna river in India for the assessment of its surface water quality with the help of QUAL2K. The total study area of 22 km was divided into 16 reaches of 0.3 km each. The calibration of the model was done for DO, temperature, Alkalinity, TN, and pH. The BOD value keeps increasing as the sewage starts flowing in the river. The DO values were found to be below the permissible limits. The pH and temperature were also not in the prescribed limits. Sensitivity analysis depicted that the model is highly sensitive to river flow and point source discharges and moderately sensitive to fast CBOD and nitrification rate. Overall the results predicted by the model were quite in agreement with the observed values.

Ashwani S et al. (2017) used QUAL2K to predict the water quality of the Pamba river in India. A stretch of 12.63 km was selected as the study area. Other than that a point 8.2 km from the last sampling point was selected for which the water quality parameters were to be predicted. The stretch was divided into 22 reaches of unequal lengths. Post monsoon data of a steady weather condition was taken for calibration. A timestep of 5.65 minutes was used. pH, temperature, EC, TSS, TDS, DO, BOD, Alkalinity, TP were the parameters considered for model input. The parameters predicted were BOD, TSS, TN, TP, and Alkalinity. The internal calculation was used. The results obtained were well in agreement with the observed data.

2.8 Lam Takhong basin

2.8.1 Characteristics

Lam Takhong River basin is a part of the Mun watershed, in the Northeastern region of Thailand (Figure 2.8). The river is 220 km in length, originated from Sangampang Range in Khao Yai National Park covering nine districts of three provinces including Pracheenburi, Nakhon Nayok, and Nakhon Ratchasima province (Regional Environment Office 11, 2010). Besides, the watershed has an area of 3,269 km^2 covering six districts in Nakhon Ratchasima province (Land Development Department, 2008). Lam Takhong flows into Mun River at Tha Chang Sub District, Chaloem Phra Kiat district.

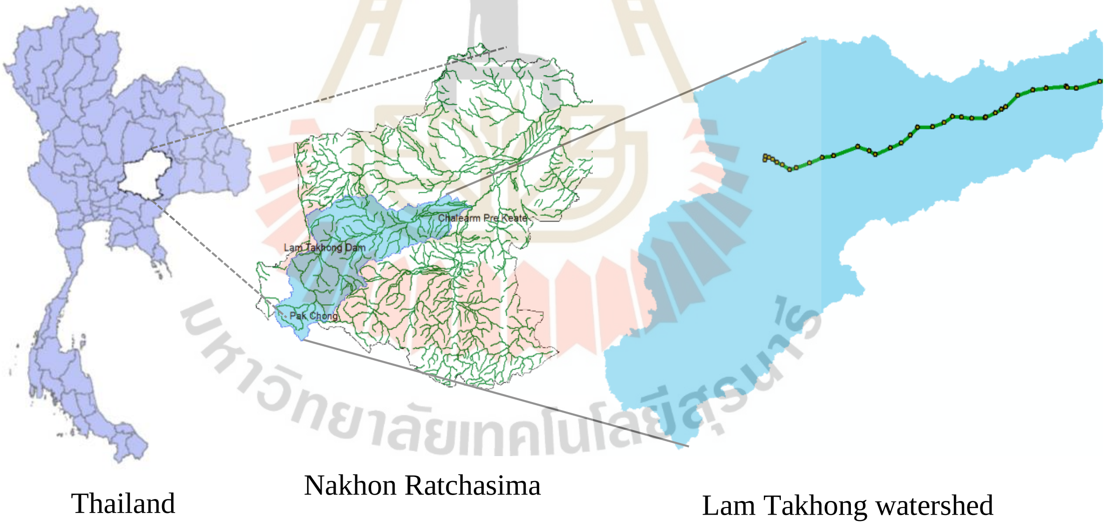


Figure 2.6 Location of Lam Takhong river.

2.8.2 Meteorology

Lam Takhong River basin is under the influence of the southwest and northeast monsoon. There are three seasons including rainy, winter, and summer season (Royal Irrigation Department, 2004). From May to October, the southwest monsoon brings moisture from the Indian Ocean causing rain, peaking in August and September (Thai Meteorological Department, 2008). The average annual amount of rainfall is 1,454.3 mm (Lam Takhong Watershed Research Station, 2010). From October to February, the wind direction is reversed. Cooler, drier northeast monsoon wind blows off the Asian landmass, bringing a cold season. Temperature falls slightly with a short transitional period between the monsoons during March and April, which is the warmest period of the years (Thai Meteorological Department, 2008). Lam Takhong River basin has an average temperature of 25.4°C. The evaporation rate is 1,379.4 mm/year, and relative humidity with a minimum of 47.8% and 83.4% maximum (Lam Takhong Watershed Research Station, 2010).

2.8.3 Pedology features

Soil features of Lam Takhong can be divided into two parts based on plant species, the Upper and Lower River basin. Most of the Upper Lam Takhong River basin are forest areas. They contain many soil series, such as Khao Yai, Kabinburi, Khorat, and Lam Narai series. Soil drainage is medium to good. Soil layer has alternately shallow and deep with medium fertility. However, most of the Lower Lam Takhong River basin is agriculture. Soil texture is quite similar to Pak Chong and Muak Lek series which is accumulated of sediment broken down from shale and limestone. This soil has good drainage, moisture retention, and moderate fertility. Deep soil is Oxic Paleustults (clayey, kaolinitic) which is mixed with fine clay. Muak Lek soil comes from sediment broken down from shale, slate, and limestone as Lithia Haplustalfs (Loamy-skeletal mixed). Shallow soil has good drainage, but it has quite low soil fertility and is easy for erosion (Lam Takhong Watershed Research Station, 2010).

2.8.4 Land utilization

Lam Takhong River basin in the past is covered with extended large forests. At the present, most areas are invaded and deforested turning into communities, farmlands, orchards, and deserted areas, and others to keep up with local progress (Lam Takhong Watershed Research Station, 2010). Land use type in Lam Takhong can be divided into nine parts which are shown and described in Table 3.3 and the topic 3.2.3.2.

2.8.5 Population

The total population of six districts was about 768,022 people in 2017 with about half of them resided in Mueang Nakhon Ratchasima District (348,578 people) followed by Pak Chong, Si Khio, Sung Noen, Chaloem Phra Kiat, and Kham Thale So district in the number of 156,749, 104,576, 97,342, 30,858, and 29,919 people, respectively (Offical Statistic Registration Systems, 2017).

2.8.6 Lam Takhong reservoir

Lam Takhong River basin contains a large irrigation project which is a rainfall catching area above the dam 1,241 km^2 that included the Upper Lam Takhong area. The dam begun the construction in 1964, and then finished and started to reserved water in 1969. It was constructed to obstruct Lam Takhong River basin between Khao Khaen Lun and Khao Tan Sisaed at Khlong Phai sub-district, Sikhio district, Nakhon Ratchasima. Sediment survey in 1978 indicated the capacity of 325.74 million cubic meters. In the second observation in 1984, the capacity was decreased to 323.955 million cubic meters. It indicated a reduction of 1.785 million cubic meters. Seven years after the first measurement, the average volume of sediment in the dam was measured at 0.2975 million cubic meters yearly and erosion rate at 0.208 millimeters per square kilometer per year. As for the third survey in 2003, the capacity revealed at 314.4906 million cubic meters. Survey results indicated that reservoir capacity reduced by 9.464 million cubic meters and depth of erosion equaled 0.3483 millimeters per square kilometer per year (Hydrology and Water Management Center for Lower Northeastern Region, 2005).

2.8.7 Water quality research in Lam Takhong

Ratmanee (2007) estimated the daily dynamic suspended sediment model in Upper Lam Takhong. Four models were applied including, the Sediment Rating Curve, ANNs with Discharge, ANNs with Hydrology parameters, and ANNs with Hydrology parameters and Landscape change parameters. The outcomes indicated that the estimation of daily dynamic suspended sediment could engage in all four models with a coefficient of determination of 0.5157, 0.9281, 0.9972, and 0.9968, respectively. ANNs with Hydrology parameters showed good results.

Pollution Control Department (2008) reported that FCB, $NH_{3,}$ and TCB were major causes. BOD loading was 18,924 kg/day. Pollution sources included urban (59%), livestock (36%), Industry (4%) and aquacultures (1%). In addition, Nakhon Ratchasima municipality (2006) found BOD as the major problem that came from dense communities.

Sarapin (2008) used a genetic algorithm (GA) to calibrate the coefficient in the QUAL2Kw model by comparing GA operator by Charbonneau and Knapp and GA operator by Goldberg and Michaelwicz. Both GA operators predicted the physical and chemical water quality in Lam Takhong river close to the monitoring station of the

Pollution Control Department and Nakhon Ratchasima Municipality. Moreover, if no water quality management in Lam Takhong river, at Ma Kham Thao Dam and Kun Phom Dam would exceed the standard class four in 2010 and 2015.

Pollution Control Department (2009) used the Water Quality Analysis Simulation Program (WASP) and Total Maximum Daily Loads (TMDL) to study water quality for Lower Lam Takhong. The results illustrated that the concentration of BOD was class four or less if the reduction of 50% wastewater. In addition, the TMDL of BOD at Lower Lam Takhong was 1,242 and 2,644 kg/day for dry and wet seasons. WASP was carried out to calculate TMDL in the Lam Takhong river basin and how a percentage of a point source to cut down to meet water quality demands, only simulated BOD loading in the study. The research has not estimated pollutant loading reduction necessary from the non-point source which was mentioned as the main source (46%) in Lam Takhong river basin. Besides, land use change in the future had not mentioned that enormously influence pollutant loading in the Lam Takhong river.

Suwanwaree and Suwannarat (2010) used a 13 years (1996-2008) data set combined with October 2008 to August 2009 study of Lam Takhong River and tributaries showed that water quality after Nakhon Ratchasima municipality was Meso-eutrophic. They suggested that additional wastewater treatments and water quality monitoring networks are needed to ensure good livelihood for people living in the area.

From the year 2008 to 2009, the Water Quality Analysis Simulation Program (WASP) was successfully calibrated and validated by Chuersuwan et al. (2013) to simulate the concentrations of dissolved oxygen for the Lam Takhong river system for empowering water quality management goal. The substantial 50% reduction result in pollution would considerably improve the water quality of the river.

Pongpetch et al. (2015) applied the Soil and Water Assessment Tool (SWAT) model for evaluations streamflow, sediment, nitrate nitrogen, and total phosphorus loading simulations in Lam Takhong river basin. From the simulation, September was the month with the highest sediment, NO_3-N, and TP yields while January and December were the lowest months. From the model, SWAT identified nine subbasins that were classified into a high loading rate of TP. SWAT model could be a useful tool for water resources management and soil conservation planning in Lam Takhong river basin.

Some water quality research were carried out in Lam Takhong river by applied the different models including ANNs, QUAL2K, WASP, SWAT. Although the SWAT software was widely applied to simulate flowrate and water quality in Thailand and the Lam Takhong Basin, particularly TMDL evaluation to cut down pollutant sources have not yet been clarified. Therefore, the goals of this study are using SWAT to simulate BOD TMDL in Lam Takhong river and cut down organic and nutrient loading from point sources and nonpoint sources in the present and when land use change in the future.

CHAPTER III

METHODOLOGY

3.1 Working process

In this study, ArcGIS10.1 software integrated with the SWAT model was used to study critical areas, and SWAT model was selected for this study because of including channel degradation routine with detail appropriate for watershed management (Staley et al. 2006). Furthermore, SWAT has proven to be an effective tool for assessing water resource and non-point source pollution problems (Arnold and Fohrer 2005). The results of these studies could be a useful tool for water resources management and land use planning in Lam Takhong River basin. The process of study for Lam Takhong River basin is shown in Figure 3.1.

The followings are eight steps of the process.

Step 1: Watershed delineator

The watershed was delineated into sub-basins using the digital elevation map. The delineated sub-basin map, land use, and soil map were overlaid. SWAT simulated different land use in each sub-basin. Base on Lam Takhong River basin's DEM, land use and soil data to accumulate flow direction and stream network, the Lam Takhong River basin was divided into subbasins outlet of Lam Takhong River.

Step 2: HRU analysis

After the watershed was divided into subbasins, SWAT would carry out slope classification in each subbasin. Land use, soil, and slope layer overlap were subdivided into HRUs.

Step 3: Input meteorological data

Meteorological data in the area were used as input including precipitation, temperature, relative humidity, wind speed, and solar radiation.

Step 4: Running SWAT

The simulation was conducted from 2002 to 2012 with a daily time step by SWAT modeling.

Step 5: Model calibration

The model was adjusted to more closely match observed data from 2005 to 2012 to improve the accuracy of modeling. The streamflow was output calibrated. Calibration is carried out until average measured and simulated surface runoff (monthly NSE> 0.5; $R^2 > 0.6$ and PBIAS < 15%)

Step 6: Model Validation

Rerunning the simulation from 2013 to 2017 without changing any parameter values which may have been adjusting during calibration. SWAT model was validated in 5 years period by using observed streamflow at gauging stations in Lam Takhong River basin.

Step 7: Model prediction

R^2, NSE, and PBIAS were used to evaluate SWAT predictions and considering the levels of correlation.

Step 8: Land use change

This scenario analysis was used to evaluate the potential impact on surface water quality by land use change in 2027 and 2035. The land use change data periods were imported in the ArcSWAT model. Finally, the SWAT model was run to simulate the impacts of land use change to flow.

Step 9: Set up Qual2k model

The flow results from SWAT was used as input data of Qual2k, combining the characteristical data of the river, meteorological, water quality, and pollution sources data to prepare the model calibration

Step 10: Qual2k model calibration

As mentioned before, the model was also adjusted to more closely match observed data in February 2019 to improve the accuracy of modeling. DO, BOD, TN, and TP were respectively calibrated. Calibration was conducted until average measured and simulated value (NSE> 0.5; $R^2 > 0.6$ and PBIAS < 15%).

Step 11: Qual2k model Validation

Validation was carried out in November 2019 without changing any parameter values which may have been adjusting during calibration.

Step 12: Current simulation scenarios

Simulated scenarios were conducted after the Qual2k model was successfully validated and TMDL estimation in the Lam Takhong River was calculated in 2019.

Step 13: Future model scenarios

The integration of the SWAT model and Qual2k model supported the water quality simulation in 2027 and 2035.

Step 14: Estimating TMDL need to cut down to meet standards

Current and future scenarios were simulated and then TMDL on the Lam Takhong River was estimated. From the calculated results it was possible to estimate the amount of cut to meet the standards.

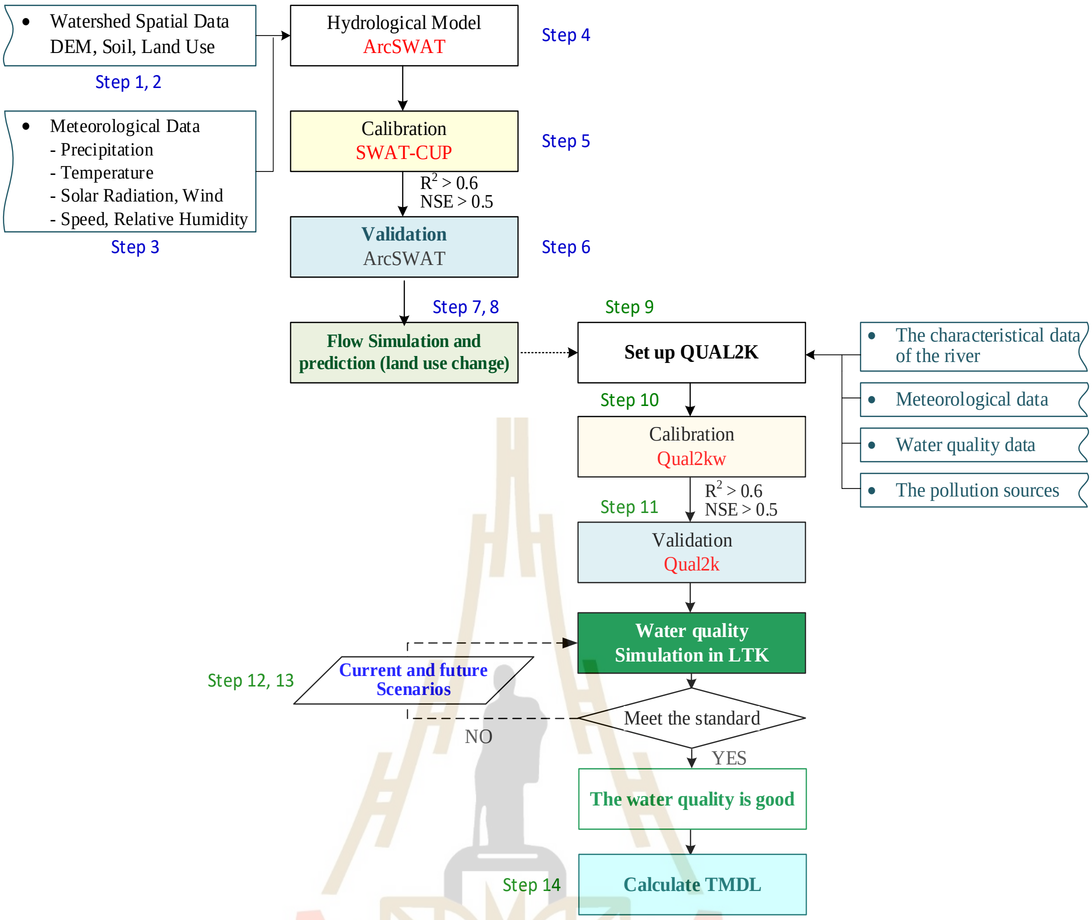


Figure 3.1 Research framework methodology

3.2 Build a watershed model of Lam Takhong basin using SWAT Model

SWAT divides the watershed into subbasins. Then, subbasins continue to be partitioned into multiple hydrologic response units (HRUs) based on soil and land use distribution of the watershed. The question is how SWAT calculate flow from diffuse source including rainfall, groundwater, etc. This is implemented as follows:

- For each HRU, the land phase of the hydrological cycle is modeled, and the flow from each HRU is calculated. Then flow from HRUs within a subbasin is summed to get flow from this subbasin.

- The flow of headwater subbasins (headwater subbasins are those with no subbasin upstream) are then routed through the main channel of respective subbasins.

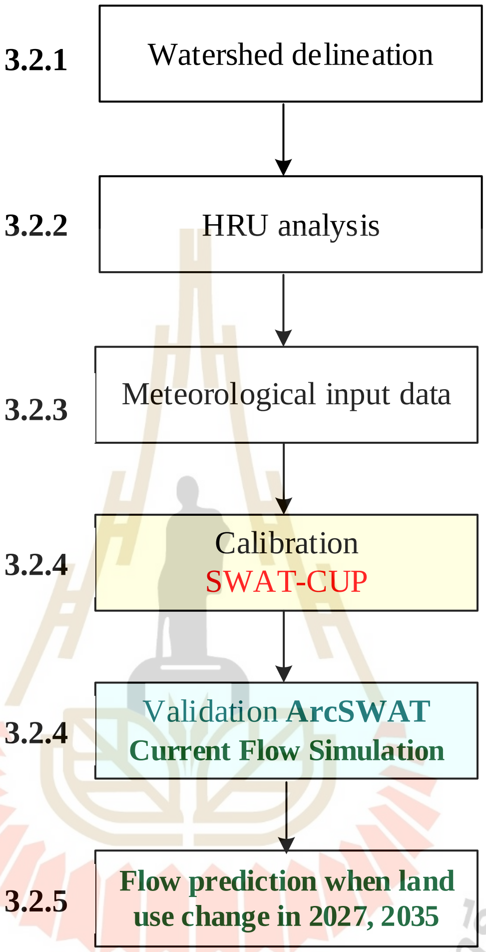


Figure 3.2 SWAT model set up diagram

3.2.1 Watershed delineation

The ArcSWAT2012 interface (Olivera et al., 2006) was used to delineate the Lam Takhong basin based on an automatic procedure using Digital Elevation Model (DEM) data. A DEM grid map with a spatial resolution was available (Figure 3.4) and it contained spatially distributed elevation information to allow an automatic delineation of the watershed. The physical features of the topography substantially influence the magnitude and dynamics of surface runoff. Topographic maps of The Land Development Department (LDD) at scale 1:4,000 were used to generate DEM. The relevant parameters that can be generated from DEM were slope, flow direction, flow length, and flow accumulation.

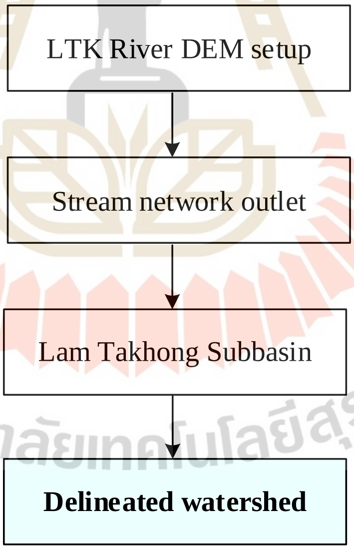


Figure 3.3 Diagram of Lam Takhong Watershed delineation

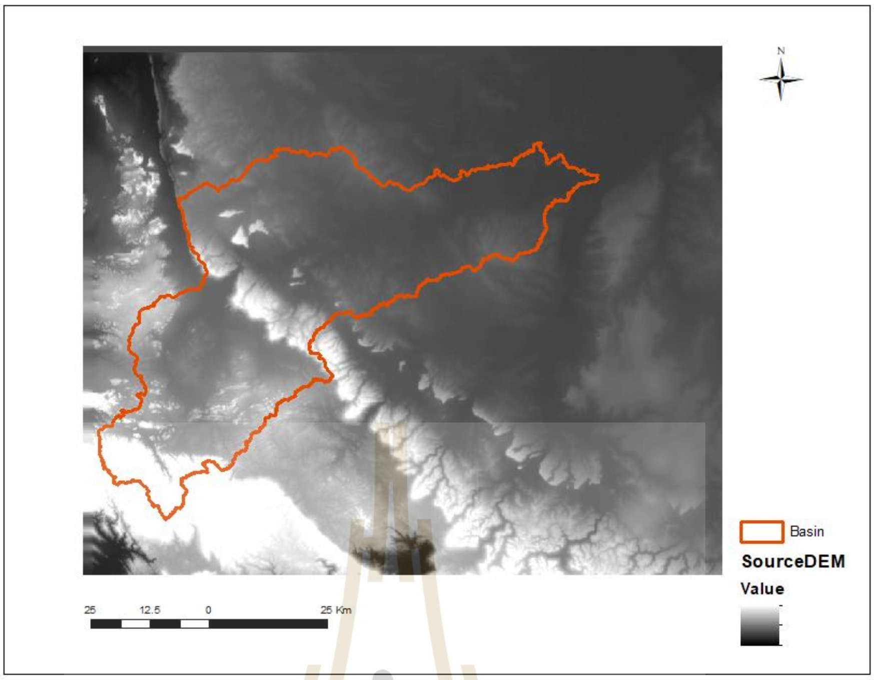


Figure 3.4 The Digital Elevation Model (DEM) of Lam Takhong basin

The spatial resolution can affect the accuracy of the simulation. The values of the grid cell represent an average value over the area of each cell. The greater the variability over the cell, the greater the error will be induced through the use of an average value. The cell size in this study was based on the fine resolution of the data set (5m) to reduce uncertainty caused by spatial averaging.

Moreover, a mask map that identifies the focused area for delineation to reduce the processing time and a burn-in river map which helps to accurately predict the location of the stream network was also the input. Eventually, the Lam Takhong river basin was divided into 75 sub-basins, and point sources were added (Figure 3.5). Two out of 75 outlets of sub-basins were added at the locations of two gauging stations (M89 and M164) which were then used for model calibration.

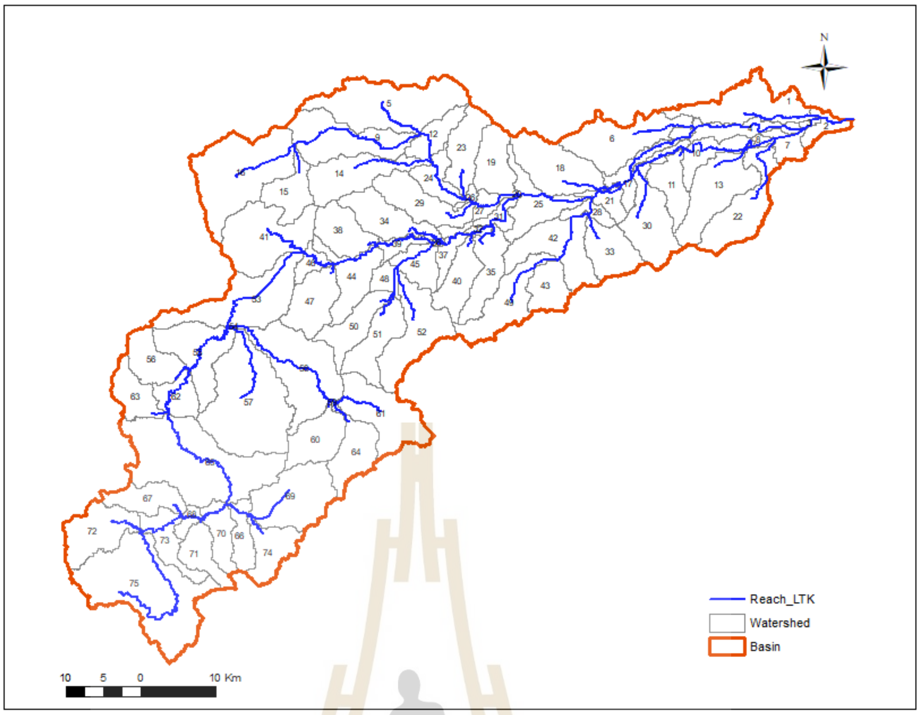


Figure 3.5 Stream network and subbasin outlet of Lam Takhong basin

3.2.2 HRU analysis

The Hydrological Response Units (HRUs) in SWAT were defined based on soil type, land use, and slope classifications following Figure 3.6.

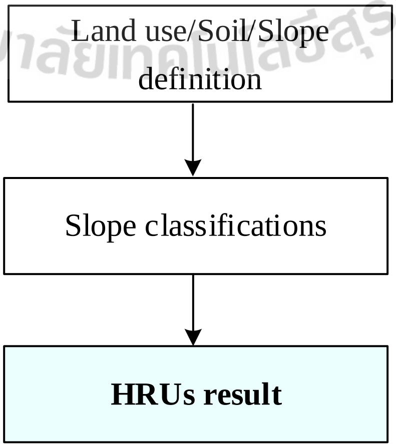


Figure 3.6 Diagram of HRUs analysis in Lam Takhong Watershed

3.2.2.1 Hydrology Soil Group (HSG) data

The available data for the soil profile (LDD, 2015) in the Lam Takhong river basin were divided into four hydrologic groups based on infiltration characteristics of the soils including group A (high infiltration rate), group B (moderate infiltration rate), group C (slow infiltration rate) and group D (very slow infiltration rate). The soil in each group was classified into different soil classes based on the percentage of clay, silt, and sand. Soil characteristics and hydraulic parameters of each soil type in each group were estimated by averaging all the values of the same soil type in the same group.

The important properties of soil data including soil texture, permeability, structure, porosity, and the number of existing nutrients were related to pollution study. Soil data was obtained at a scale of 1:4,000 from LDD. As a result, soil series with soil texture class and quantitative particle size distribution analysis by LDD were transformed into hydrologic soil groups (Figure 3.7). Various soil series present, including Khao Yai, Kabinburi, Khorat, and Lam Narai series. Soil drainage is medium to good. The soil layers alternate between shallow and deep areas with universally moderate fertility (Pongpetch et al. 2015).

3.2.2.2 Land use data

The land use map divided the area into nine types of land use: urbanization, rice, corn, sugar cane, cassava, agriculture, forest, water, and miscellaneous. According to Land Development Department (2015), land use in Lam Takhong River basin was dominated by agricultural land (55.73%), followed by forested areas (21.28%) and urban areas (11.81%).

Land use data are required for pollution assessment because they provide the activities on land that generate the pollutants. The digital land use data at scale 1:4,000 were obtained from the Land Development Department in the year 2015 (Figure 3.8).

3.2.2.3 Slope classifications

The number of slope classes was divided into three class including Class 1 (0-10), class 2 (10-20), and class 3 as 20-9999 shown in Figure 3.9.

3.2.2.4 Calculating HRUs

After the watershed was divided into subbasins, SWAT will carry out slope classification in each subbasin. Land use, soil, and slope layer overlap will be subdivided into HRUs (Figure 3.10).

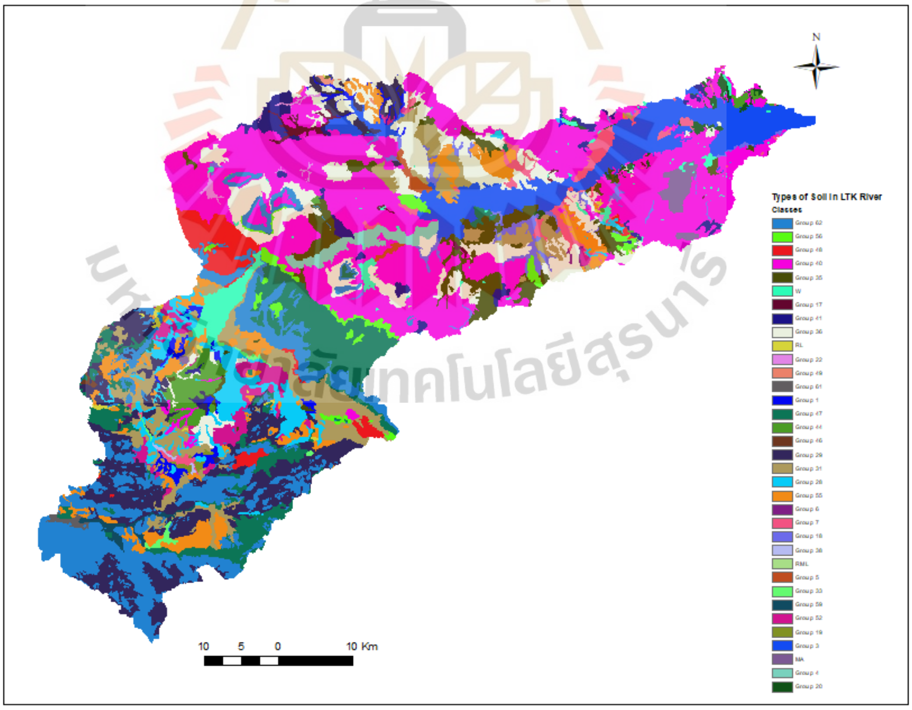


Figure 3.7 Soil data of Lam Takhong basin

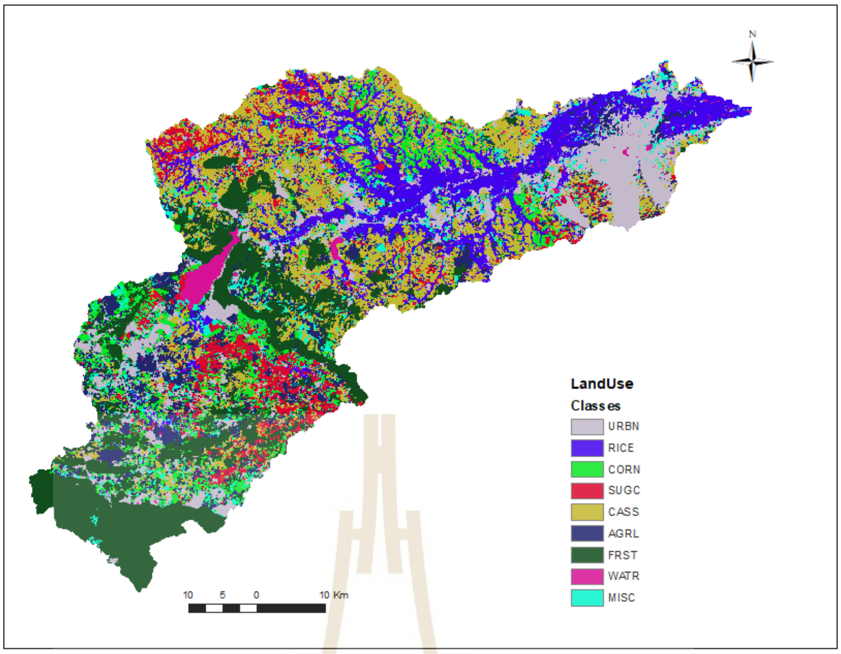


Figure 3.8 The land use of Lam Takhong basin

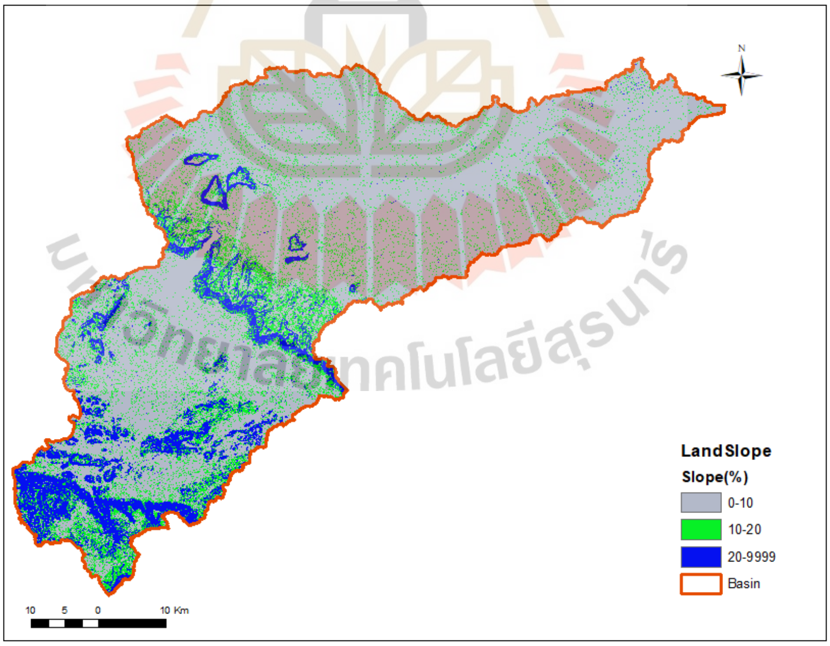


Figure 3.9 Landslope of Lam Takhong basin

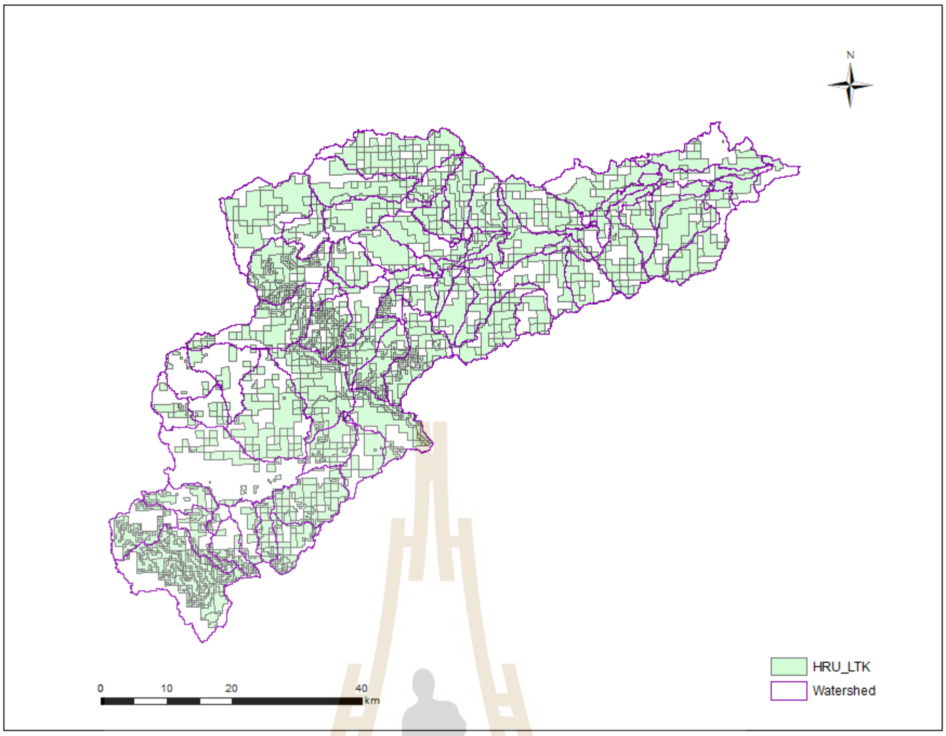


Figure 3.10 HRUs in Lam Takhong watershed

3.2.3 Input data

Meteorological data presents the input of climate data into the SWAT model. SWAT only obtains climate data from stations. Therefore, these available data were input to SWAT by creating rainfall stations and temperature stations located at the centroid of each precipitation or temperature station. Solar radiation, relative humidity, and wind speed data were taken from a single weather station for the whole area.

The main input data for simulating the hydrological processes in Arc SWAT were the base map data, meteorological data, and observed data (Table 3.1). Climate data input consisted of temperature, relative humidity, wind speed, solar radiation, rainfall, location of rainfall station, and weather gauging station as shown in Figure 3.11.

Table 3.1 Model input data sources for the Lam Takhong basin

Data type	Scale	Source	Detail
Topography (DEM)	5mx5m	The Land Development Department	Elevation, slope
Soil	1:4,000	The Land Development Department	Spatial soil variability Soil types and properties
Land use	1:4,000	The Land Development Department	Land cover classification and spatial representation
Weather stations	6 Rainfall 2 Meteorology	Thai Meteorological Department	Daily precipitation Temperature (max, min) Relative humidity Wind speed Solar radiation
River discharge	2 points	Royal Irrigation and Meteorology department The Hydrology and Water Management Center for Lower Northeastern Region, Nakhon Ratchasima	M89 and M164 stations (m^3/day)

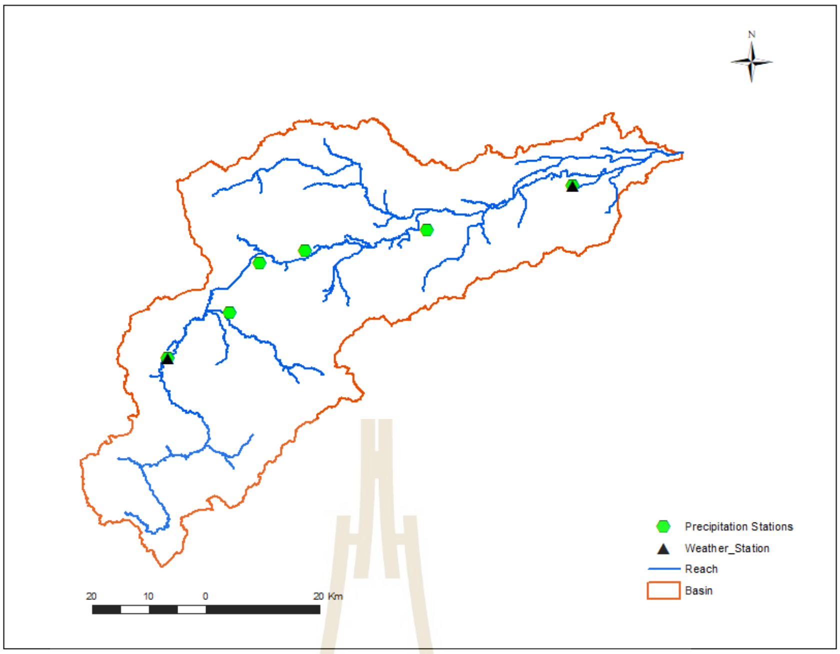


Figure 3.11 Precipitation and weather gauging station of Lam Takhong basin

For improving accuracy, data obtained from stations must capture the variability of rainfall in the watershed. In this study, rainfall data were gathered from rain gauges located within the watershed by the Thai Meteorology Department. Moreover, the humidity data, temperature, wind, and solar were also collected from a meteorological station.

3.2.4 SWAT model calibration and validation

Calibration was performed manually and consists of changing model input parameter values to produce simulated values that were within a certain range of the measured data. An iterative approach was used for manual calibration involving the following steps: (1) perform the simulation; (2) compare measured and simulated values; (3) assess if reasonable results have been obtained; (4) if not, adjust input parameters based on expert judgment and other guidance within reasonable parameter value ranges; (5) repeat the process until it is determined that the best results have been obtained.

The sensitive parameters from the sensitivity analysis results were considered in the calibration process. Moreover, the following additional parameters relating to tile drainage simulation were included in the calibration: *tdrain* and *gdrain* and *dep_imp*. Table 3.2 shows the list of calibrated parameters and their default.

Table 3.2 List of calibrated flow parameters and their default

No	Parameters	Description	Process	Default value
1	ESCO	Soil evaporation compensation factor (-)	Evapotranspiration	0.95
2	EPCO	Plant water uptake compensation factor (-)	Evapotranspiration	1.0
3	CN2	SCS runoff curve number for moisture condition II	Surface runoff	0
4	SURLAG	Surface runoff lag time (days)	Surface runoff	4
5	ALPHA_BF	Baseflow alpha factor (days)	Groundwater flow	0.048
6	CH_N2	Manning's n value for main channel (-)	Channel routing	0.014
7	CH_K2	Effective hydraulic conductivity (mm/hr)	Channel routing	0
8	SOL_AWC	Available water capacity of the soil layer (mm/mm)	Percolation	0
9	SOL_Z	Depth from soil surface to bottom of soil layers	Percolation	0
10	DEP_IMP	Depth to impervious layer for modelling perched water tables (mm)	Tile drainage	6,000
11	TDRAIN	Time to drain soil to field capacity (hrs)	Tile drainage	0
12	GDRAIN	Drain tile lag time (hrs)	Tile drainage	0

Many parameters impacted multiple processes. The CN parameter directly impacts surface runoff; however, as surface runoff changes, all components of hydrology balance change. It is evident from table Table 3.2 that hydrology is calibrated in most studies, with CN2, AWC, ESCO, and SURLAG used routinely. The baseflow process from the station of outlet sub-basin was calibrated with the baseflow recession parameters.

However, when the number of parameters used in the manual calibration was large, especially for complex hydrologic models, manual calibration became labor-intensive and automated calibration methods were preferred. Calibration of SWAT can be performed autocalibration using SWAT-CUP. Automatic calibration and uncertainty analysis capability were directly incorporated in SWAT2012 via the SWAT-CUP software developed by Eawag (2015) and R^2 (Krause, Boyle, and Bäse 2005). SWAT is a comprehensive model that simulates process interactions and many parameters will impact multiple processes. Nowadays, autocalibration is usually conducted for the calibration becomes easier and simpler.

SWAT-CUP provides a decision-making framework that incorporates a semi-automated approach (SUFI2) using both manual and automated calibration incorporating sensitivity and uncertainty analysis. Users can manually adjust parameters and ranges iteratively between autocalibration runs, and can also use the output from sensitivity and uncertainty analysis as moving between manual and autocalibration. Parameter sensitivity analysis helps focus the calibration, and uncertainty analysis is used to provide statistics for goodness-of-fit.

SWAT-CUP includes automated as well as semi-automatic procedures for model calibration. The following steps are suggested in a calibration exercise with the semi-automated program SUFI2:

(1) Develop initial or default SWAT input and prepare the input files for SWAT-CUP.

(2) Run the model with initial parameters and plot the simulated and observed variables at each gauging station for the entire period of record.

(3) Based on step 2, divide the entire period into calibration and validation periods while attempting to ensure that both periods have a similar number of wet and dry years and similar average water balances.

(4) Determine the most sensitive parameters for the observed values of interest. This information can usually be deduced from the literature.

(5) Assign an initial uncertain range (typically 20% to 30%) to each parameter globally, meaning scaling the parameters identically for each HRU.

(6) Run the SWAT-CUP-SUFI2.

(7) Perform global sensitivity analysis and view the results. At this stage, the P-factor and p-value t-statistic can be used to eliminate non-sensitive parameters from the calibration process.

(8) After observing model performance in step 6, regionalize the respective parameters.

3.2.4.1 Model Calibration

Calibration of SWAT was conducted following steps as shown in Figure 3.12.

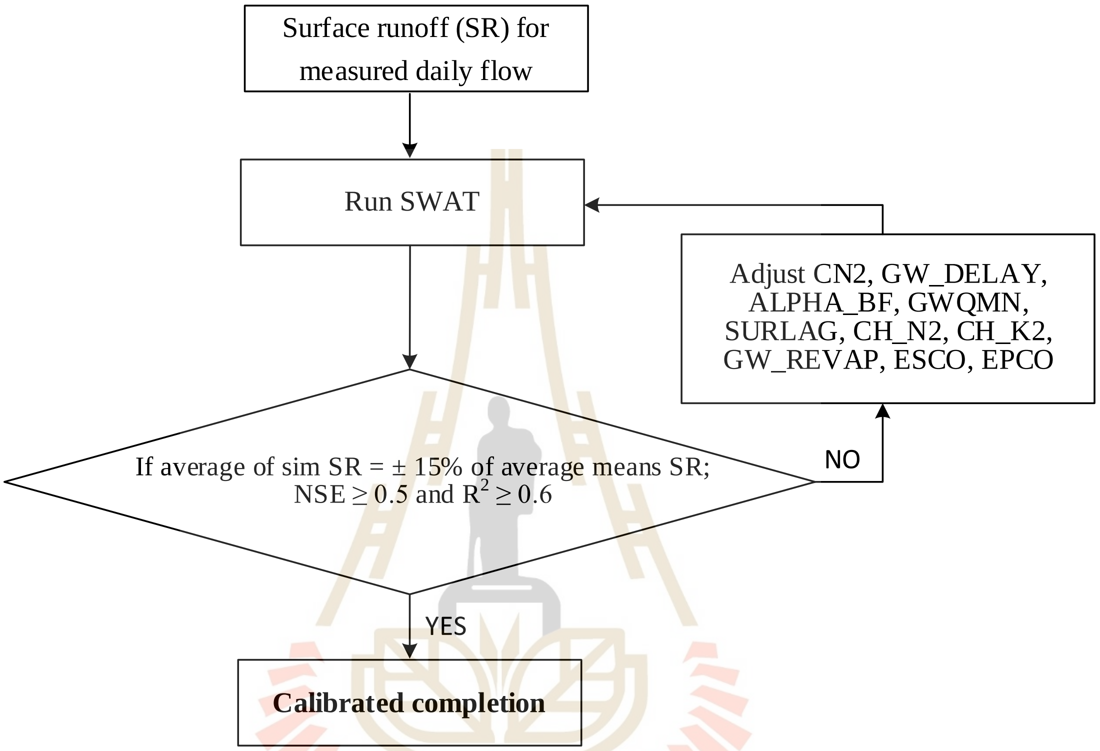


Figure 3.12 Calibration procedures

The SWAT model was run with a daily time-step in the 13-year period of 2002 to 2012. The first three years from 2002 to 2004 were used as a warming-up period. Calibration was carried out from 2005 to 2012. There were two gauging stations at which data for flow are available including M89 and M164 which correspond to outlets at M164 gauge. The downstream gauging station M164 was chosen as a calibrated station for flow. This station is located just downstream of the urban area, so it is affected by not only outflow from WWTPs and but also from urban areas.

M89 (Pak Chong district) and M164 (Mueang district) stations were selected to calibrated streamflow (Figure 3.13) due to:

- M89 station is located in the Upper Lam Takhong River basin which it is the last station before flowing into Lam Takhong reservoir. Therefore, this station is an exponent of flow at the Upper Lam Takhong River basin above Lam Takhong reservoir.
- M164 station is located in Lower Lam Takhong River basin which it is the last station before flowing into Moon watershed. Therefore, this station is representative of flow in the Lower Takhong River Basin, above the Moon basin.
- M89 and M164 are complete of flow data in the same period.

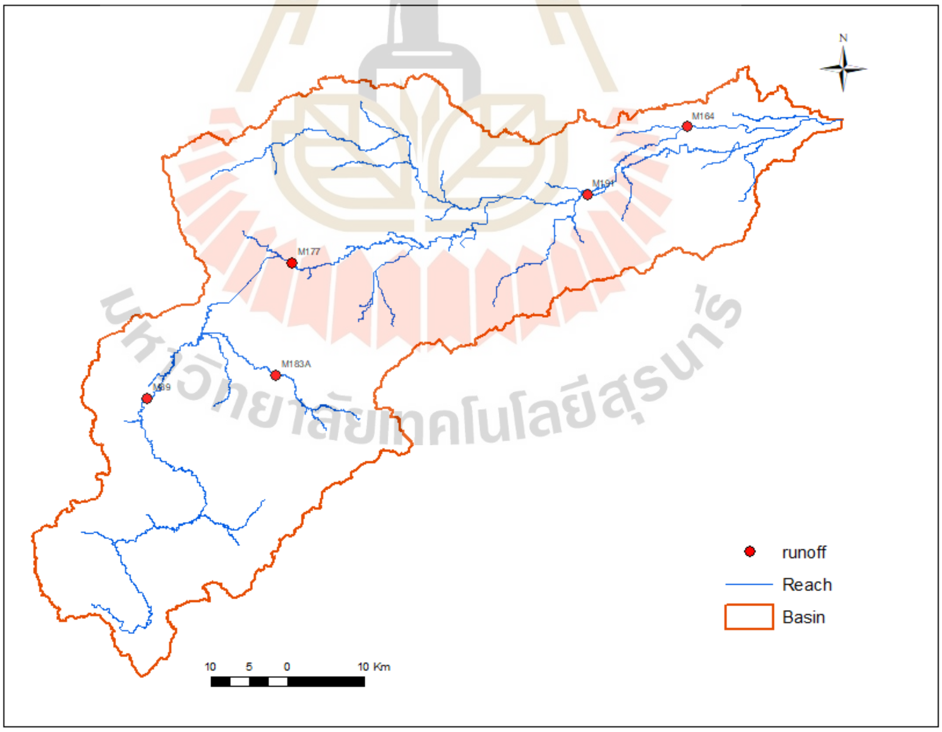


Figure 3.13 Gauging stations in Lam Takhong River basin.

Model calibration greatly improved the accuracy of a model. Streamflow was the first output calibrated and surface runoff was calibrated until average measured and simulated surface runoff was within 15 percent and daily NES > 0.5 and $R^2 > 0.6$.

3.2.4.2 Model Validation

Model validation is the process of rerunning the simulation, using a different time-series for input data, without changing any parameter values which may have been adjusting during calibration. Model validation can also occur during the same period as calibration, but at a different spatial location (Chekol et al., 2007).

The year 2013 to 2017 served as the validation period of the SWAT model by using observed streamflow at M89 (Pak Chong district) and M164 (Mueang district) stations in Lam Takhong River basin provided by the Hydrology and Water Management Center for Lower Northeastern Region, Nakhon Ratchasima, Thailand.

Besides, model validation and performance evaluation are usually done based on

- Graphical measures including scatter plots between measured and simulated values with the regression slope and intercept displayed, time series of simulated and measured values, cumulative distributions, duration curves, maps for field-scale and watershed-scale result comparison.
- Statistical measures including R-squared correlation (R^2), Nash-Sutcliffe efficiency (NSE, Nash and Sutcliffe, 1970), index of agreement (d,

d-index, Willmott et al., 2011), percent bias (PBIAS, Moriasi et al., 2007), a ratio of RMSE to observations standard deviation (RSR, Moriasi et al., 2007).

This study used R-squared correlation, Nash-Sutcliffe efficiency, and percent bias to evaluate the performance of the model.

3.2.5 Impact of land use change on hydrological data in 2027 and 2035

When the prediction of land use change in the future was conducted, the simulated scenarios were correspondingly run as shown in Figure 3.14.

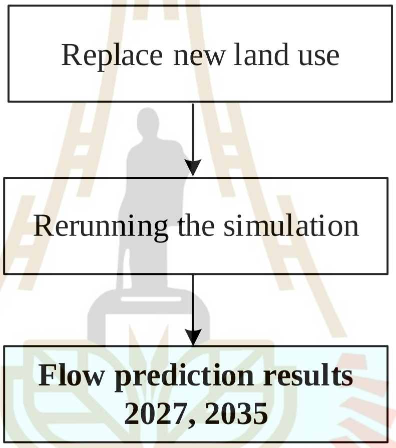


Figure 3.14 Diagram of flow prediction in 2027, 2035

SWAT calculated flow from diffuse sources of each subbasin in 2017 and 2035 based on land use change in the future. Land use change was predicted in 2027 and 2035 following in Figure 3.15 and 3.16.

The land use change data was imported in the ArcSWAT model. Then, the SWAT model was run to simulate impacts of land use change on net flow from subbasins. The flow predicted scenarios were used to evaluate the potential impact of land use change on surface water quality in 2027 and 2035.

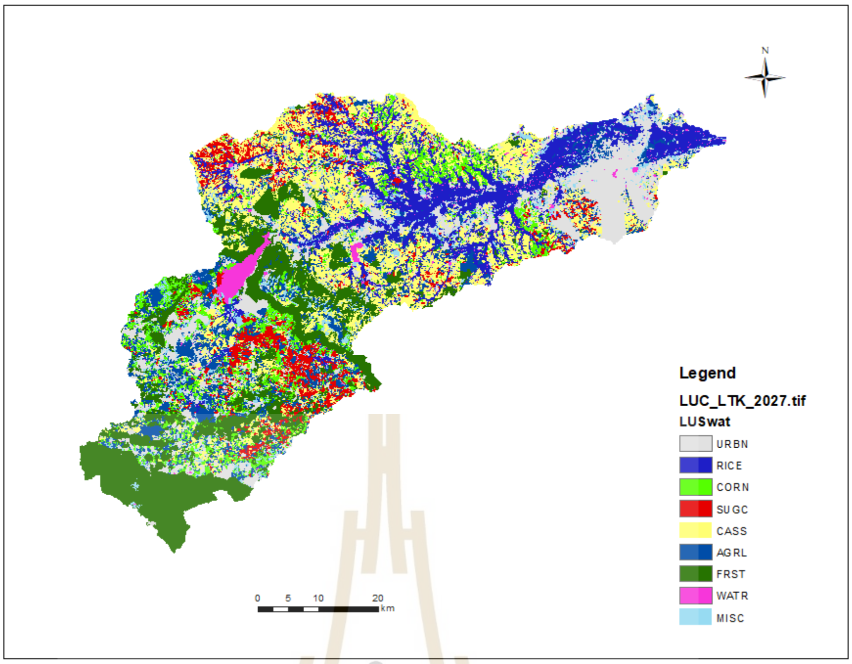


Figure 3.15 The land use of Lam Takhong basin in 2027

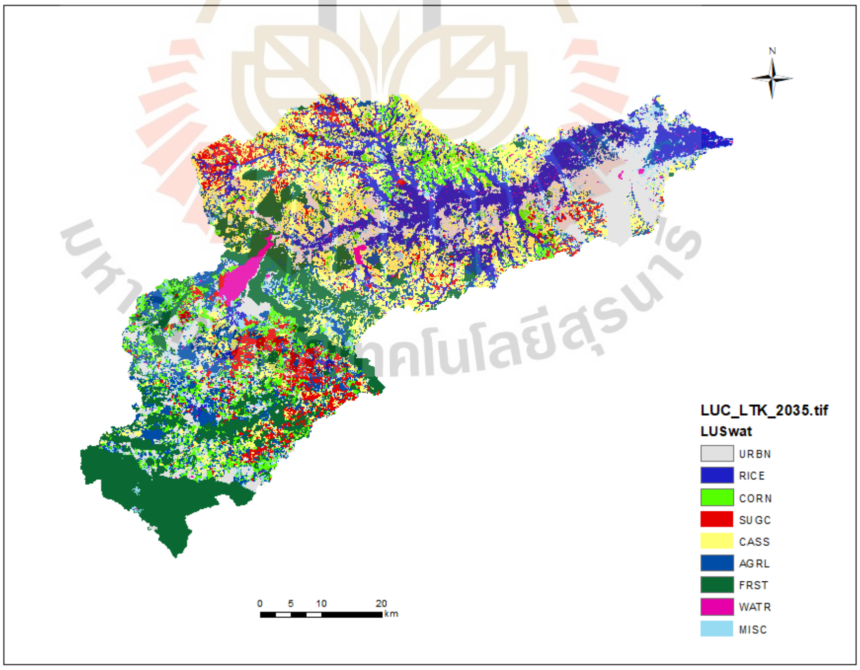


Figure 3.16 The land use of Lam Takhong basin in 2035

3.3 QUAL2K Model

To obtain the second, third, and fourth objectives of the study, the Qual2k model needed to be built up and performed following steps as shown in Figure 3.17.

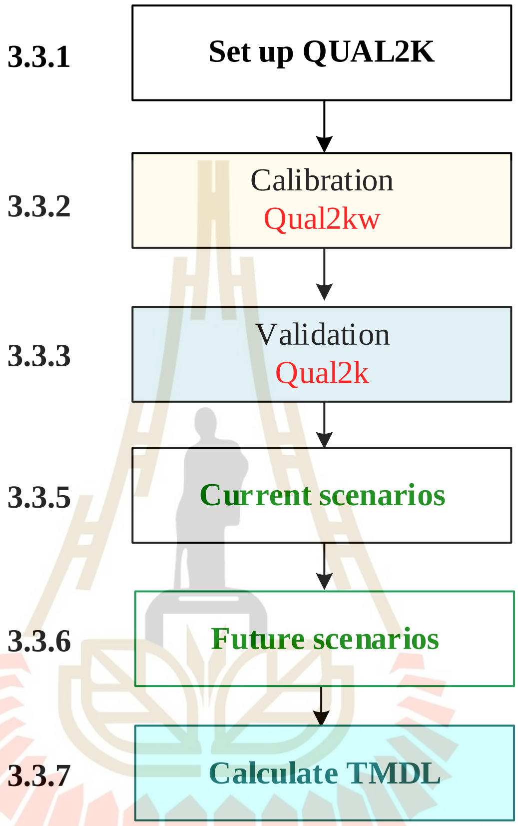


Figure 3.17 QUAL2K model set up diagram

Figure 3.17 illustrates the sequence of the steps of developing and transforming the Qual2K water quality model.

3.3.1 Set up Qual2k model

Firstly, the Qual2k model was set up and run before be calibrated by dividing the Lam Takhong river into segmentations and combining characteristical, meteorological, polluted sources, and water quality data as shown in the figure 3.18.

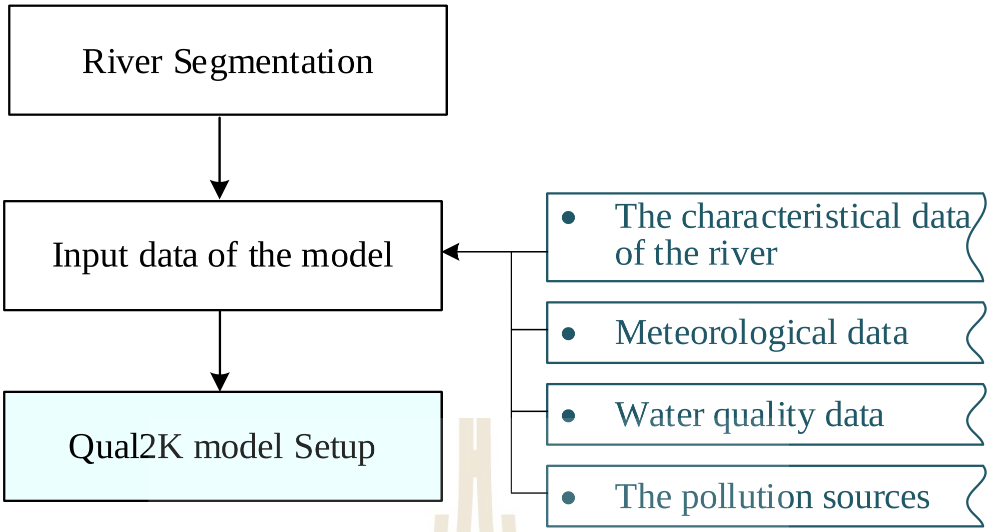


Figure 3.18 Diagram of Qual2k model set up

3.3.1.1 Lam Takhong River Segmentation

It was discussed earlier that applying the Qual2K model required that the river system be divided into several reaches and each reach segmented into equally spaced elements, based on the available data that obtained to comprise the river system and satisfy the Qual2K model requirements.

Subsequently, the river system was divided into 35 reaches that were numbered beginning with reach one at the headwater which is the outlet of Lam Takhong Dam, after which the numbering continued toward the downstream and was numbered consecutively following a sequencing scheme similar to that of the reaches as shown schematically in Figure also share here. The figure also shows the headwaters of the network. Each individual reach of the Lam Takhong river network was segmented into equally spaced elements of approximately 1 km length to satisfy the model requirements.

3.3.1.2 Input Data

There are two types of data that need to be collected including primary and secondary data. Primary data is the data collected first-hand from the original source, while secondary data is defined as the data collected indirectly from other sources. The methods applied for collecting primary data include surveys, direct measurements, and experiments, while secondary data is obtained from several sources such as literature, computerized or mathematical models, and information systems.

In the study, the primary data contains hydraulic data measurements from the Lam Takhong River as input data for the QUAL2K model. The secondary data for this research were gathered from various sources like the Regional Environmental Office 11, the Land Development Department, the Thai Meteorology Department, Lam Takhong Water Supply and Maintenance Project. The secondary data gathered consists of spatial information, such as Digital Elevation Model, a Lam Takhong river network map, a sub-watershed map, and land-use digital map from SWAT model, water quality monitoring data, sources of pollution and climatology data.

Primary Data

The hydraulic data plays an essential role in running the Qual2K model. This information includes flow rates at the headwater, the length of each reach, channels slope, cross-sections data, locations, and heights of the up and downstream for each reach and roughness coefficient values.

Secondary Data

The river network map and the sub-basin map for Lam Takhong River were obtained from the results of SWAT under a shapefile format. They are shown in Figure 3.5.

3.3.1.3 Model Setup

Qual2K requires several data spread on worksheets, and there are two worksheet types regarding input data in Qual2K, i.e. simulation data worksheets and calibration data worksheets. Simulation data worksheets are headwater, reach, point sources, and diffuse sources, while calibration data worksheets are hydraulic and water quality data. Table 3.3 shows the input data of the worksheets and their sources.

Table 3.3 Qual2K input data of the worksheets and their sources

No	Worksheet name	Data	source
1	Headwater	Q, Channel Slope, roughness ‘n’, Bottom width	Secondary data/ SWAT
		Elevation	DEM
		Water quality parameters	Water quality data
2	Reach	Location (Up and downstream of each reach), Downstream Long/Lat	Digital map
		Elevation (up and downstream)	DEM
		Channel Slope, roughness ‘n’, Bottom width	Secondary data
3	Diffuse sources	Location	SWAT model
		Inflow	SWAT model
		Water quality	Estimated
4	Point sources	Location	Digital map
		Inflow	Secondary data
		Water quality	Secondary data
5	Hydraulic data	Gauging stations locations	Digital map
		Q	Gauging station/ SWAT
6	Water quality data	Water quality stations locations	Digital map
		Water quality parameters	Water quality data

A. Headwater Data

The necessary headwater data for input into the Qual2K model is water quality parameters and hydraulic data. The model allows several water quality parameters to be input in accordance with data availability as well as the study objectives. The hydraulic data needed by Qual2K at the headwaters include elevation, discharge, cross-section (bottom width), channel slope, and the roughness coefficient. On the other hand, the water quality parameters were obtained from the water quality monitoring data Table 3.4.

Table 3.4 Headwater Boundary Data of Lam Takhong River in February 2019

Headwater Flow and Water Quality	Units	Value
Flow	m^3/sec	5.500
Temperature	C	28.70
Conductivity	uS/cm 25^0C	500.00
Dissolved Oxygen	mg/L	9.40
CBOD fast	mgO2/L	1.50
NH_4-Nitrogen	µgN/L	300.00
NO_3-Nitrogen	µgN/L	910.00
Organic Phosphorus	µgP/L	40.00
Inorganic Phosphorus (SRP)	µgP/L	50.00
Alkalinity	mgCaCO3/L	2555.00
pH		8.74

B. Reaches Data

Similar data are required for each reach with an addition of the number of elements as well as the location of up and downstream for each segmented reach in kilometers. These data were obtained from the digital spatial map, DEM, and gauging stations data. Table 3.5 illustrated information of reaches in the model and Figure 3.19 showed elevation of upstream and downstream in Lam Takhong River.

Table 3.5 Data of reaches in Lam Takhong River

Reach No	**Reach length** *(km)*	**Downstream**		**Upstream** *(km)*	**Downstream** *(km)*	**Element Number**
		Latitude	*Longitude*			
1	0.846	14.87	101.56	0.000	0.846	1
2	0.839	14.87	101.57	0.846	1.684	1
3	1.026	14.87	101.58	1.684	2.710	1
4	1.324	14.86	101.58	2.710	4.034	1
5	1.430	14.86	101.59	4.034	5.464	1
6	3.069	14.85	101.60	5.464	8.533	3
7	1.677	14.85	101.62	8.533	10.211	2
8	3.199	14.86	101.64	10.211	13.410	3
9	5.154	14.87	101.66	13.410	18.564	5
10	4.523	14.87	101.68	18.564	23.087	5
11	9.213	14.89	101.73	23.087	32.300	9
12	4.629	14.88	101.75	32.300	36.929	5
13	2.091	14.87	101.76	36.929	39.020	2
14	5.482	14.88	101.78	39.020	44.502	5
15	3.517	14.89	101.80	44.502	48.018	4
16	3.688	14.90	101.82	48.018	51.707	4
17	3.663	14.92	101.83	51.707	55.370	4
18	4.183	14.92	101.86	55.370	59.553	4
19	3.709	14.93	101.88	59.553	63.262	4
20	3.102	14.94	101.89	63.262	66.364	3
21	2.704	14.93	101.91	66.364	69.068	3
22	3.115	14.93	101.93	69.068	72.184	3
23	3.728	14.93	101.95	72.184	75.911	4
24	3.040	14.94	101.97	75.911	78.952	3
25	3.369	14.95	101.98	78.952	82.320	3
26	1.233	14.95	101.99	82.320	83.553	1
27	6.161	14.97	101.01	83.553	89.715	6
28	4.458	14.98	102.04	89.715	94.172	4
29	3.964	14.98	102.06	94.172	98.136	4
30	6.211	14.98	102.09	98.136	104.347	6
31	3.070	14.98	102.11	104.347	107.417	3
32	4.871	14.99	102.15	107.417	112.289	5
33	4.917	15.00	102.20	112.289	117.206	5
34	2.876	15.01	102.22	117.206	120.082	3
35	1.983	15.01	102.23	120.082	122.065	2

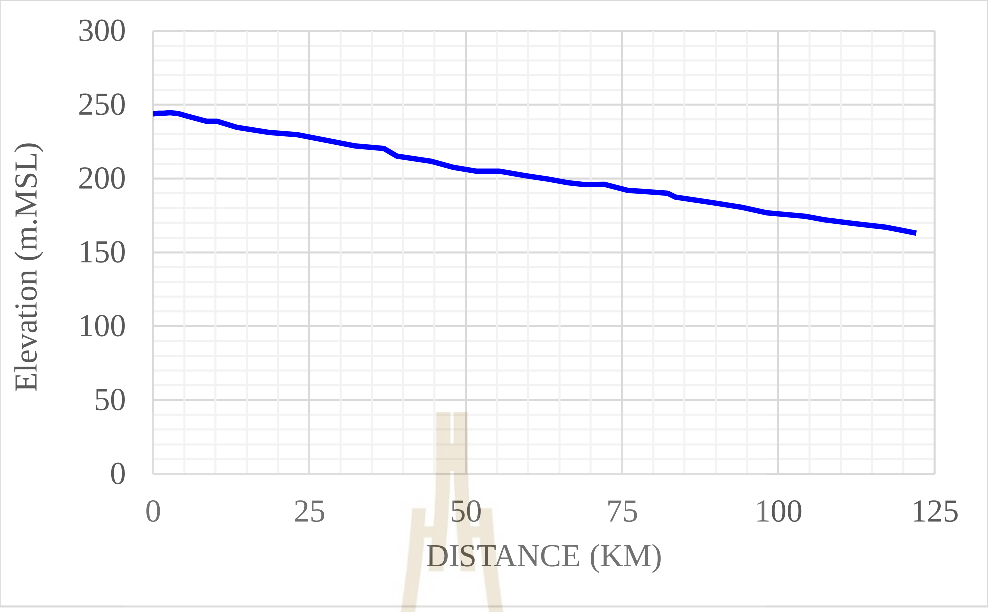


Figure 3.19 Elevation of Lam Takhong River

C. Diffuse Sources Data

The diffuse sources in Lam Takhong River include urban areas and agricultural land. Input data from these nonpoint sources in Lam Takhong watershed includes the location of up and downstream, flow from subbasin, BOD discharge, TN, TP, NH4-N, Organic Nitrogen. Flow and pollutant discharge was determined from SWAT, and these data was described in detail in the model calibration and validation section.

D. Point Sources Data

There are several point sources of wastewater discharge into the Lam Takhong river discharging the wastewater from industries, pig farms, industrial factories, etc, their location was shown in Figure 3.20. The point source data was collected from the Regional Environmental Office 11.

Wastewater treatment plants (WWTPs) are treatment facilities that receive wastewater from households, commercial sewage, and industrial areas via sewerage pipe systems. These facilities may be oxidation ponds, activated sludge, trickling filters, aerated lagoons, and rotating biological contactors.

The average daily flow design of WWTP depends on the daily wastewater produced by people in community. It was assumed according to the effluent standard for Wastewater treatment systems into the water bodies in Thailand (Table 3.6) Several parameters were chosen to determine the standard type for a cleaner and safer environment that improves the living conditions of Thai. However, the most important measured parameter is the Biochemical Oxygen Demand (BOD).

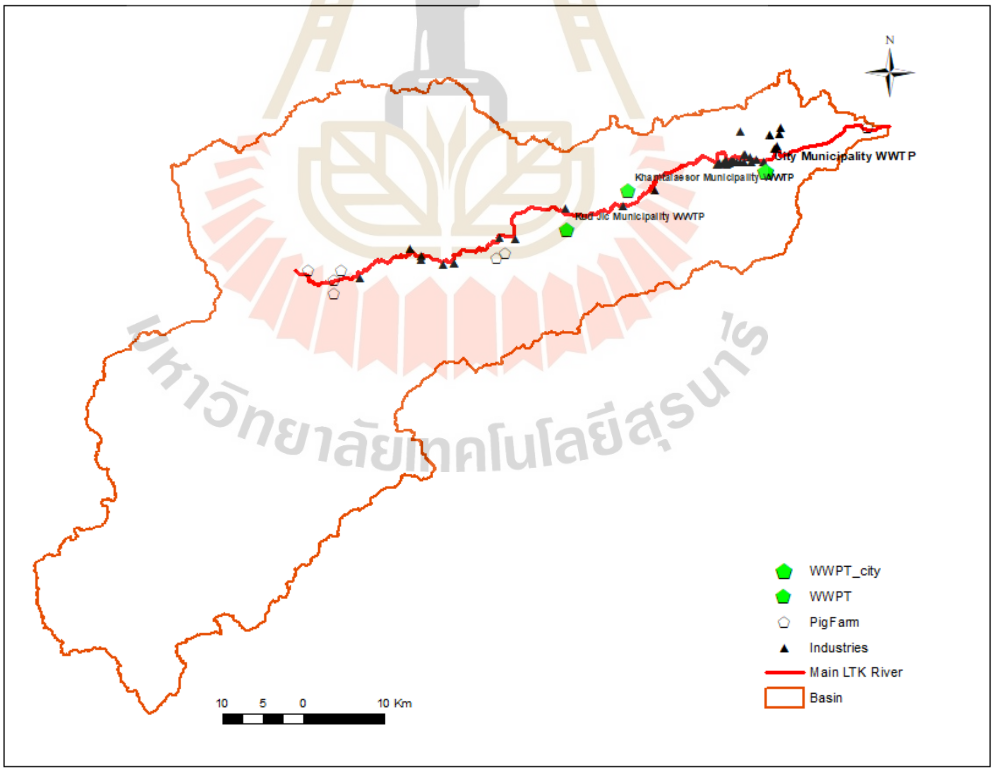


Figure 3.20 Point sources along main Lam Takhong River

Table 3.6 The effluent standard for sanitary wastewater treatment systems (the Ministry of Natural Resources and Environment 2010)

Parameter	Unit	Standard
pH value	-	5.5-9.0
BOD5	(mg/l)	Not more than 20
Total Phosphorus	(mg-P/l)	Not more than 2
Total Nitrogen	(mg-N/l)	Not more than 20

Concerning the point sources, the model defines the location as a single point based on its distance from the reach's downstream. Thus, GIS tools were used to determine the locations of the point sources. The inflow data for each point source was obtained from the collection point source data.

Table 3.7 Point sources input data along Lam Takhong River

No.	Point source	Location (km)	Q (m^3/s)	BOD (mg/L)
1	3-4(3)-1/23นม	95.65	0.0052	20
2	2-4(3)-4/29นม	100.48	0.0052	20
3	จ2-4(4)-1/36นม	100.48	0.0052	20
4	3-9(1)-51/15นม	31.324	0.0026	17
5	จ2-9(1)-338/32นม	61.00	0.0026	17
6	จ2-9(1)-2/41นม	77.14	0.0026	17
7	จ2-10(2)-1/42นม	102.04	0.0010	14
8	จ2-10(3)-3/47นม	94.73	0.0010	14
9	3-12(11)-2/32นม	94.725	0.0001	57
10	3-13(2)-2/17นม	95.65	0.0001	17
11	จ3-14-1/46นม	36.86	0.0003	20
12	ศ3-14-2/35นม	31.324	0.0003	20
13	ศ3-14-1/36นม	102.043	0.0003	20
14	3-14-1/31นม	94.725	0.0003	20

Table 3.7 Point sources input data along Lam Takhong River (Cont'd)

No.	Point source	Location (km)	Q (m^3/s)	BOD (mg/L)
15	3-14-7/15นม	94.725	0.0003	20
16	3-14-3/30นม	94.725	0.0003	20
17	3-14-3/47นม	94.725	0.0003	20
18	จ2-15(1)-1/42นม	95.65	0.0004	22
19	จ2-20(1)-1/36นม	91.47	0.0065	78
20	จ3-32(1)-1/44นม	104.49	0.0000	20
21	3-34(1)-2/23นม	47.70	0.0000	20
22	จ2-39-8/59นม	104.49	0.0000	20
23	จ2-41(1)-1/39นม	98.52	0.0003	20
24	จ3-64(13)-95/60นม	16.518	0.0003	20
25	จ2-65-20/37นม	36.855	0.0003	20
26	3-66-1/24นม	29.688	0.0003	20
27	3-95(1)-8/29นม	71.266	0.0003	20
28	3-95(1)-9/31นม	91.474	0.0003	20
29	3-95(1)-1/27นม	91.474	0.0003	20
30	3-95(1)-16/34นม	91.474	0.0003	20
31	3-95(1)-21/34นม	94.725	0.0003	20
32	จ3-95(1)-1/37นม	94.725	0.0003	20
33	จ3-95(1)-13/46นม	94.725	0.0003	20
34	จ3-95(1)-42/57นม	94.725	0.0003	20
35	จ3-95(1)-229/48นม	95.65	0.0003	20
36	3-95(1)-13/32นม	95.65	0.0003	20
37	3-95(1)-2/33นม	100.477	0.0003	20
38	3-95(1)-4/28นม	95.65	0.0003	20
39	จ3-95(1)-113/47นม	95.65	0.0003	20
40	จ3-95(1)-144/47นม	95.65	0.0003	20
41	จ3-95(1)-15/35นม	95.65	0.0003	20

Table 3.7 Point sources input data along Lam Takhong River (Cont'd)

No.	Point source	Location (km)	Q (m^3/s)	BOD (mg/L)
42	3-95(1)-1/19นม	98.522	0.0003	20
43	จ3-95(1)-226/54นม	95.65	0.0003	20
44	จ3-95(1)-46/56นม	95.65	0.0003	20
45	3-95(1)-19/34นม	95.65	0.0003	20
46	จ3-95(1)-93/59นม	98.522	0.0003	20
47	3-95(1)-42/33นม	98.522	0.0003	20
48	จ3-95(3)-1/42นม	94.725	0.0003	20
49	3-105-118/60นม	35.831	0.0003	20
50	จ3-105-54/50นม	50.289	0.0003	20
51	Pig Farm 1	14.933	0.0001	60
52	Pig Farm 2 (Buakhao)	13.348	0.0006	60
53	Pig Farm 3 (Buakhao Agriculture)	9.345	0.0007	60
54	Pig Farm 4 (Chutima Farm)	118.606	0.0004	60
55	City Municipality of Korat WWTP	105	0.81019	20
56	Khamtalaesor Municipality WWTP	80	0.00058	20
57	Kud Jic Municipality WWTP	70	0.00579	20

E. Hydraulic Data

The above information represents the data used for hydraulic calibration. The gauging station locations were measured and inserted in this worksheet. Furthermore, the discharge for each station was inserted based on the gauging stations data.

A gauging station is a place on a water body where observations are made and hydraulic data is obtained. Such stations are surface water monitoring infrastructures and they are located near streams. Several sorts of information can be gained at these stations, such as water discharge, height, and some water quality parameters. For the study area, three gauging stations including M177, M191, and M164 have been set out along the mainstream of the Lam Takhong River (Figure 3.13).

F. Water Quality Data

The water quality monitoring data also was collected from the Regional Environmental Office 11, the location and information of monitoring stations are shown in Table 3.8 and Figure 3.21. The parameters for measurements are pH, temperature, conductivity, dissolved oxygen, BOD, TN, TP.

Table 3.8 Water quality monitoring stations in the Lam Takhong River

Station No.	Name of Stations	Distance from downstream	Location
2	LT03	30.46	Ban Kutchan Bridge, Mittraphap Subdistrict, Sikhio District
3	LTK03	49.86	Makham Tao Dam, Ban Mai Sub-district, Mueang District
4	LTK04	82.94	Lam Ta Khong Bridge Kham Thale So, Kham Thale So Subdistrict, Kham Thale So District
5	LTK02	107.31	Lam Ta Kong Bridge, Ban Tha Krasang, Hua Thale Subdistrict, Mueang District
6	LT02	108.00	Samakkhi Temple Community Bridge, Nai Mueang Subdistrict, Mueang District
7	LTK01	118.00	Hair Dam, Phra Phut Subdistrict, Chalerm Phrakiat District
8	LT01	119.00	Lam Ta Khong River Mouth, Yongyang Co., Pha Nao Subdistrict, Mueang District

The water quality data was collected in February and November in 2019 from fourteen locations which Regional Environment Office 11 are monitoring DO, BOD, and nutrient concentrations in the Lam Takhong River basin. The location of water quality was shown in Figure 3.22.

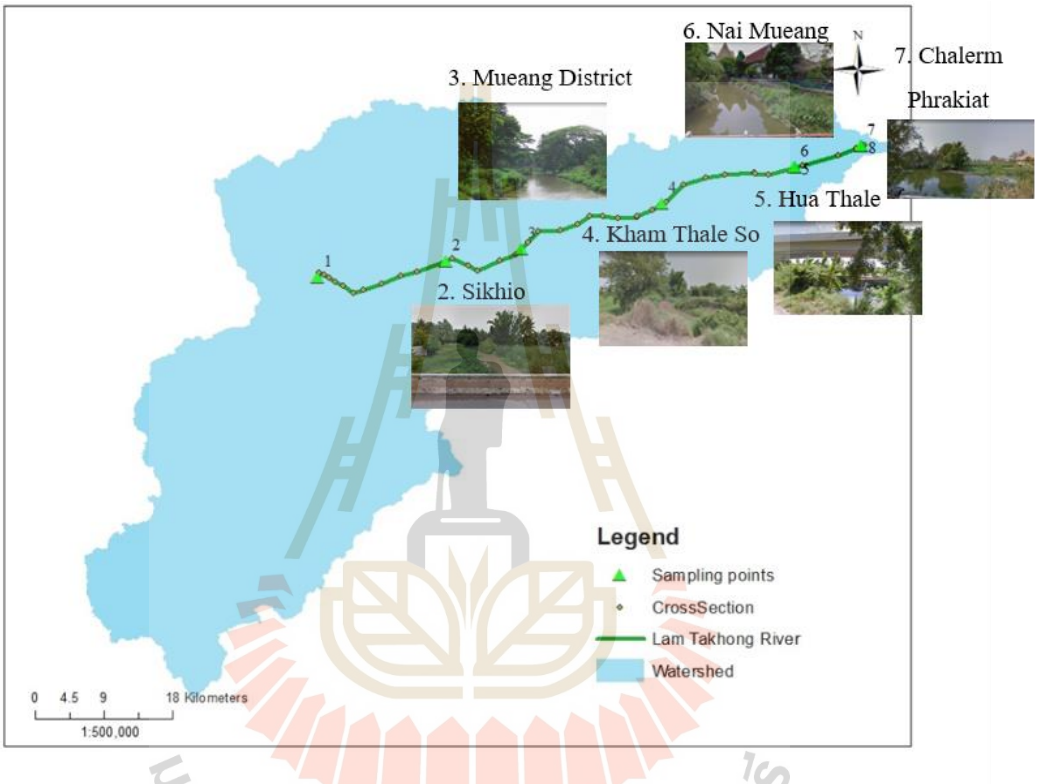


Figure 3.21 Cross-section and Sampling sites in Lam Takhong river

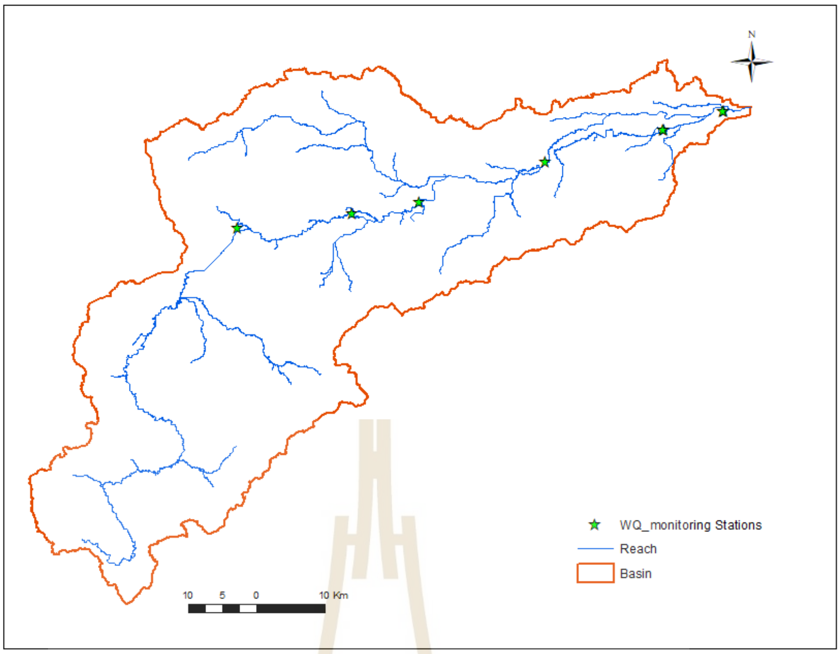


Figure 3.22 Observed points of Lam Takhong River

3.3.2 Qual2k model calibration

Model calibration is a critical step in achieving good model performance as shown in Figure 3.23. Model calibration is defined as the process of tuning the parameter values to attain optimal agreement between the simulated and observed data. In other words, model calibration is the method of justifying the input data of the parameters until the model's output matches the observed data set (Mohamed, 2008). And the value estimation of different parameters and constants in the model structure is involved in this step.

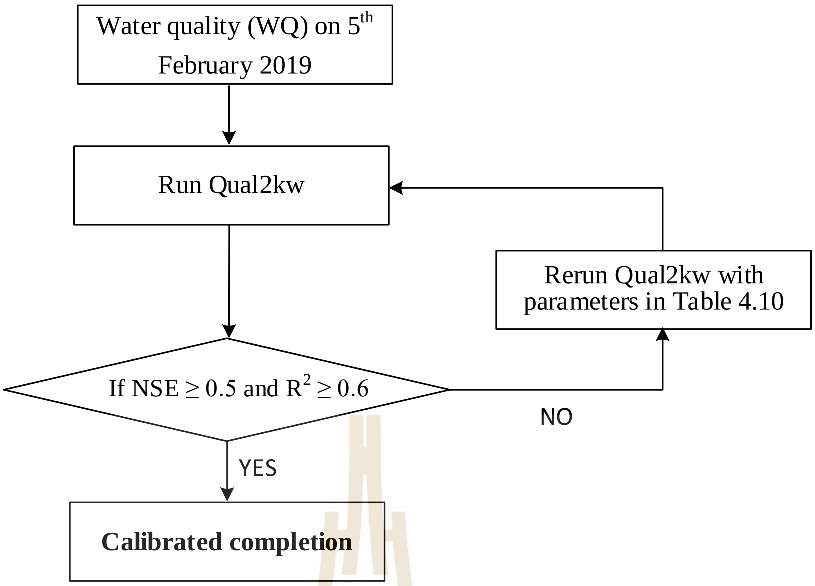


Figure 3.23 Diagram of Qual2k model calibration

As mentioned in SWAT calibration, Qual2k model calibration should be supplied with the numerical parameter values as well as the initial condition of the state variables and boundary conditions. The process of parameter justification can be done automatically, by searching for an optimal value of a given criterion.

In this study, two model calibration stages have been done, i.e. hydraulic and water quality parameter calibration. Water discharge was chosen for hydraulic calibration, while the DO and BOD parameters were selected for water quality calibration. The calibration was done using average data in February 2019. Diffuse sources discharge and water quality data are used to calibrate qual2k model shown in Table 3.9 and Table 3.10

- The nonpoint sources data in Lam Takhong river include urban areas and agricultural activities, regarding inflow and pollutant discharge is determined from SWAT model.

Table 3.9 Discharge data from urban areas in Lam Takhong watershed for calibration of Qual2k model in February 2019

Up (km)	Down (km)	Q (m^3/s)	BOD (mg/L)	TN (µg/L)	TP (µg/L)	NH_4-N (µg/L)	OrgN (µg/L)
0.00	15.91	0.470	0.096	329.13	10.62	286.66	42.47
15.91	31.32	0.428	0.080	277.14	8.94	241.38	35.76
31.32	43.19	0.148	0.104	359.16	11.59	312.81	46.34
43.19	51.25	1.074	0.079	273.43	8.82	238.15	35.28
51.25	63.63	0.032	0.549	1890.82	60.99	1646.84	243.98
63.63	69.60	0.336	0.145	499.96	16.13	435.45	64.51
69.60	85.56	0.221	0.460	1584.64	51.12	1380.17	204.47
85.56	101.28	0.075	2.614	9003.76	290.44	7841.98	1161.78
101.28	109.31	0.195	0.670	2306.44	74.40	2008.83	297.60
109.31	120.00	0.061	1.053	3626.53	116.98	3158.59	467.94

- Water quality data used for water quality calibration are represented in this table. The water quality monitoring station locations were collected from REO11.

Table 3.10 Water quality in Lam Takhong River in 5th February 2019

Distance (Km)	Temp (ºC)	DO (mg/L)	BOD (mg/L)	NH_4-N (µgN/L)	NO_3+NO_2 (µg/L)	pH	Total N (µg/L)	Total P (µgP/L)
30.5	28.2	-	1.9	100	2600	7.87	-	60
35.0	28.0	7.00	-	200	1010	8.56	1210	120
49.9	28.0	-	1.1	-	610	7.79	-	100
82.9	24.8	7.24	1.0	100	710	8.80	810	90
107.3	28.0	4.52	5.9	4000	810	8.07	4810	1620
108.0	26.9	4.06	5.7	4300	710	0.77	5010	610
118.0	29.6	7.64	2.8	-	-	7.91	6610	1360

3.3.3 Qual2k model validation

On the other hand, model validation entails assessing the degree of reliability of the calibrated model using one or more independent data sets, but not the same data that is utilized for model calibration.

Qual2k model was validated by using observed water quality at six locations in Lam Takhong river provided by the pollution control department, Regional Environment Office 11, and the Hydrology and Water Management Center for Lower Northeastern Region, Nakhon Ratchasima, Thailand. Similarly, diffuse sources discharge and water quality data were used to validate the model in November 2019 shown in Table 3.11 and Table 3.12.

3.3.4 Performance measures and evaluation criteria of model

Satisfactory for monthly flow simulations if $R^2 > 0.60$, NSE > 0.50, and PBIAS ≤ ±15% for watershed-scale models can be judged for model performance as recommended by Moriasi et al. (2015). The evaluation criteria of the model are shown in Table 3.13.

Table 3.11 Discharge data from urban areas in Lam Takhong watershed for validation of Qual2k model in November 2019

Up (km)	Down (km)	Q (m^3/s)	BOD (mg/L)	TN (µg/L)	TP (µg/L)	NH_4-N (µg/L)	OrgN (µg/L)
0.00	15.91	3.218	0.014	48.041	1.550	41.842	6.199
15.91	31.32	2.885	0.012	41.157	1.328	35.847	5.311
31.32	43.19	0.959	0.016	55.602	1.794	48.427	7.174
43.19	51.25	6.896	0.012	42.567	1.373	37.075	5.493
51.25	63.63	0.278	0.062	214.692	6.926	186.989	27.702
63.63	69.60	2.175	0.022	77.312	2.494	67.337	9.976
69.60	85.56	1.622	0.063	215.511	6.952	187.703	27.808
85.56	101.28	0.665	0.296	1017.976	32.838	886.625	131.352
101.28	109.31	1.484	0.088	303.455	9.789	264.299	39.155
109.31	120.00	0.538	0.120	413.703	13.345	360.322	53.381

Table 3.12 Water quality in Lam Takhong River in 28 November 2019

Distance (Km)	Temp (°C)	DO (mg/L)	BOD (mg/L)	NH_4-N (µgN/L)	NO_3^-+NO_2^- (µg/L)	pH	Total N (µg/L)	Total P (µgP/L)
30.5	25.58	4.98	1.9	0	1110.00	9.60	1110	60
35.0	25.30	5.47	-	600	3050.00	9.20	3650	280
49.9	26.40	7.57	1.1	1000	710.00	8.80	710	110
82.9	26.50	-	1.0	100	2310.00	9.00	2410	120
107.3	25.90	4.94	5.9	10600	4420.00	8.20	15020	1840
108.0	25.80	-	5.7	10900	4920.00	8.70	15820	1240
118.0	27.90	6.60	-	9300	4610.00	8.10	-	-
119.0	28.30	6.92	2.8	9500	4950.00	8.10	-	-

Table 3.13 Equations, ranges, optimal values, and advantages and disadvantages for statistical performance measures in the Moriasi et al. (2015) special collection (*O* and *P* are observed and predicted values, respectively).

Statistic	Equation	Range	Optimal value	Advantages	Disadvantages
R^2	$\left[\frac{\sum_{i=1}^{n}(O_i-\bar{O})(P_i-\bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\bar{P})^2}}\right]^2$	0 - 1	1	R^2 and r are widely used in hydrological modeling studies, thus serving as a benchmark for performance evaluation.	R^2 and r are oversensitive to high extreme values and insensitive to additive and proportional differences between model predictions and measured data
NSE	$1-\frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2}$	-∞; 1	1	(1) a quantitative measure; (2) good for use with continuous long-term simulations; (3) robust and can be used to evaluate model performance; (4) commonly used	NSE cannot help identify model bias and cannot be used to identify differences in timing and magnitude of peak flows and shape of recession curves; it cannot be used for single-event simulations.
PBIAS	$\frac{\sum_{i=1}^{n}O_i-P_i}{\sum_{i=1}^{n}O_i}\times 100$	-∞; ∞	0	(1) can be used to determine how well the model simulates the average magnitudes; (2) is useful for continuous long-term simulations; (3) is robust and commonly used; (4) can identify average model simulation bias; (5) can incorporate measurement uncertainty	PBIAS cannot be used (1) for single-event simulations (2) to determine how well the model simulates residual variations and/or trends for the output response of interest.

3.3.5 Current simulation scenarios

After the Qual2k was successfully validated, current simulated scenarios were carried out with load change of polluted sources discharging into the Lam Takhong river. The results obtained from scenarios found out which polluted source affected most of the water quality in the river, and calculation of TMDL was estimated to water quality can meet the standard targets in Thailand as shown in Figure 3.24, and these scenarios were determined in details in 4.2.1.

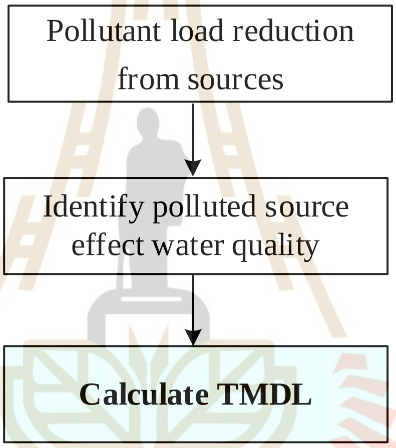


Figure 3.24 Diagram of current simulation scenarios

3.3.5.1 Pollutant load reductions

The current characteristics conditions, quantify point and nonpoint source loadings determine the loading reductions necessary to meet the water quality targets.

3.3.5.2 Pollutant sources identification

The study applies the selected modeling methodology and calculates existing loadings, TMDLs for Lam Takhong River. From simulated results and the demand for TMDL reduction, we can identify how many percentages point and the nonpoint source is cut down to meet targets.

3.3.6 Future simulation scenarios

Similar to current simulated scenarios, future simulation scenarios were conducted with load change of polluted sources discharging into the Lam Takhong river as shown in Figure 3.25.

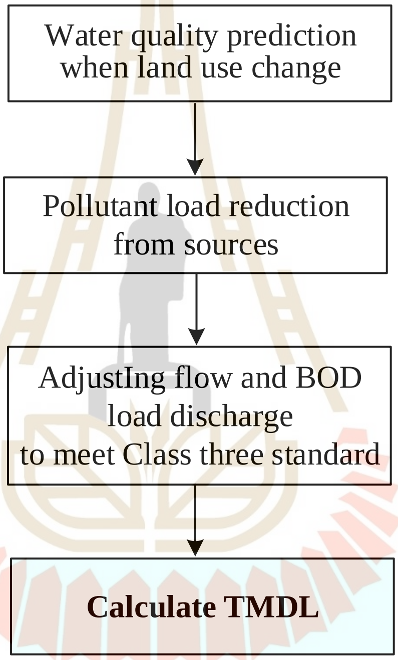


Figure 3.25 Diagram of prediction scenarios

3.3.6.1 Land use change in the future

This scenario analysis was used to evaluate the potential impact of land use change and point source and non-point source loading change in 2019, 2027, 2035 years on surface water quality by changing land cover (Table 3.14 and 3.15).

Table 3.14 Discharge data from urban areas in Lam Takhong watershed when land use change in February 2027

Up (km)	Down (km)	Q (m^3/s)	BOD (mg/L)	TN (µg/L)	TP (µg/L)	NH_4-N (µg/L)	OrgN (µg/L)
0.00	15.91	1.35	0.04	121.52	3.92	105.84	15.68
15.91	31.32	1.32	0.03	96.69	3.12	84.21	12.48
31.32	43.19	0.13	0.13	457.01	14.74	398.04	58.97
43.19	51.25	1.46	0.06	213.14	6.88	185.64	27.50
51.25	63.63	0.03	0.54	1857.01	59.90	1617.40	239.61
63.63	69.60	0.29	0.19	654.29	21.11	569.86	84.42
69.60	85.56	0.22	0.52	1780.05	57.42	1550.37	229.68
85.56	101.28	0.11	1.84	6327.37	204.11	5510.93	816.43
101.28	109.31	0.21	0.77	2639.83	85.16	2299.21	340.62
109.31	120.00	0.07	1.15	3968.74	128.02	3456.64	512.09

Table 3.15 Discharge data from urban areas in Lam Takhong watershed when land use change in November 2027

Up (km)	Down (km)	Q (m^3/s)	BOD (mg/L)	TN (µg/L)	TP (µg/L)	NH_4-N (µg/L)	OrgN (µg/L)
0.00	15.91	4.14	0.0115	39.69	1.28	34.57	5.12
15.91	31.32	3.76	0.0099	34.03	1.10	29.64	4.39
31.32	43.19	1.21	0.0140	48.34	1.56	42.10	6.24
43.19	51.25	8.82	0.0102	35.21	1.14	30.67	4.54
51.25	63.63	0.35	0.0522	179.65	5.80	156.47	23.18
63.63	69.60	2.74	0.0204	70.30	2.27	61.23	9.07
69.60	85.56	2.05	0.0558	192.24	6.20	167.43	24.80
85.56	101.28	0.85	0.2359	812.46	26.21	707.63	104.83
101.28	109.31	1.88	0.0842	289.92	9.35	252.51	37.41
109.31	120.00	0.68	0.1161	399.95	12.90	348.34	51.61

From discharge data from urban areas in Lam Takhong watershed when land use change in 2027, future prediction scenarios were conducted. And forecasted results and the TMDL calculation, the impact from land use change on the water quality in Lam Takhong river then can be identified.

3.3.6.2 Emission source adjustment

The land use change can affect the water quality in Lam Takhong river in the future. Therefore, it is necessary to determine the loading reductions to meet the water quality targets in the future.

The land use change in 2019, 2027 and 2035 years and the TMDLs were considered and cut down to meet the water quality demand in this period.

3.3.7 Estimating TMDL

Applicability to TMDL studies Qual2K is applicable to WLA and TMDL studies of rivers and streams and to investigate problems related to dissolved oxygen, biochemical oxygen demand, nitrogen, and phosphorus (EPA, 2013).

In order to determine the magnitude of pollutant load reductions necessary to attain all water quality standards and targets in the Lam Takhong River, flow out and load reduction scenarios were evaluated. These scenarios considered the various percentage of BOD, phosphorous or nitrogen load reductions from point sources, and nonpoint sources.

Then, using the calibrated watershed model, the concentration of various parameters during the research period were projected and were compared with the Thailand water quality standards and targets.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Hydrological modeling for Lam Takhong River using SWAT

4.1.1 Model calibration

4.1.1.1 Model Setup

DEM, soil, and land use were converted to a grid raster data and projected to the projection coordinate system of the Universal Transverse Mercator (WGS_1984_UTM_Zone_48N) before building up the SWAT model. SWAT divided the watershed into subbasins that subbasins continue to be partitioned into HRUs based on land use and soil distribution of the basin. The land use, soil, and slope were defined in SWAT proportionate, land use (10%), soil (10%), and slope (10%) (Yuan and Forshay 2020) to calculate each response unit. The calibrated period of the study was from January 2005 to December 2012 and the process of study for Lam Takhong basin is shown in Figure 4.1.

The SWAT model was set up with a daily time-step in the 16-year period from 2002 to 2017. A warming-up period was selected in the first three years and the calibration was conducted for the period from 2005 to 2012 while from 2013 to 2017 as the validation period. There are two gauging stations including M89 and M164 that data for flow is available and corresponds to outlets at M164 gauge. The downstream gauging station M164 was chosen as the calibrated station for flow.

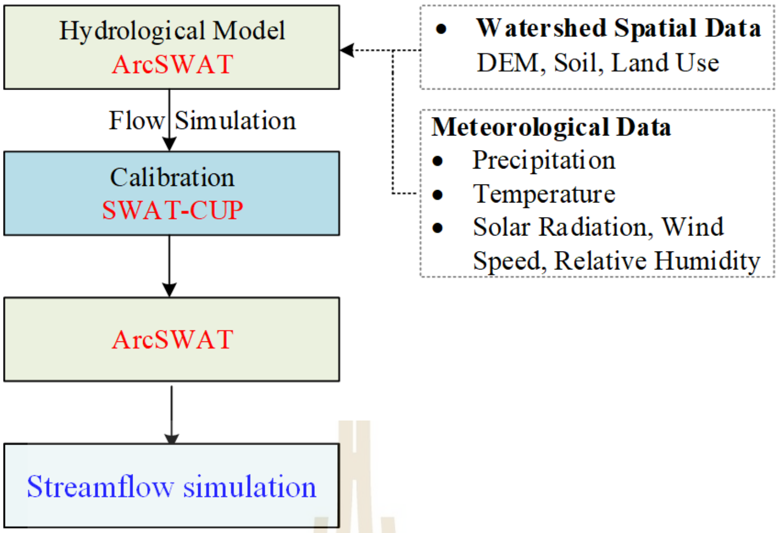


Figure 4.1 Diagram of the study framework.

The methods to compare observed data to prediction using statistical methods by the coefficient of determination (R^2) (Coffey et al. 2004) that the R^2 value can range from 0 to 1 value (where 0 indicates no correlation, values greater than 0.50 are considered acceptable and 1 represents perfect correlation). This is one of the methods to identify the compatibility between observed and simulated data that Ghoraba mentioned in 2015.

4.1.1.2 Sensitivity analysis

Sensitivity analysis is a pre-step of calibration to identify parameters affecting on the simulation. In the hydrological simulation, CN2 (initial SCS runoff curve number for moisture condition II) is the most sensitive parameter and ALPHA_BF (baseflow alpha factor) is also a highly sensitive parameter for all constituents. Besides, CN2, ALPHA_BF, ESCO (soil evaporation compensation factor), and SOL_AWC (available water capacity of the soil layer) were highly sensitive for flow. Maharjan et al. (Maharjan et al. 2013) indicated that CN2, ESCO, ALPHA_BF, and SOL_AWC parameters were identified in previously SWAT sensitivity analysis as influencing the respective variable.

In this study, CN2, GW_DELAY, ALPHA_BF, GWQMN, GW_REVAP parameters were identified in the sensitivity analysis process. However, not all of the parameters identified by sensitivity analysis were modified during calibration, since it was possible to change parameters other than those identified during sensitivity analysis.

4.1.1.3 Parameter calibration

Modeling was calibrated by adjusting the input value of eleven parameters from initial default conditions by SWAT-CUP software version 2012. Input data to calibrate modeling is mentioned in Table 4.1. The calibration is conducted in lower Lam Takhong (outlet subbasin) on 11 parameters and eleven input parameters were calibrated for the flow process (Table 4.2).

Four parameters affected on surface runoff formation are CN2, SURLAG, CH_N2, and CH_K2 and there were seven main parameters affecting base flow generation (ALPHA_BF, GW_DELAY, GWQMN, ESCO, EPCO, GW_REVAP, and REVAPMN). In addition, GW_REVAP and GWQMN also affect on the amount of groundwater flow.

4.1.1.4 Streamflow

The calibration was conducted for the period from 2005 to 2012 of monthly flow. The M89 gauging station is located in upstream of Lam Takhong River and M164 gauging station is outlets of the river where was chosen as the calibrated station for downstream flow. The calibrated values are shown in Table 4.3. The study has selected the value of parameters by monthly calibration in eight years.

Table 4.1 Input data of the SWAT-CUP calibration in Lam Takhong river.

Input File		Data
Calibaration Inputs	Par_inf.txt	Number of parameters: 11 Number of simulations: 500
	SUFI2_swEdit.def	Starting simulation number: 1 Ending simulation number: 500
	File.Cio	Number of years simulated: 13 Beginning year of simulation: 2005
	Absolute_SWAT_Values.txt	All parameters to be fitted should be in this file plus their absolute min and max ranges.
	Absolute_SWAT_Values.txt	CN2, GW_DELAY, ALPHA_BF, GWQMN, SURLAG, CH_N2, CH_K2, GW_REVAP, ESCO, EPCO
Observation	Observed_rch.txt	Number of observed variables (1): Flow
Extraction	Var_file_rch.txt	Flow.txt;
	SUFI2_extract_rch.def	Number of variables to get: 1 Total number of reaches (subbasins) in the project: 75 Time step: monthly
Objective function	Observed.txt	Number of observed variables: 2 Objective function type: 3 = R^2
	Var_file_name.txt	Flow.txt

Table 4.2 Lit of calibrated parameters and their default.

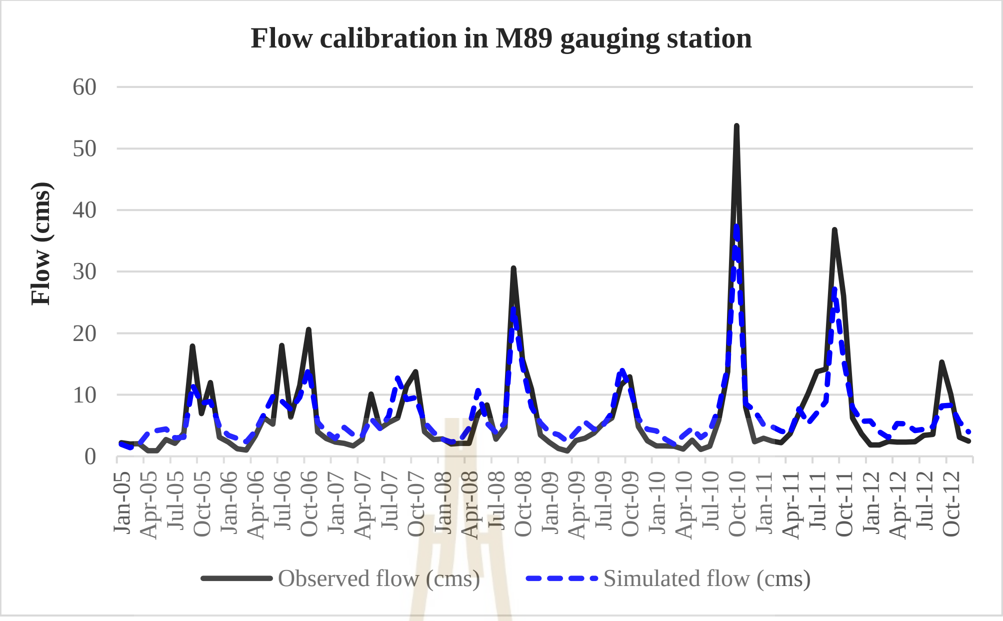
No.	Parameters	Description	Calibrated value	Default Value
1	CN2	Initial SCS CN II value	-0.148	0
2	ALPHA_BF	Baseflow alpha factor [days]	1.064	0.048
3	GW_DELAY	Groundwater delay [days]	91.872	31
4	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur [mm]	2.374	0
5	SURLAG	Surface runoff lag time [days]	4.000	4
6	ESCO	soil evaporation compensation factor	0.246	0.95
7	EPCO	plant water uptake compensation factor	0.957	1
8	CH_N2	Manning's value for main channel	0.101	0.014
9	CH_K2	Effective hydraulic conductivity [mm/hr]	312	0
10	GW_REVAP	Groundwater "revap" coefficient	0.157	0.02
11	REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur [mm]	513	1

Table 4.3 The value of calibration of the SWAT model in Lam Takhong river.

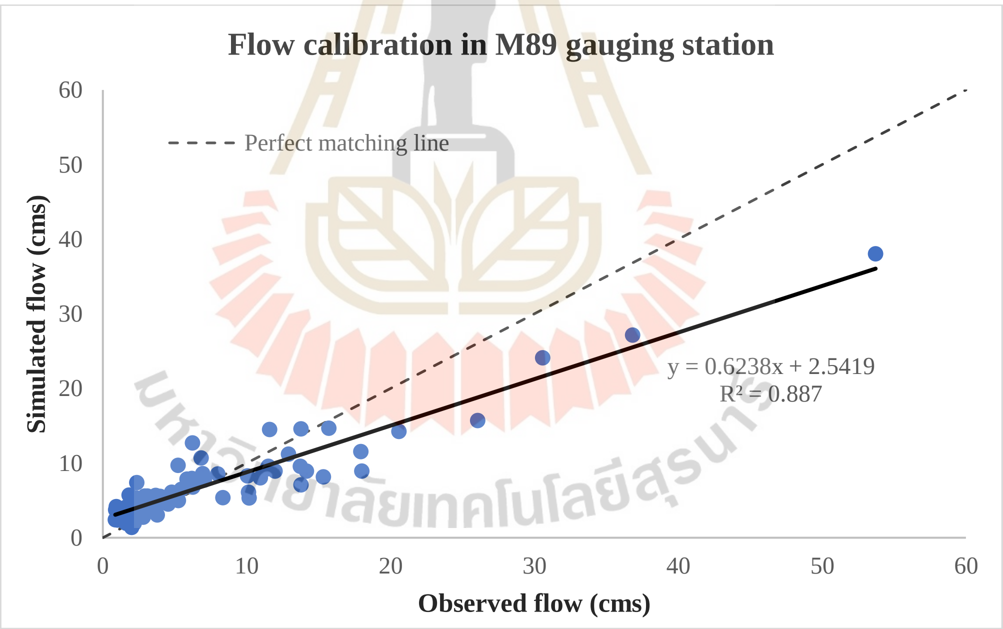
Gauging station	R^2	NSE	PBIAS (%)
M89	0.887	0.809	6.90
M164	0.858	0.806	5.40

A good calibration was shown by R^2 and NSE greater than 0.8 and PBIAS less than 10% (Table 4.3). As suggested by Moriasi et al. (2015), model performance can be judged satisfactory for flow monthly simulations if $R^2 > 0.60$, NSE > 0.50, and PBIAS $\leq \pm 15\%$ for watershed-scale models. This means satisfactory model performance between the monthly observed and simulated streamflow in the calibration process (Figures 4.2 and 4.3).

The calibration of the monthly flow stream was improved significantly from 0.69 value of R^2 (Tran and Yossapol, 2019) increase to 0.89 in upstream and 0.86 in downstream of the river for eight years (2005-2012). Parameters were identified during calibration because of the aim of matching the model as closely as possible. PBIAS showed that the average magnitude of monthly simulated flow was close to the observed flow in M89 and M164 stations. The hydrological processes in the SWAT model were realistically simulated in the Lamtakhong watershed.



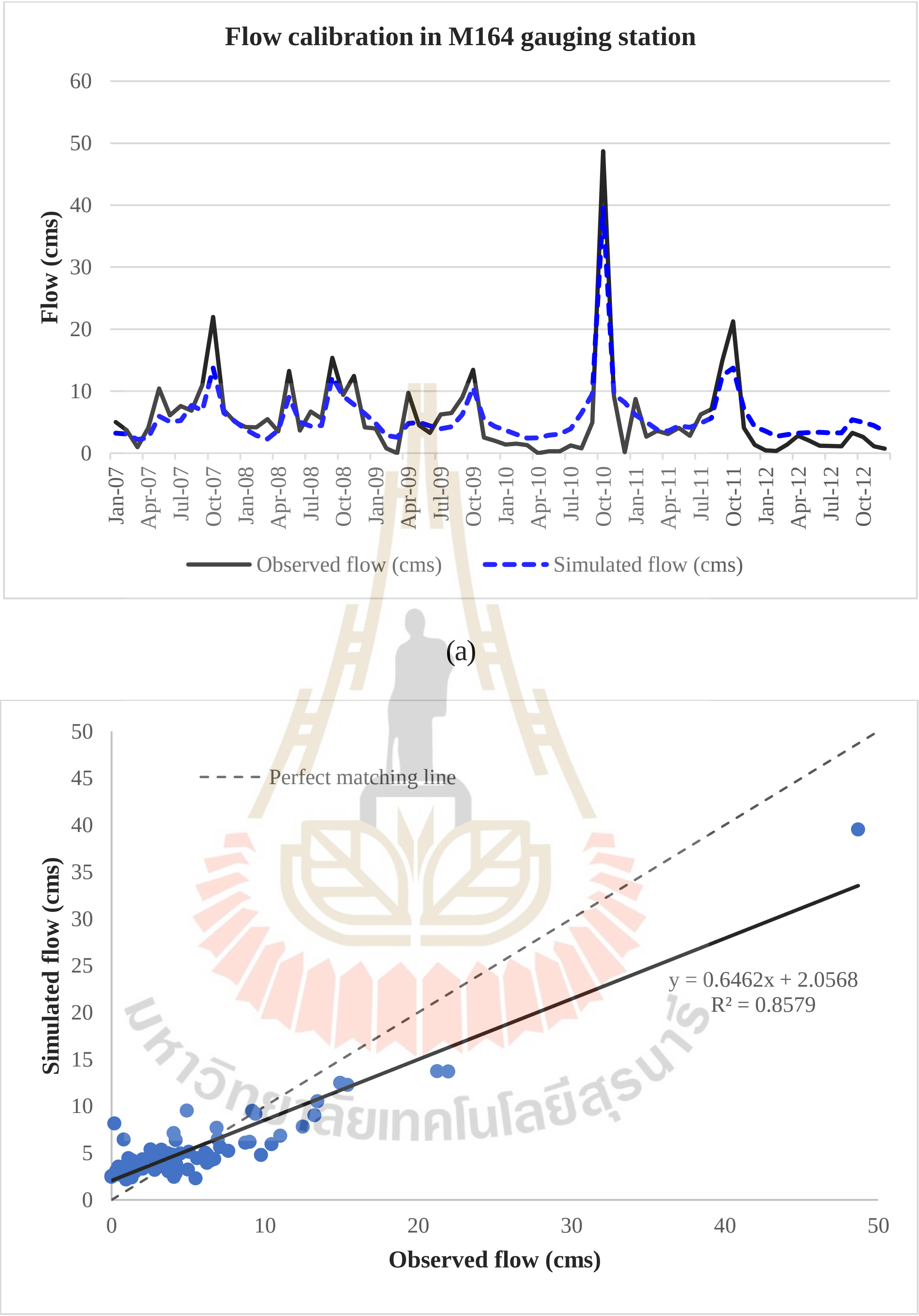
(a)



(b)

Figure 4.2 Observed and simulated monthly flow

(a) and scattergram (b) at M89 for calibration.



(a)

(b)

Figure 4.3 Observed and simulated monthly flow

(a) and scattergram (b) at M164 for calibration.

The scatter plot of monthly streamflow at M89 and M164 (Figures 4.2b and 4.3b) were under the perfect matching line shown that simulated flow is lower than observed flow. Regression analysis between the observed and simulated values resulted in high values of R^2, which were 0.89 and 0.86 at M89 and M164, respectively. The NSE was estimated to be 0.81 at both M89 and M164. The high values of NSE indicated a close agreement between the observed and simulated streamflows.

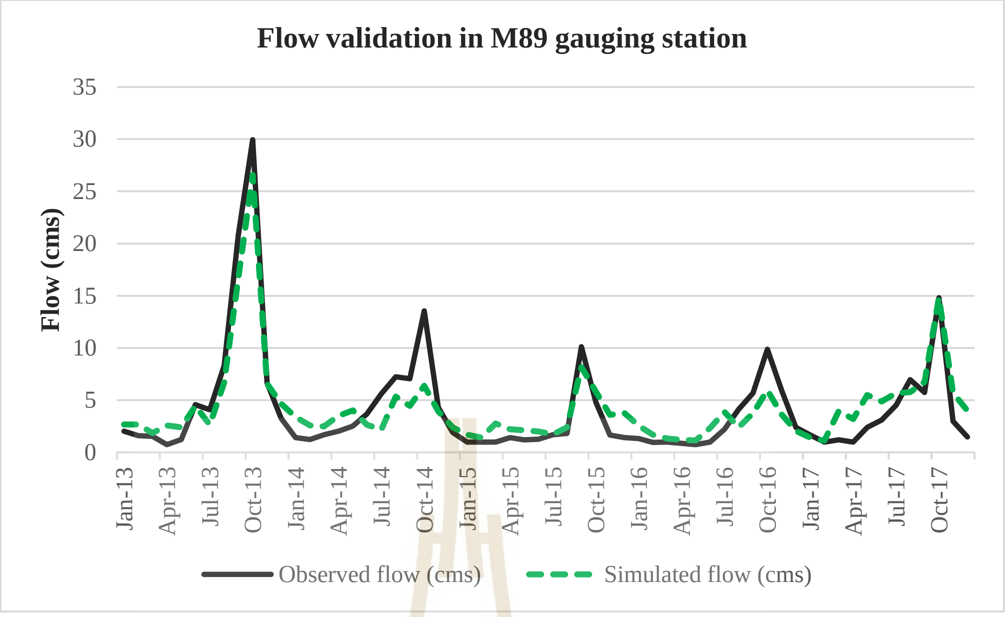
4.1.2 Model validation

At M89, it was shown that the monthly simulated flow is close to the monthly observed flows (Figure 4.4). Besides, a good validation was also shown by R2, NSE greater than 0.85 upstream and 0.74 downstream (Table 4.4). The streamflow simulation results in Lam Takhong river at M89 and M164 station is shown in Figure 4.4 and Figure 4.5.

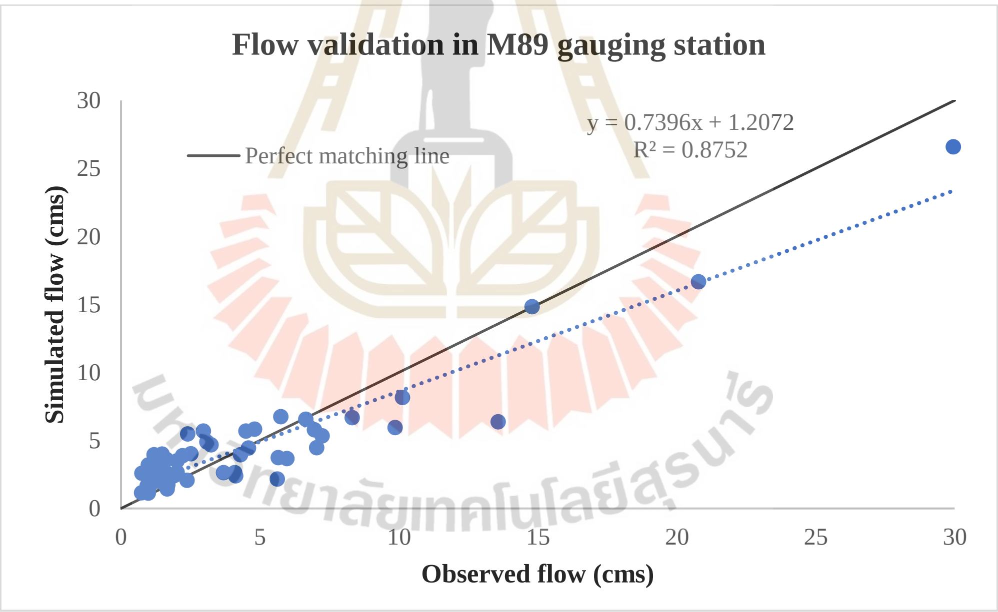
Table 4.4 The value of validation of the SWAT model in Lam Takhong river.

Gauging station	R^2	NSE	PBIAS (%)
M89	0.875	0.854	13.10
M164	0.825	0.742	23.80

The validated result had $R^2 > 0.85$ and NSE >0.8 at M89 is very good performance (Moriasi et al. 2015) but 10 < PBIAS < 15 is only satisfactory. However, at M164 gauging station R^2 and NSE showed that modeling performance is good have PBIAS > 15% the modeling at this station is unsatisfactory (Moriasi, 2015b), in an opposite way Moriasi (2007) (D. N. Moriasi et al. 2007) indicated that 15% < PBIAS < 25% is satisfactory performance rating.



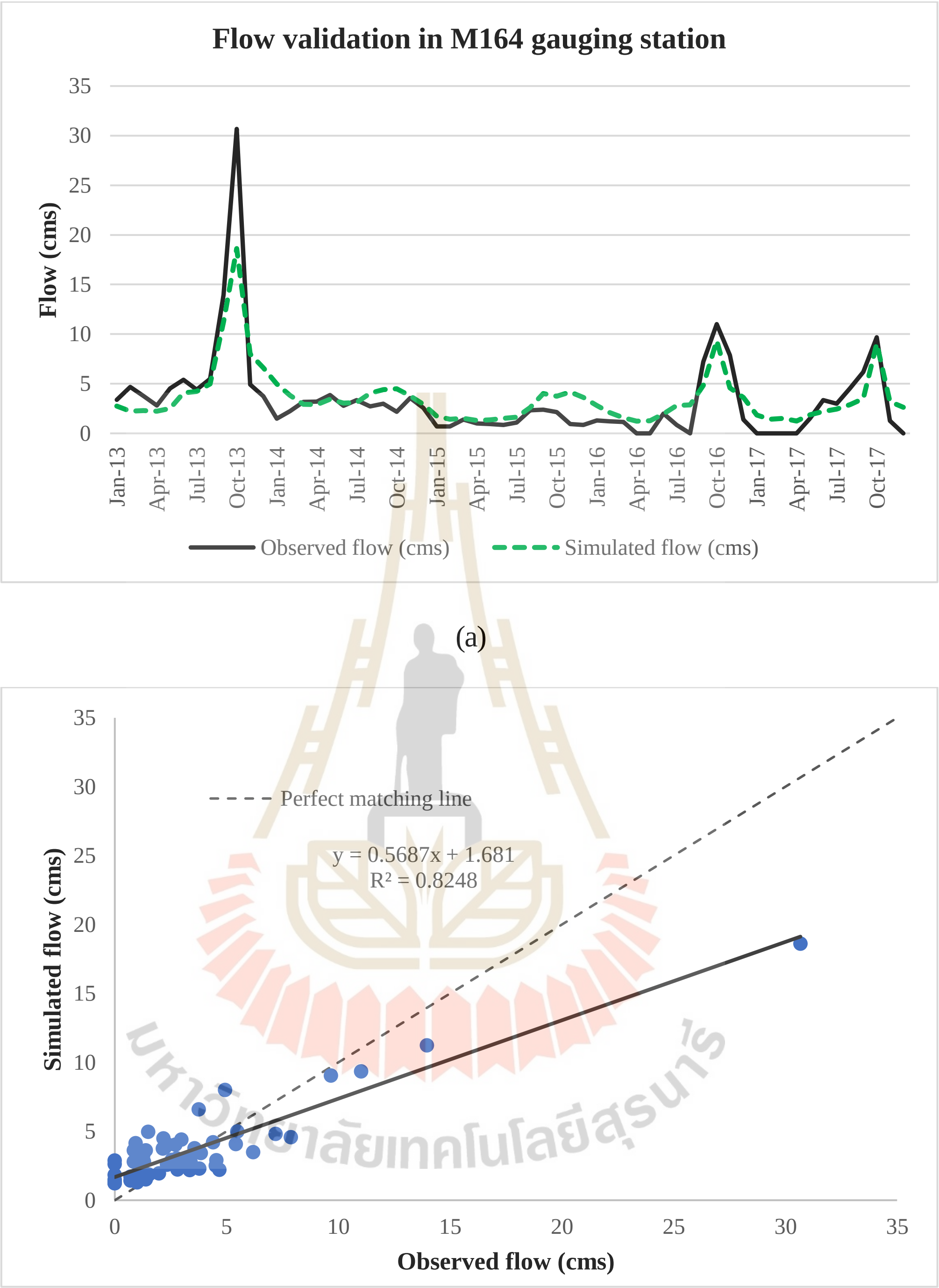
(a)



(b)

Figure 4.4 Observed and simulated monthly flow

(a) and scattergram (b) at M89 for validation.



(a)

(b)

Figure 4.5 Observed and simulated monthly flow

(a) and scattergram (b) at M164 for validation.

The observed peak flow values are around 53.72 m^3/s which is larger than that of 38.05 m^3/s of simulated flow, while minimum values are similarly at 0.74 m^3/s 1.11 m^3/s respectively at M89 station, showing a very good satisfactory. The deviation between simulated and observed maximum value in M164 station is lower than the M89 station. However, the deviation of the average value in upstream and downstream is similar (Table 4.5).

Table 4.5 Observed and simulated flow in M89 and M164 gauging stations with maximum, minimum, and average value from 2005 to 2017

Flow (m^3/s)	M89		M164	
	Observed	Simulated	Observed	Simulated
Max	53.72	38.05	48.70	39.54
Min	0.74	1.11	0.00	1.23
Average	5.63	5.73	4.61	4.74

4.1.3 Evaluation of hydrology predictions and water yield from the subbasin contributes to streamflow

4.1.3.1 Evaluation of hydrology

The SWAT flow model is used as input data of water quality model and outlet of Lam Takhong Dam is the headwater of Lam Takhong River in this study (Figure 4.6). After SWAT model was calibrated and validated, the flow was calculated at the headwater of the river in 2027 (Table 4.6) and the trend of flow is shown in Figure 4.7.

The average streamflows of headwater in February and November 2027 are 5.63 and 6.53 cms, respectively. The results are compared to the monthly mean flow from 2001 to 2019, and the average February flow is slightly larger than November flow (Figure 4.8). The trend of flow in the Lam Takhong River gradually reduces from 2014 until recently.

Figure 4.6 Outlet of Lam Takhong Dam. (www.google.co.th/maps)

Table 4.6 Flow in the headwater of Lam Takhong River in 2019 and 2027.

Month	Flow in 2027 (m^3/s)
Jan	4.03
Feb	5.63
Mar	5.68
Apr	6.18
May	7.55
Jun	5.80
Jul	7.02
Aug	8.79
Sep	19.07
Oct	12.21
Nov	6.53
Dec	3.19

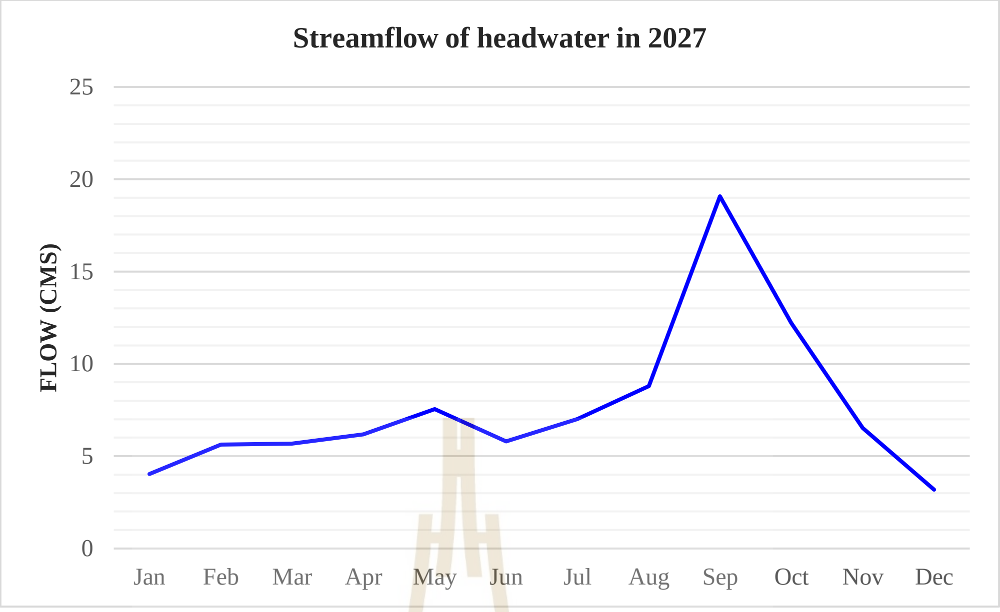


Figure 4.7 Streamflow in Lam Takhong River headwater.

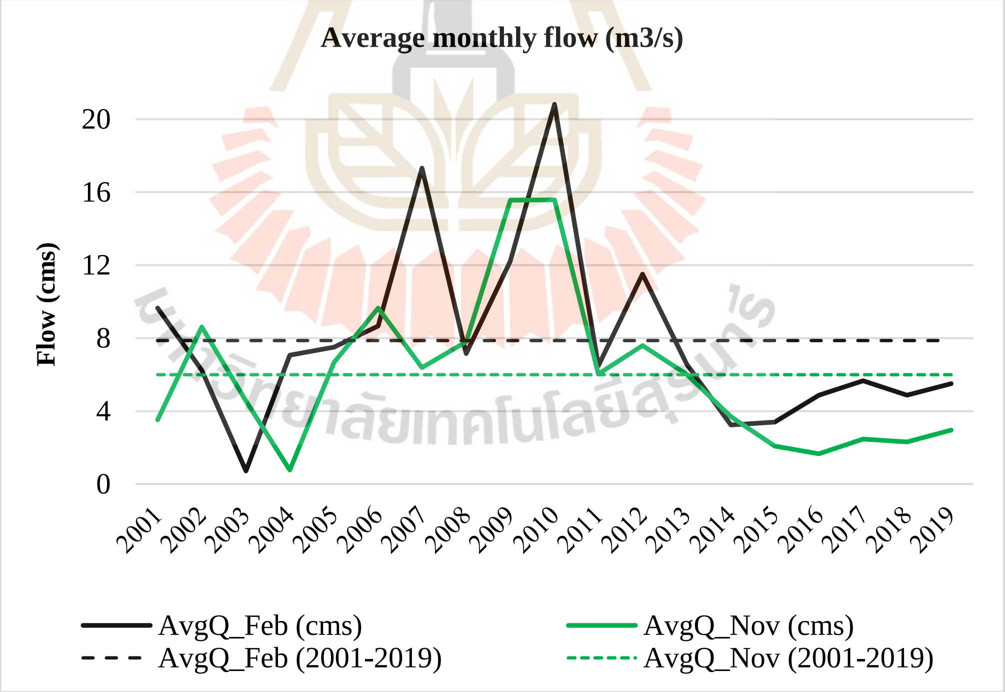


Figure 4.8 Monthly February and November flow from 2001 to 2019

4.1.3.2 Water yield from the subbasin contributes to streamflow

The result of simulated and predicted flow from the SWAT model, the net amount of water from subbasin contributes to streamflow in the river in 2019 and 2027 was calculated in Table 4.7 and 4.8. The monthly mean flow of February and November in 2027 is higher than present because precipitation in 2019 is lower in previous years and the rain season also came late.

Table 4.7 The net amount of water from subbasin contributes to streamflow in the river in 2019.

ID	Upstream (km)	Downstream (km)	Q_Feb_2019 (cms)	Q_Nov_2019 (cms)
NPS1	0.00	15.91	0.47	3.22
NPS2	15.91	31.32	0.43	2.88
NPS3	31.32	43.19	0.15	0.96
NPS4	43.19	51.25	1.07	6.90
NPS5	51.25	63.63	0.03	0.28
NPS6	63.63	69.60	0.34	2.17
NPS7	69.60	85.56	0.22	1.62
NPS8	85.56	101.28	0.08	0.66
NPS9	101.28	109.31	0.20	1.48
NPS10	109.31	120.00	0.06	0.54
	Total		**3.04**	**20.72**

Table 4.8 The net amount of water from subbasin contributes to streamflow in the river in 2027

ID	Upstream (km)	Downstream (km)	Q_Feb_2027 (m^3/s)	Q_Nov_2027 (m^3/s)
NPS1	0.00	15.91	1.35	4.14
NPS2	15.91	31.32	1.32	3.76
NPS3	31.32	43.19	0.13	1.21
NPS4	43.19	51.25	1.46	8.82
NPS5	51.25	63.63	0.03	0.35
NPS6	63.63	69.60	0.29	2.74
NPS7	69.60	85.56	0.22	2.05
NPS8	85.56	101.28	0.11	0.85
NPS9	101.28	109.31	0.21	1.88
NPS10	109.31	120.00	0.07	0.68
	Total		**5.19**	**26.47**

4.2 Water quality modeling using QUAL2K

4.2.1 Configuration of Lam Takhong River and Scenarios Description

4.2.1.1 Configuration of Lam Takhong River

The river system was divided into 35 reaches beginning at the headwater which is the outlet of Lam Takhong Dam, and the downstream is at Mun river as shown in Figure 4.9. The figure also shows the polluted source locations including point sources and nonpoint sources.

ArcGIS and SWAT combination was employed in the flow simulation in the Lam Takhong river and from subbasin into the river, while the Qual2K model was used to simulate and assess the river quality status. The SWAT model outputs were the hydrological boundary inputs for the QUAL2K model. However, the water quality outputs of the SWAT model were not used as inputs for the QUAL2K model in the study.

Input water quality data for the QUAL2K model was collected on 5th February and 28th November 2017 and was used to calibrate and validate in Qual2k. There are 36 collected cross-sections and the Lam Takhong River is divided into 35 reaches which vary in length. Besides, downstream coordination, length of reaches, element number, and others of reach were also collected (Table 3.7). Locations of point sources, nonpoint sources, and configuration of the Lam Takhong River are shown in Figure 4.9.

Figure 3.20 indicated that locations of polluted source were distributed in details and Figure 4.9 provides a simple description of the location of the waste sources, making the built-up of the modeling more comfortable.

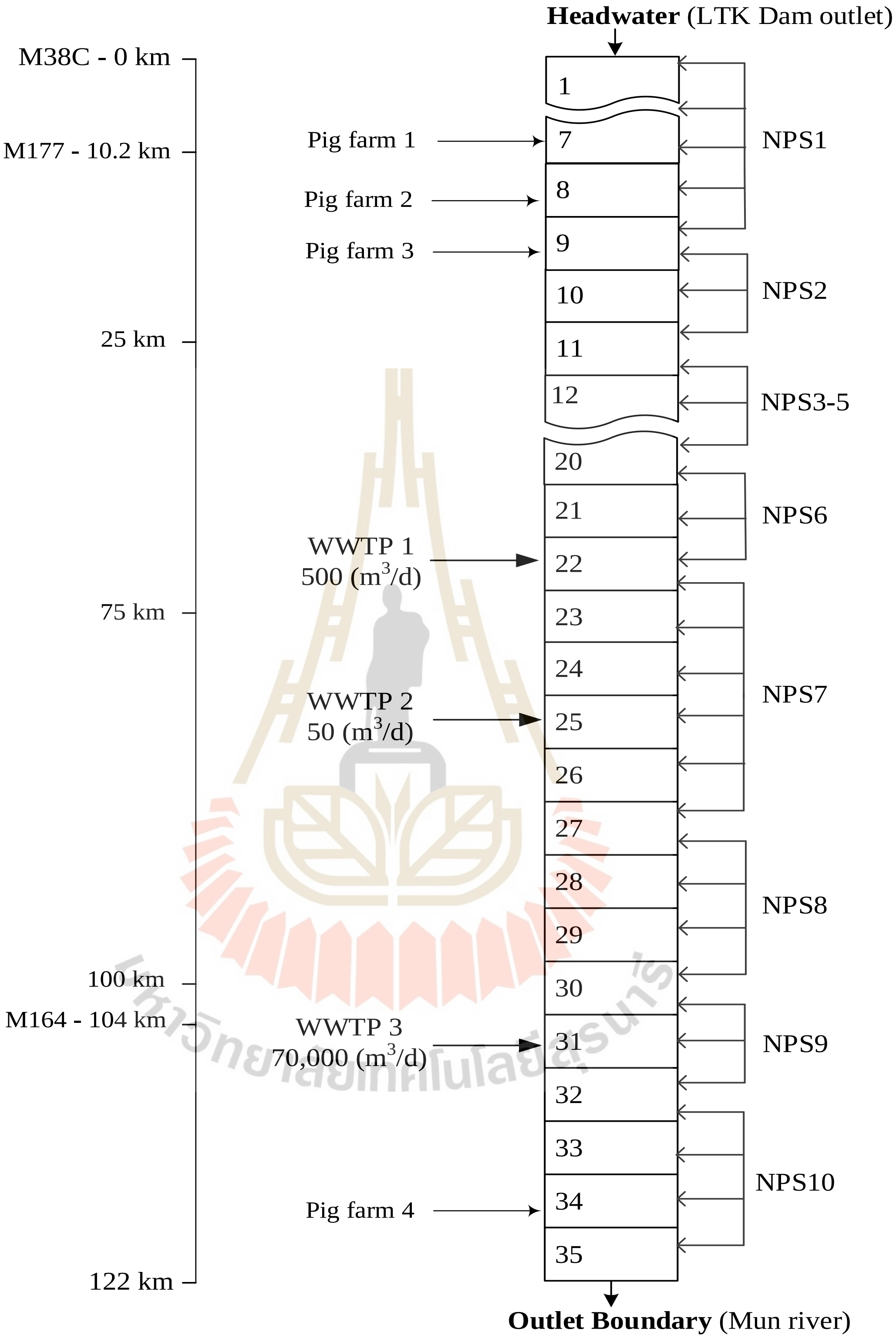


Figure 4.9 Configuration of Lam Takhong River

4.2.1.2 Scenarios description of the study

After the Qual2K model was calibrated and validated, the trend of water quality was generally evaluated. The water quality compared to surface water quality standards in Thailand, and it is showed that water quality of many sites in the river did not meet this standard. Therefore, the study have conducted the water quality simulated scenarios to identify which resources discharge the highest BOD loading in the Lam Takhong River and help water resources managers improve water quality in the area. The scenarios set up are described in detail in Table 4.9.

Lam Takhong River receives pollutants from many sources including diffuse sources (urban area and agricultural land) and several point sources of wastewater from pig farms, industrial factories, and wastewater treatment plants. Therefore, this study conducted different predicted and simulated scenarios to identify which polluted source has the greatest impact on water quality in the Lam Takhong River. Then, it is possible to calculate and modify polluted sources to water quality in the area that can meet class three of surface water quality standards in Thailand.

The P1 calibrated scenario (BAU of February) was run in February 2019 when BOD load from WWTP, Industrial, and urban areas accounted for 89.13%, 6.98%, and 3.89% respectively and flow of headwater, WWTP and the nonpoint source was 5.5 m^3/s, 0.817 m^3/s, 3.04 m^3/s. While BOD load from WWTP, Industrial, urban area, and flow from WWTP of the P2 validated scenarios (BAU of November) did not change but the flow of headwater and nonpoint source were 2.9 m^3/s, 20.72 m^3/s in November 2019.

Table 4.9 Describe the water quality simulated scenarios of the study.

No	Scenario	Q m^3/s			Point Sources		Nonpoint Sources	Note
		Headwater	PS	NPS	WWTP	Industrial	Urban	
1	P1	5.5	0.817	3.04	89.13% BOD load	6.98% BOD load	3.89% BOD load	Present, Feb 2019, Calibration
2	P2	2.9	0.817	20.72	-	-	-	Present, Nov 2019, Validation
3	P2_W1	-	-	-	↓ 25% BOD	-	-	Present, Nov-2019, ↓25%BOD
4	P2_W2	-	-	-	↓ 50% BOD	-	-	Present, Nov-2019, ↓50%BOD
5	P2_W3	-	-	-	↓ 60% BOD	-	-	Present, Nov 2019, ↓60% BOD
6	P2_W4	-	-	-	70% BOD	-	-	Present, Nov-2019, ↓70%BOD
7	P2_W2+N1	2.9	0.817	20.72	↓50%BOD +↓25%N,P	-	-	Present, Nov-2019, ↓50%BOD +↓25% nutrient
8	P2_W2+N2	-	-	-	↓50%BOD +↓50%N,P	-	-	Present, Nov-2019, ↓50%BOD + ↓50% nutrient
9	P2_U1	-	-	-	-	-	↓ 25% BOD	Present, Nov-2019, ↓25% nutrient of Urban
10	P2_U2	-	-	-	-	-	↓ 50% BOD	Present, Nov-2019, ↓50% nutrient of Urban
11	F1	5.6	0.817	5.19	89.13% BOD load	6.98% BOD load	3.89% BOD load	Future, Feb 2027
12	F1_LUC	-	-	-	88.78% BOD load	6.95% BOD load	4.27% BOD load	Future, Feb-2027, Land use change
13	F1_110%Qw	-	↑110%	-	-	-	-	Future, Feb-2027, 110%Qwwtp
14	F1_120%Qw	-	↑120%	-	-	-	-	Future, Feb-2027, 120% Qwwtp
15	F1_120%Qw+W1	-	120%	-	↓ 25% BOD	-	-	Future, Feb-2027, 120% Qwwtp+25 BOD reduction
16	F1_120%Qw+W2	-	120%	-	↓ 50% BOD	-	-	Future, Feb-2027, 120%Qwwtp + ↓50% BOD
17	F1_120%Qw+HWa	7.87	120%	-	-	-	-	Future, Feb-2027, 120%Qwwtp+ Qmean headwater
18	F1_HW1	110%	-	-	-	-	-	Future, Feb-2027, 110%Q headwater
19	F1_HW2	120%	-	-	-	-	-	Future, Feb-2027, 120%Q headwater
20	F1_HW3	90%	-	-	-	-	-	Future, Feb-2027, 90%Q headwater
21	F1_HW4	80%	-	-	-	-	-	Future, Feb-2027, 80%Q headwater

Table 4.9 Describe the water quality simulated scenarios of the study. (Cont'd)

No	Scenario	Q m^3/s			Point Sources		Nonpoint Sources	Note
		Headwater	PS	NPS	WWTP	Industrial	Urban	
22	F2	6.53	0.817	26.47	89.13% BOD load	6.98% BOD load	3.89% BOD load	Future, Nov-2027
23	F2-LUC	6.53	0.817	26.47	88.78% BOD load	6.95% BOD load	4.27% BOD load	Future, Nov-2027, Land use change
24	F2_110%Qw	6.53	110%	26.47	-	-	-	Future, Nov-2027, 110%Qwwtp
25	F2_120%Qw	-	120%	-	-	-	-	Future, Nov-2027, 120% Qwwtp
26	F2_120%Qw+W1	-	120%	-	↓ 25% BOD	-	-	Future, Nov-2027, 120%Qwwtp + ↓25% BOD
27	F2_120%Qw+W2	-	120%	-	↓ 50% BOD	-	-	Future, Nov-2027, 120%Qwwtp + ↓50% BOD
28	F2_120%Qw+HWa	5.99	120%	-	-	-	-	Future, Nov-2027, 120% Qwwtp + Qmean headwater
29	F2_HW1	110%	-	-	-	-	-	Future, Nov-2027, 110%Q headwater
30	F2_HW2	120%	-	-	-	-	-	Future, Nov-2027, 120%Q headwater
31	F2_HW3	90%	-	-	-	-	-	Future, Nov-2027, 90%Q headwater
32	F2_HW4	80%	-	-	-	-	-	Future, Nov-2027, 80%Q headwater
33	F2_33%Qw	6.53	33%	-	100%BOD	-	-	Future, Nov-2027, 33%Qwwtp
34	F2_42%BODw	6.53	100% (0.817)	-	42%BOD	-	-	Future, Nov-2027, 42%BODwwtp
35	F2_77%Qw+ 50%BODw	6.53	77%	-	50%BOD	-	-	Future, Nov-2027, 77%Q+50%BODwwtp

Agricultural resources are ignored because BOD emissions from agriculture are negligible and these sources only discharged 0.08%, 0.07%, and 0.06% total nitrogen while 1.8%, 1.64%, 1.47% total phosphorus of all sources into the Lam Takhong River respectively in 2019, 2027, and 2035 (Table 4.17, 4.19, and 4.22). Scenarios are classified according to each impact source separately with two time periods of the year in February and November 2019 including WWTP, industrial, urban area sources from scenario No. 3 to No. 10.

- From P2_W1 to P2_W4 scenarios (No.3 – No.6), the study was conducted to evaluate the effect of BOD load from WWTPs on water quality in Lam Takhong River by reducing BOD load discharge into the river following 25%, 50%, 60%, and 70% reduction.
- A combination of BOD load and the nutrient reduction from WWTPs was simulated in the P2_W2+N1 and P2_W2+N2 scenarios (No.7-8) that the research objective wanted to find out how the nutrition from WWTPs affects water quality in Lam Takhong River.
- To estimate the effect of BOD load from urban diffuse sources on water quality in Lam Takhong River, the P2_U1 and P2_U2 scenarios were performed.

The F1 forecasted scenario was set up in February 2027 that BOD load from WWTP, Industrial, and urban area are similar to the P1, P2 scenarios but flow of headwater, and nonpoint source are 5.6 m^3/s, and 5.19 m^3/s because the flow in headwater and from subbasins will change in the future. Besides, the F2 forecasted scenario is the same to F1 scenarios, only the flow of headwater and nonpoint source will change 6.53 m^3/s, and 26.47 m^3/s in November 2027.

To fulfill the third objective of the study is how land use changes affect water quality future, the F1-LUC and F2_LUC scenarios (No. 12 and No. 23) were run. When land use changes in 2027 and 2035, so do the flow at the headwater and net flow from sub-basin, and how this affects the water quality and which location is the most affected area in Lam Takhong River.

The target of the forecast scenarios is similar to the current simulated scenario, desiring to find out which factors or sources of pollution make an important contribution to the deterioration of water quality in the Lam Takhong River region in general, and in downstream areas in particular. The affected factors include flow out, BOD load from WWTPs, and the flow at the headwater (No. 13-21, and No. 24-32 scenarios). The nutrient from WWTPs and BOD load from agricultural diffuse sources are not simulated the effect capacity because it accounts for too low percentage and has a small impact on water quality.

- It is predicted that the population in the study area will increase from 10% to 20% by 2027. That is why F1_110%Qw, F1_120%Qw, F2_110%Qw, F2_120%Qw scenarios (No.13-14, and No.24-25) are forecasted to evaluate when the wastewater flow from the WWTPs increase and how it will affect water quality in February and November in 2027.
- If the flow out from WWTPs increase to 20%, BOD load discharge from WWTPs will need to be lower to meet the target of water quality. The F1_120%Qw+W1, F1_120%Qw+W2 scenarios (No. 15-16) in February 2027 and the F2_120%Qw+W1, F2_120%Qw+W2 scenarios (No. 26-27) in November 2027 was carried out to evaluate the effect ability of the combination of flow out increase and BOD load reduction from WWTPs on water quality in Lam Takhong River.

- In addition to the factors of the waste sources is also investigated how the flow at headwater effects on water quality. The F1_120%Qw+Hwa (No.17) and The F2_120%Qw+Hwa (No.28) are combining of 120% flow out of WWTPs and the monthly mean flow of February and November in 19 years (Figure 4.8).

- The F1_HW1, F1_HW2, F1_HW3, F1_HW4 scenario group (No.18-21) and The F2_HW1, F2_HW2, F2_HW3, F2_HW4 scenario group (No.29-32) were predicted to estimate the effected ability of the flow at the headwater of Lam Takhong River when 10%, 20% increase and 10%, 20% reduction of flow in the headwater boundary compare to the predicted value (5.6 m^3/s in February and 6.53 m^3/s in November) Table 4.9.

Finally, to find out how water quality in the Lam Takhong River can achieve the target of class three of surface water quality standards in Thailand. The study conducted the F2_33%Qw, F2_42%BODw, F2_77%Qw+50%BODw scenarios (No. 33-35). These scenarios calculate the combination of flow out and BOD load change from WWTPs on water quality in Lam Takhong River. The F2_33%Qw scenario only simulated a factor that the flow out from WWTPs reduce 77%; F2_42%BODw scenario concentrated lower 58% BOD load from WWTPs; and F2_77%Qw+50%BODw scenario was a combination of 23% flow out and 50% BOD load reduction from WWTPs.

4.2.2 Water quality calibration

Calibration is the process of adjusting model parameters and comparing the model output to measured data until an acceptable level of agreement is achieved. An exponential model was chosen for oxygen inhibition of CBOD oxidation, nitrification, and Phyto-respiration. The range of CBOD oxidation rate was assumed as 0–5, the other parameters were set as default value in QUAL2Kw.

The calculation step was set at 5.625 min. Euler's method was set for the solution of integration; Newton–Raphson method was used for pH modeling. To perform goodness of fit different weighting factors were given to different parameters. The model was run for a population size of 100 with 50 generations in the evolution because according to Pelletier et al. (2006) population size of 100 performs better than smaller numbers and as nearly as a population size of 500. The calibrated physicochemical parameter values in the model are presented in Table 4.10.

Figure 4.10 to Figure 4.13 presents the simulation result in comparison with the observed data at 6 stations along the mainstream of the Lam Takhong River.

Table 4.10 Parameters were calibrated by Qual2kw.

Parameters	**Values**	**Units**	**Auto-calibration**	**Min. value**	**Max. value**
Carbon	40	gC	No	30	50
Nitrogen	7.2	gN	No	3	9
Phosphorus	1	gP	No	0	4.2
Dry weight	100	gD	No	100	100
Chlorophyll	1	gA	No	0.4	2
ISS settling velocity	0.222	m/day	Yes	0	2
O2 reaeration model	Internal		No		
Slow CBOD hydrolysis rate	0.224	day^{-1}	Yes	0	5
Slow CBOD oxidation rate	1.110	day^{-1}	Yes	0	0.5
Fast CBOD oxidation rate	2.857	day^{-1}	Yes	0	5
Organic N hydrolysis	0.081	day^{-1}	Yes	0	5
Organic N settling velocity	1.356	m/day	Yes	0	2
Ammonium nitrification	2.910	day^{-1}	Yes	0	10
Nitrate denitrification	1.727	day^{-1}	Yes	0	2
Organic P hydrolysis	0.154	day^{-1}	Yes	0	5
Organic P settling velocity	0.113	m/day	Yes	0	2
Inorganic P settling velocity	0.344	m/day	Yes	0	2

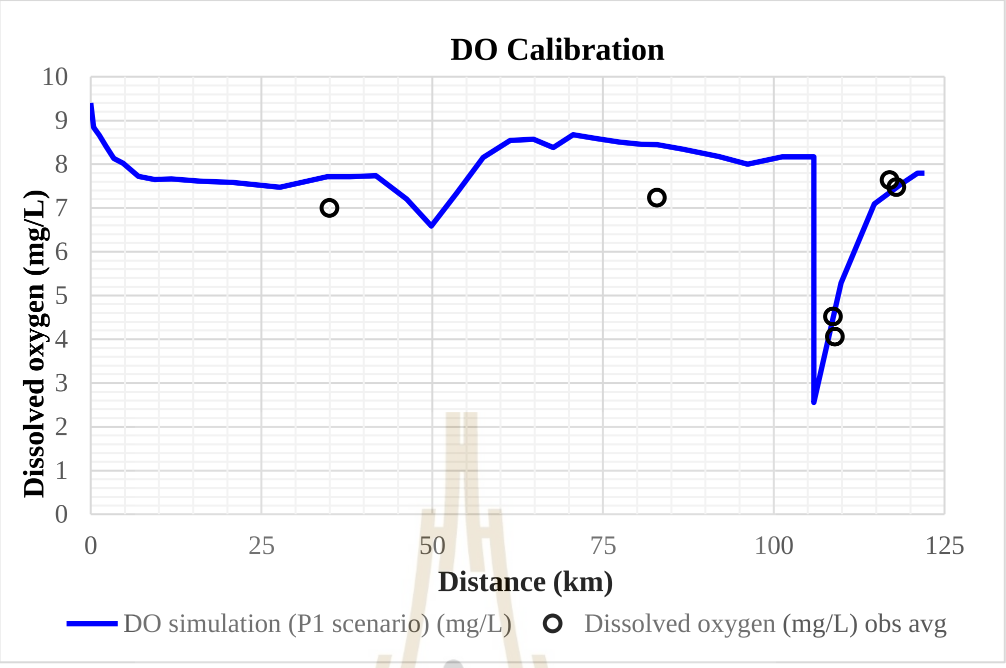


Figure 4.10 Calibration of DO concentration in Lam Takhong River in February 2019.

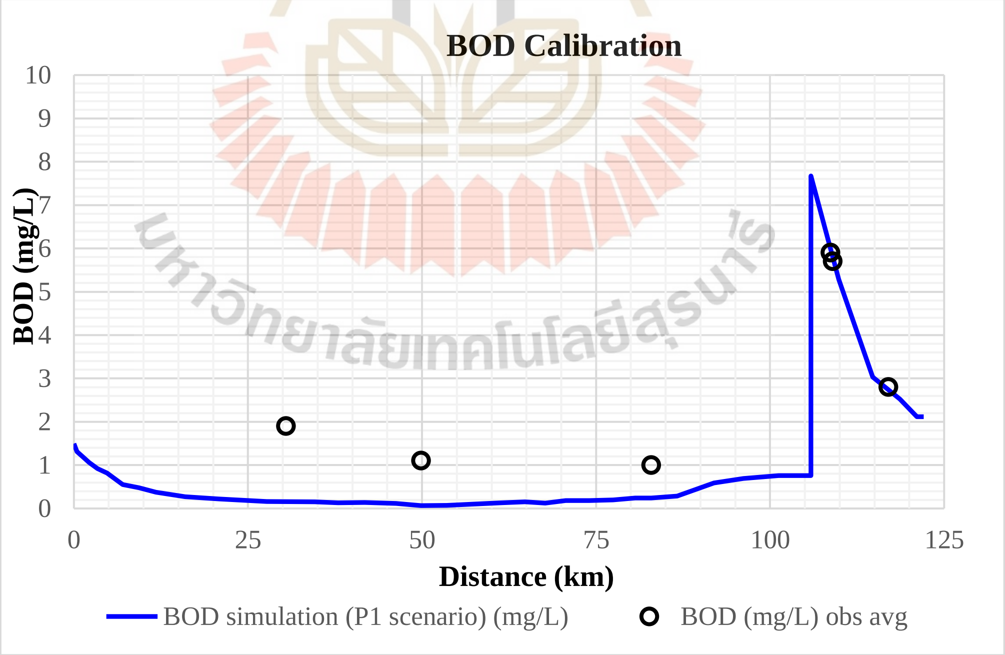


Figure 4.11 Calibration of BOD concentration in Lam Takhong River in February 2019.

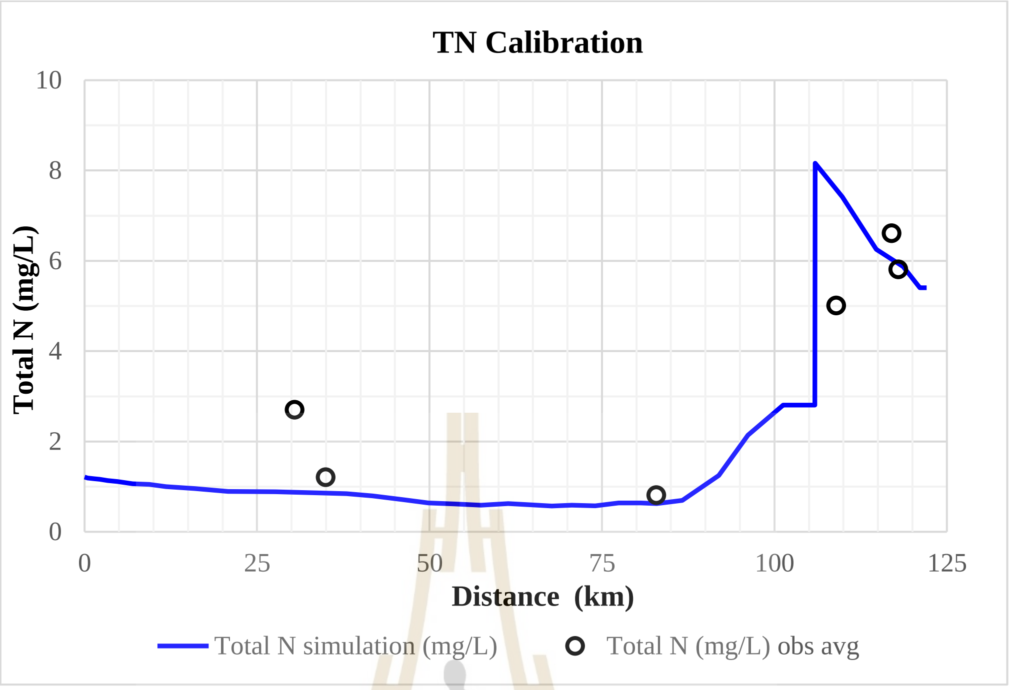


Figure 4.12 Calibration of TN in Lam Takhong River in February 2019.

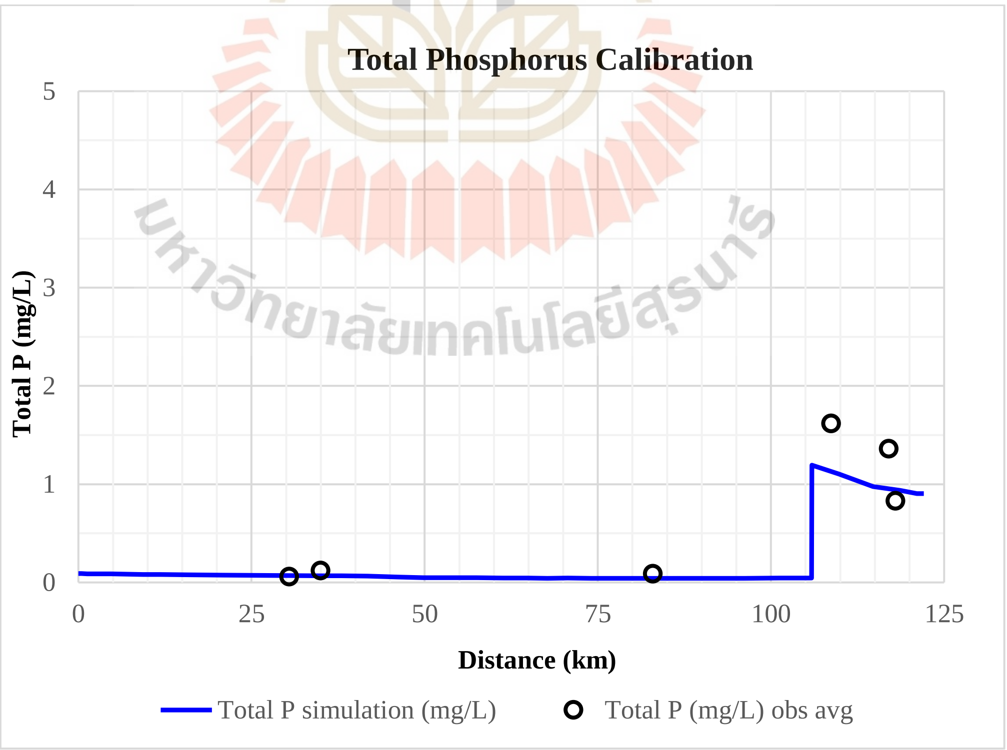


Figure 4.13 Calibration results of TP in Lam Takhong River in February 2019.

The results showed the simulation data were comparable to the observed data at six stations along the mainstream of the Lam Takhong River and the calibration results were a very good agreement between simulated and observed values for DO, BOD, TN, and TP (Figure 4.10 to Figure 4.13).

Table 4.11 Observed and simulated water quality data in February 2019.

DO_obs (mg/L)	DO_sim (mg/L)	BOD_obs (mg/L)	BOD_sim (mg/L)	TN_obs (mg/L)	TN_sim (mg/L)	TP_obs (mg/L)	TP_sim (mgP/L)
7	7.71	1.9	0.20	2.7	0.90	0.06	0.07
7.24	8.84	1.1	0.10	1.21	0.85	0.12	0.09
4.52	4.50	1	0.30	0.81	0.63	0.09	0.05
4.06	4.52	5.9	5.90	5.01	7.40	1.62	1.12
7.64	7.40	5.7	5.70	6.61	6.10	1.36	0.96
7.48	7.50	2.8	2.79	5.81	5.85	0.83	0.94

Table 4.12 Performance rating for QUAL2K model Calibration in February 2019.

Evaluation statistics	**DO**	**BOD**	**TN**	**TP**
R^2 (R-squared correlation)	0.86	0.97	0.83	0.92
RSR (The RMSE-observations standard deviation ratio)	0.49	0.42	0.54	0.42
NSE (The Nash-Sutcliffe efficiency)	0.74	0.82	0.69	0.82

Table 4.11 shows the results of the calibration period for different water quality variables. R^2 from 0.83 to 0.97 for all variables, these can be viewed as a very good level of performance if R^2 is higher than 0.75 according to Hessa (2012). NSE value of DO and TN has from 0.74 and 0.69 showed that the performance of the model is good, besides the NSE value of BOD and TP is very good (Moriasi et al. 2015). In

addition, the RSR values vary between 0.42 and 0.54 and these magnitudes are as very good as or better than those regularly reported in water quality studies (Hesse et al., 2012). It can be concluded that the BOD calibration in the Lam Takhong river by the Qual2K model obtained a very good result.

The correlation between simulated and observed values for DO, BOD, TN, and TP showed a high correlation coefficient (R^2), the Nash-Sutcliffe efficiency (NSE), and RSR as shown in Table 4.12. These high correlation coefficients and lower RSR reaching to zero between observed and simulated values show that this model is perfectly reliable in modeling streams due to an acceptable match of the simulated data with measured data. This can be concluded that the QUAL2K model can be used to predict the effect of point and non-point diffusion on river water quality in the downstream of Lam Takhong river. The Qual2K applied in this study can provide a basis for water resources management in decision making for the future.

4.2.3 Water quality validation

Input data was collected on 28 November 2019 and was used to validated by the Qual2K model. The validation results for the water quality in Lam Takhong river at six monitoring locations are presented from Fig 4.14 to Fig 4.17. The simulated results are presented as continuous lines and the observed data as symbols. The model validated results are in well fit with the measured data, with some exceptions.

The model was validated with observed water quality data in November 2019 using parameters that were derived from the model calibration with the observed data. The validation results (Table 4.13) showed that the calibrated parameters used in the model were able to reproduce the observed data in the validation period.

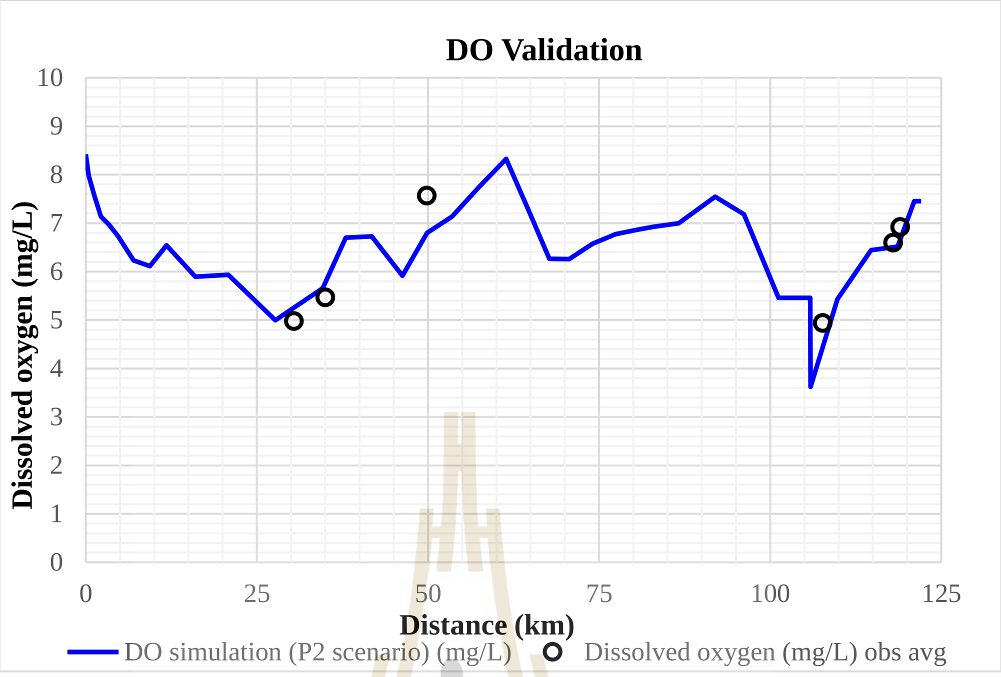


Figure 4.14 Validation results of DO in Lam Takhong River in November 2019.

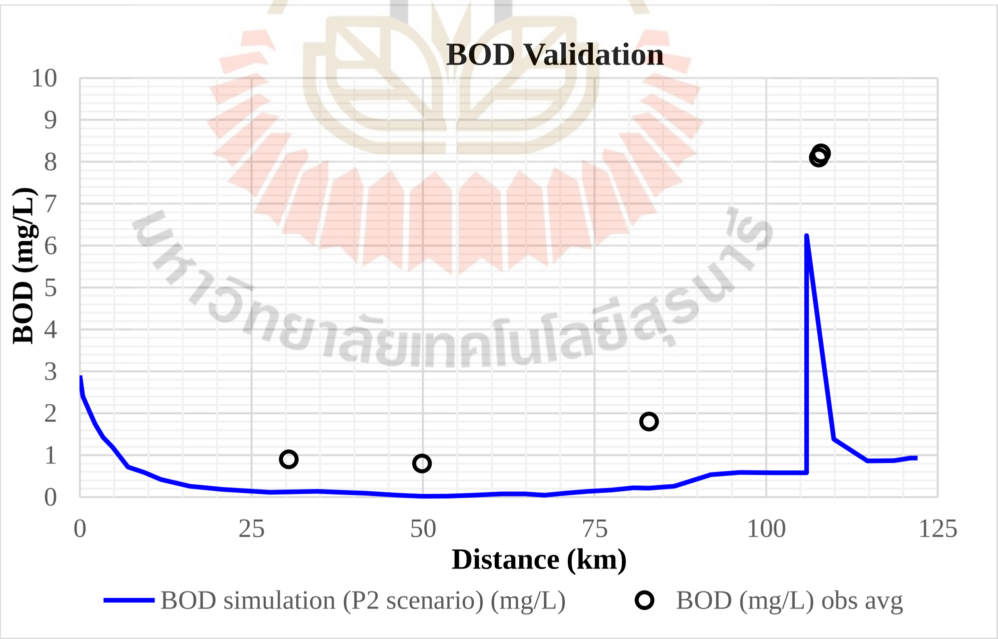


Figure 4.15 Validation of BOD in Lam Takhong River in November 2019.

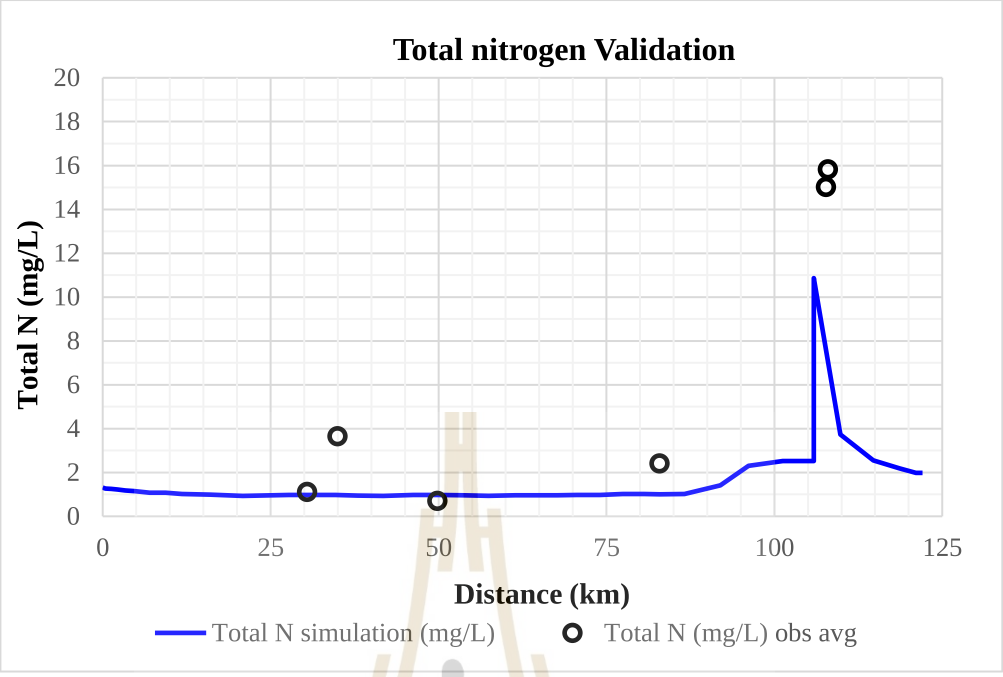


Figure 4.16 Validation of total nitrogen in Lam Takhong River in November 2019.

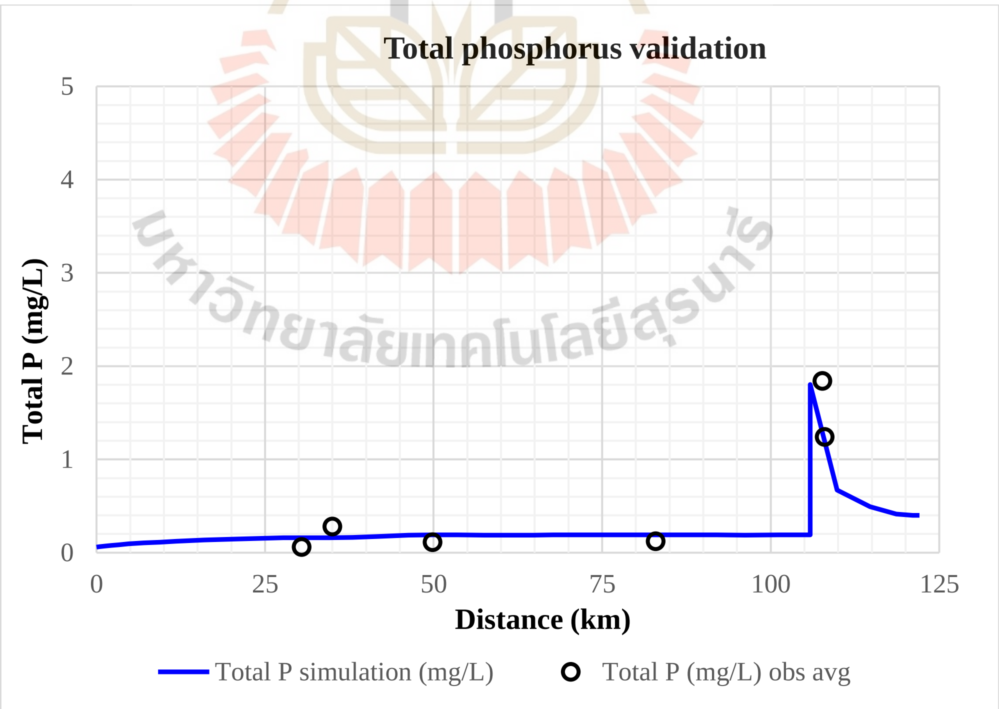


Figure 4.17 Validation results of TP in Lam Takhong River in November 2019.

Table 4.13 Observed and simulated water quality data in November 2019.

DO_obs (mg/L)	DO_sim (mg/L)	BOD_obs (mg/L)	BOD_sim (mg/L)	TN_obs (mg/L)	TN_sim (mg/L)	TP_obs (mg/L)	TP_sim (mgP/L)
4.98	5.20	0.90	0.20	1.11	0.97	0.06	0.16
5.47	5.60	0.80	0.05	3.65	0.95	0.28	0.16
7.57	6.80	1.80	0.25	0.71	0.98	0.11	0.19
4.94	4.60	1.80	0.20	2.41	1.01	0.12	0.19
6.60	6.50	8.10	5.40	15.02	10.00	1.84	1.60
6.92	6.85	8.20	5.25	15.82	9.50	1.24	1.20

Table 4.14 Performance rating for QUAL2K model validation in November 2019.

Evaluation statistics	DO	BOD	TN	TP
R2	0.91	0.99	0.97	0.98
RSR	0.36	0.44	0.55	0.18
NSE	0.87	0.65	0.70	0.97

Table 4.14 presents the performance ratings for the validation period for different water quality variables. It shows that for downstream of the river fit between observed and simulated DO, BOD, TN, and TP values are good. These results are not a large difference between observed and simulated values. However, in km105.88 location in the downstream value of BOD, TN, TP sudden increase in the highest value because of WWTP of city discharge a high loading in 105km.

The statistics value of DO and TP parameters in both calibration and validation are in a very good range (R2, NSE ≥ 0.75, and RSR ≤ 0.5). Besides, results showed that, for the downstream part of the river (from reach of 30), the fit between observed and simulated values is good for all parameters but at the upstream reaches the observed values decrease more rapidly than the simulated ones.

4.3 Contribution of pollution sources to the pollution of Lam Takhong River

4.3.1 TMDL and percentage of contribution from different pollution sources to the pollution of Lam Takhong River in 2019

4.3.1.1 TMDL and percentage of BOD contribution from different pollution sources

Pollutant resources discharge into Lam Takhong river consisting of wastewater treatment plants, pig farms, industrials, urban areas, and agricultural diffuse sources. WWTPs is the pollutant source that contributes to the highest loading in the river. The BOD contribution from different pollution sources is shown in Table 4.15.

Table 4.15 TMDL and percentage of BOD contribution from different pollution sources in Lam Takhong river in 2019

PS	**BOD (mg/l)**	**Q (m3/s)**	**WLA (kg/day)**	**Contribution (%)**
WWTP	20	0.8495	1468	89.13
PS_Industrial	20-77.5	0.0461	115	6.98
Total			**1583**	
NPS	**BOD (mg/l)**	**Q (m^3/s)**	**LA (kg/day)**	
Urban	-	-	**64**	3.89
TMDL = WLA (ps) **(96.11%)** + LA (NPS) **(3.89%)**			**1647**	

Table 4.15 pointed out that WWTP is the main source (89.13%) distributing pollutants into in downstream of Lam Takhong River and affecting water quality in the study area.

4.3.1.2 TMDL and percentage of nutrient contribution from different pollution sources

Pollution sources release nutrients into the Lam Takhong River including point sources and diffuse sources (urban and agriculture). Table 4.16 showed nutrient load from agricultural sources.

Table 4.16 Nutrient contribution from agriculture land in 2019

Land use	Area (km^2)	%	Load_N (kg/yr)	%	Load_P (kg/yr)	%
Rice	456.72	32.27	14.89	23.35	10.23	21.42
Corn	81.57	5.76	6.16	9.66	1.96	4.10
Sugercane	82.27	5.81	4.01	6.30	0.99	2.07
Cassava	628.55	44.40	30.17	47.32	30.17	63.16
others	166.39	11.75	8.52	13.36	4.43	9.26
Total	1415.50	100.00	63.75	100.00	47.77	100.00

In the Lam Takhong basin, land use area for cassava and rice occupies the majority around 77%. Thus Nitrogen and Phosphorus load from these sources dominate, approximately 71% for nitrogen and 85% for phosphorus in all agricultural discharge sources.

Table 4.17 Pollutant contribution from agriculture land and urban area in 2019

Land use	Area	POP	BOD (kg/d)	%	TN (kg/d)	%	TP (kg/d)	%
Urban	1598.42	709921	64	100	220	99.92	7.10	98.2
Agriculture	1415.50		0	0	0.175	0.08	0.13	1.8
Total	64	100	220.175		100	7.23		100

Rice and cassava are two kinds of plants accounting for the majority of the region. However, the total loading of nutrients from the agriculture area is very low (under 2%) compare to loading from urban areas (Table 4.17) For this reason, the water quality simulation process of this study only focuses on urban discharge sources for diffuse sources.

4.3.2 TMDL and percentage of contribution from different pollution sources to the pollution of Lam Takhong River in future

Similar to 2019, the WWTPs is also the main point resource (88.78%) in 2027, the urban area is the main diffuse resource showed in Table 4.19, and rice and cassava are also plants accounting for the majority of the region Table 4.18.

Table 4.18 Nutrient contribution from agriculture land in 2027

Land use	Area(km^2)	%	Load_N (kg/yr)	%	Load_P (kg/yr)	%
Rice	456.72	32.28	14.89	23.37	10.23	21.42
Corn	81.15	5.74	6.13	9.62	1.95	4.08
Sugercane	82.27	5.81	4.01	6.30	0.99	2.07
Cassava	628.54	44.42	30.17	47.36	30.17	63.18
others	166.18	11.75	8.51	13.36	4.42	9.26
Total	1414.86	100%	63.71	100%	47.76	100%

Table 4.19 Pollutant contribution from agriculture land and urban area in 2027

Land use	Area	POP	BOD (kg/d)	%	TN (kg/d)	%	TP (kg/d)	%
Urban	1602.58	784142	70.57	**100**	243.08	**99.93**	7.84	**98.36**
Agriculture	1414.86		0.00	0	0.175	0.07	0.13	1.64
Total			70.57	100	243.255	100	7.97	100

Land use will increase the area in 2027 and polluted loading from urban source also rise accordingly around 10.3% compared to 2019 (Table 4.17).

Table 4.20 TMDL and percentage of BOD contribution from different pollution sources in 2027

PS	BOD (mg/l)	Q (m3/s)	WLA (kg/day)	Contribution (%)
WWTP	20	0.8495	1468	88.78
PS_Industrial	20-77.5	0.0461	115	6.95
Total			**1583**	
NPS	**BOD (mg/l)**	**Q (m^3/s)**	**LA (kg/day)**	
Urban	-	-	**70.57**	4.27
TMDL = WLA (ps) **(88.78%)** + LA (NPS) **(4.27%)**			**1653.57**	

Nevertheless, the percentage of discharge load into the river has not increased significantly (increasing 0.38%) and still accounts for a low proportion of the total emission source (4.27%) mentioned in Table 4.20.

The pollutant loading and percentage of contribution from pollution sources in 2035 are slightly different in 2027, mainly increasing emissions from urban waste in Table 4.21 and Table 4.22.

Table 4.21 Nutrient contribution from agriculture land in 2035

Land use	Area(km^2)	%	Load_N (kg/yr)	%	Load_P (kg/yr)	%
Rice	456.72	32.28	14.89	23.37	10.23	21.42
Corn	81.15	5.74	6.13	9.62	1.95	4.08
Sugercane	82.27	5.81	4.01	6.30	0.99	2.07
Cassava	628.54	44.42	30.17	47.36	30.17	63.18
others	166.17	11.74	8.51	13.36	4.42	9.26
Total	1414.85	100.00	63.71	100.00	47.76	100.00

Table 4.22 Pollutant contribution from agriculture land and urban area in 2035

Land use	Area	POP	BOD (kg/d)	%	TN (kg/d)	%	TP (kg/d)	%
Urban	1602.58	879521	79.16	**100**	272.65	**99.94**	8.795	**98.53**
Agriculture	1414.86		0.00	0	0.175	0.06	0.131	1.47
Total			79.16	100	272.825	100	8.926	100

Agriculture area will not increase in the future but population will be go up approximately 10% so pollutant loading of BOD and nutrient from urban area will increase in 2027 and 2035 (Table 4.23).

Table 4.23 Contribution of diffuse sources into the Lam Takhong River

Year	Agricultural load class 2-6 (kg/yr)			Urban (kg/yr)				
	Area (Km^2)	Load_N	Load_P	Area (Km^2)	POP	BOD	TN	TP
2019	1415.50	63.75	47.77	1598.4	709921	23320.9	80327.5	2591.2
2027	1414.86	63.71	47.76	1602.6	784142	25759.1	88725.7	2862.1
2035	1414.86	63.71	47.76	1602.6	879522	28892.3	99517.9	3210.3

4.4 Scenarios for water quality control

4.4.1 BOD loading reduction of point sources

4.4.1.1 Reduction of BOD discharge from WWTPs

From simulation results of the calibration and validation, it can be said that the river water is not appropriate for fisheries survival in location km 105.88 from upstream where the minimum DO concentration is 3.63 mg/L and BOD5 concentration is 6.24 mg/L (below class 3 standard) in rivers. Therefore the study conducted scenarios of BOD reduction released into the Lam Takhong River from WWTPs as shown in Figure 4.18. While BAU is the P1 scenario, P2_W1 to P2_W4 scenarios were described in the table 4.9.

The reduction of BOD from WWTP does not significantly affect the DO trend in the river. When 50% of BOD discharge was reduced, DO value rise 0.11 mg/L from 3.62 mg/L to 3.73 mg/L (Table 4.24). However, BOD value meaningfully lower from 6.24 mg/L down to 3.25 mg/L (Table 4.25) can meet the class three standard (Figure 4.19).

4.4.1.2 Combining reduction of BOD and nutrient discharge from WWTPs

The result of the simulated scenario indicates that nutrient discharge of WWTPs has a slight effect on DO concentrations in rivers (Figure 4.20). When 50% nutrient is reduced, DO increases 0.25 mg/L (Table 4.26). This reduced value is not significant compared to the investment cost to reduce the nutrient discharge from WWTPs by 50%.

Nutrient value from WWTPs does not greatly change BOD value in LTK River compared to initial BOD before reducing nutrients from this source (Figure 4.21), only BOD reduction will effect on BOD trend in the river (Table 4.27).

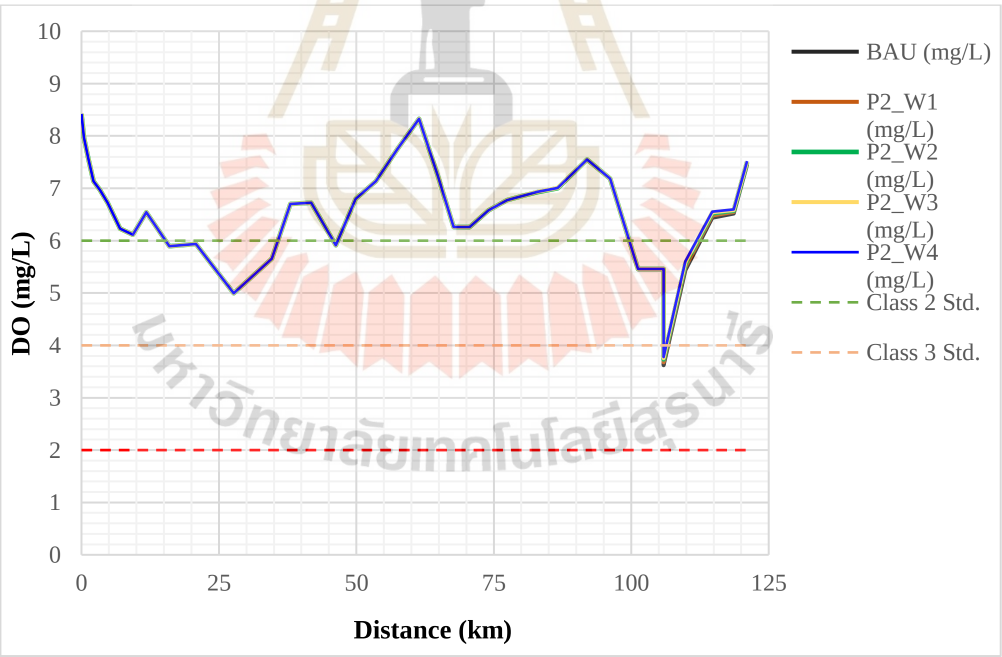


Figure 4.18 Scenarios BOD reduction of WWTP into LTK River and impact on DO

Table 4.24 DO change according to BOD discharge reduction from WWTPs.

NO.	Distance (km)	BAU (mg/L)	P2_W1 (mg/L)	P2_W2 (mg/L)	P2_W3 (mg/L)	P2_W4 (mg/L)
1	0.00	8.42	8.42	8.42	8.42	8.42
2	9.37	6.11	6.11	6.11	6.11	6.11
3	20.83	5.94	5.94	5.94	5.94	5.94
4	41.76	6.72	6.72	6.72	6.72	6.72
5	61.41	8.32	8.32	8.32	8.32	8.32
6	80.64	6.86	6.87	6.87	6.87	6.87
7	101.24	5.46	5.46	5.46	5.46	5.46
8	**105.88**	**3.62**	**3.68**	**3.73**	**3.76**	**3.78**
9	109.85	5.43	5.50	5.56	5.58	5.61
10	114.75	6.44	6.48	6.52	6.54	6.56
11	118.64	6.52	6.55	6.58	6.59	6.60
12	122.00	7.45	7.48	7.50	7.51	7.52

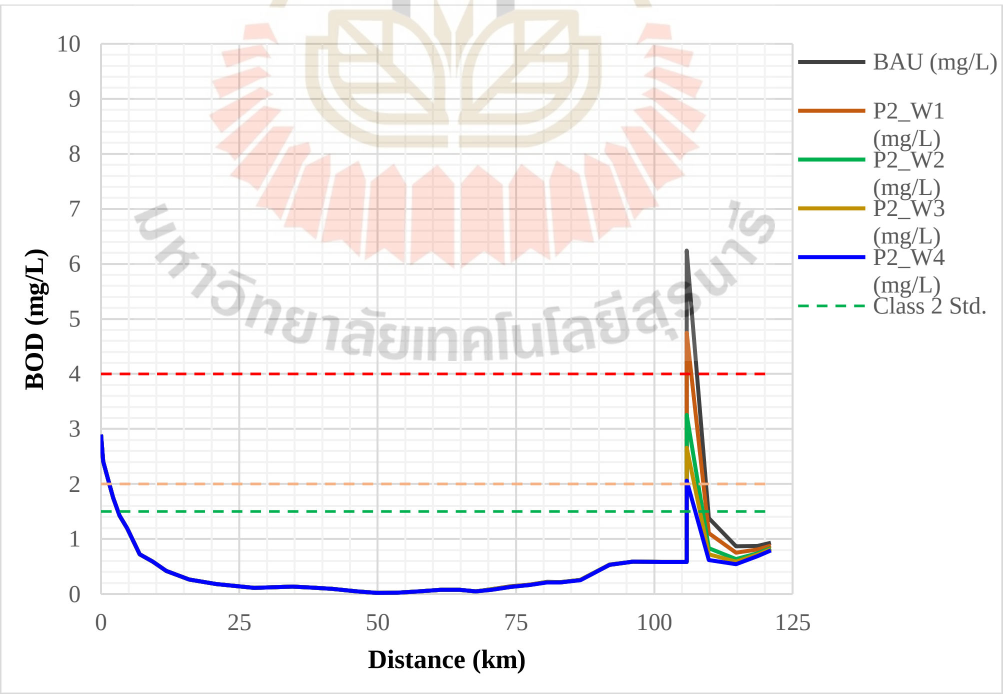


Figure 4.19 Scenarios BOD reduction of WWTP into LTK River and impact on BOD

Table 4.25 BOD concentration in LTK River according to the reduction of BOD discharge from WWTPs

No.	Distance (km)	BAU (mg/L)	P2_W1 (mg/L)	P2_W2 (mg/L)	P2_W3 (mg/L)	P2_W4 (mg/L)
1	0.00	2.90	2.90	2.90	2.90	2.90
2	9.37	0.59	0.59	0.59	0.59	0.59
3	20.83	0.18	0.18	0.18	0.18	0.18
4	41.76	0.09	0.09	0.09	0.09	0.09
5	61.41	0.08	0.08	0.08	0.08	0.08
6	80.64	0.22	0.22	0.22	0.21	0.21
7	101.24	0.58	0.58	0.58	0.58	0.58
8	**105.88**	**6.24**	**4.75**	**3.25**	**2.66**	**2.06**
9	109.85	1.38	1.11	0.83	0.72	0.62
10	114.75	0.87	0.75	0.63	0.59	0.54
11	118.64	0.87	0.81	0.74	0.72	0.69
12	122.00	0.93	0.88	0.83	0.81	0.79

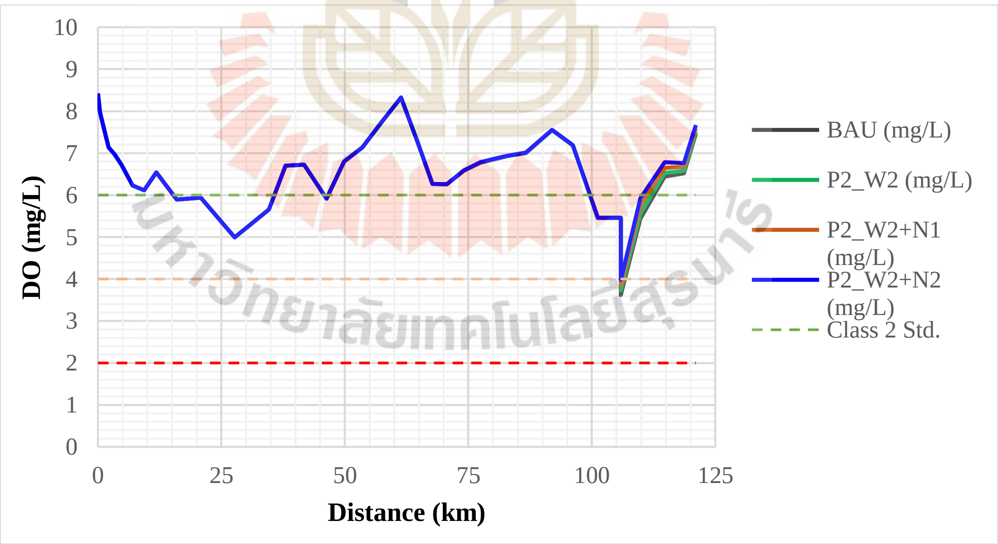


Figure 4.20 DO concentration in LTK River when combining the reduction of BOD and nutrient discharge from WWTPs

Table 4.26 DO concentration in LTK River according to the reduction of BOD and nutrient discharge from WWTPs

No.	Distance (km)	BAU (mg/L)	P2_W2 (mg/L)	P2_W2+N1 (mg/L)	P2_W2+N2 (mg/L)
1	0.00	8.42	8.42	8.42	8.42
2	9.37	6.11	6.11	6.11	6.11
3	20.83	5.94	5.94	5.94	5.94
4	41.76	6.72	6.72	6.72	6.72
5	61.41	8.32	8.32	8.32	8.32
6	80.64	6.86	6.87	6.87	6.87
7	101.24	5.46	5.46	5.46	5.46
8	**105.88**	**3.62**	**3.73**	**3.85**	**3.98**
9	109.85	5.43	5.56	5.74	5.92
10	114.75	6.44	6.52	6.65	6.78
11	118.64	6.52	6.58	6.67	6.76
12	122.00	7.45	7.50	7.58	7.67

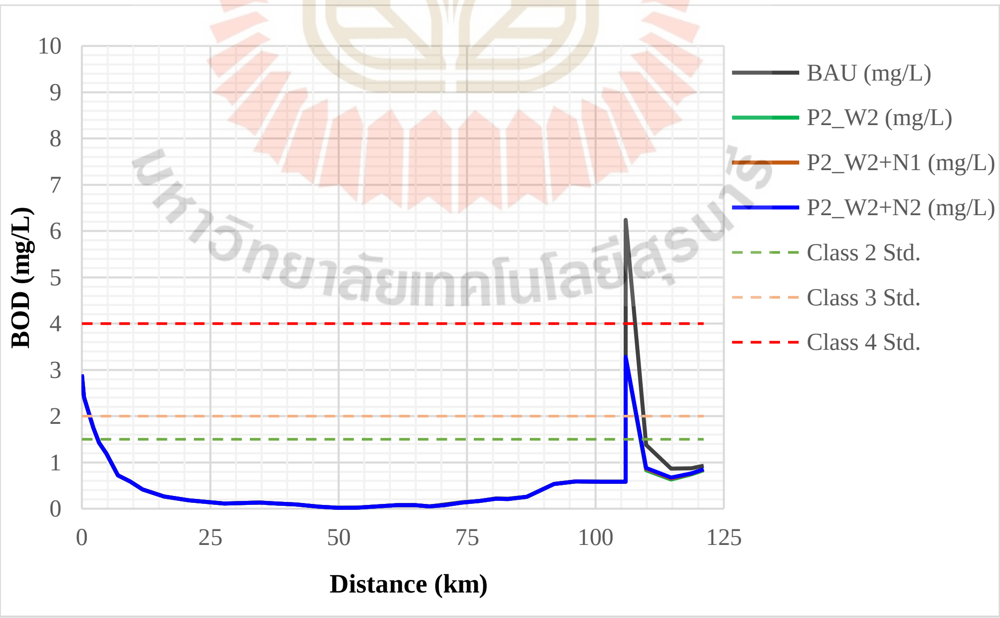


Figure 4.21 BOD concentration in LTK River when combining the reduction of BOD and nutrient discharge from WWTPs.

Table 4.27 BOD concentration in LTK River according to the reduction of BOD and nutrient discharge from WWTPs.

No.	Distance (km)	BAU (mg/L)	P2_W2 (mg/L)	P2_W2+N1 (mg/L)	P2_W2+N2 (mg/L)
1	0.00	2.90	2.90	2.90	2.90
2	9.37	0.59	0.59	0.59	0.59
3	20.83	0.18	0.18	0.18	0.18
4	41.76	0.09	0.09	0.09	0.09
5	61.41	0.08	0.08	0.08	0.08
6	80.64	0.22	0.22	0.22	0.22
7	101.24	0.58	0.58	0.58	0.58
8	**105.88**	**6.24**	**3.25**	**3.27**	**3.28**
9	109.85	1.38	0.83	0.86	0.88
10	114.75	0.87	0.63	0.65	0.67
11	118.64	0.87	0.74	0.75	0.77
12	122.00	0.93	0.83	0.84	0.85

4.4.2 BOD loading reduction of diffuse sources

In the scenarios group of BOD load reduction, these are two scenarios P2_U1 and P2_U2 that BOD load from the urban area is reduced 25% and 50% compared to BAU scenario in November 2019 (Figure 4.22 and 4.23).

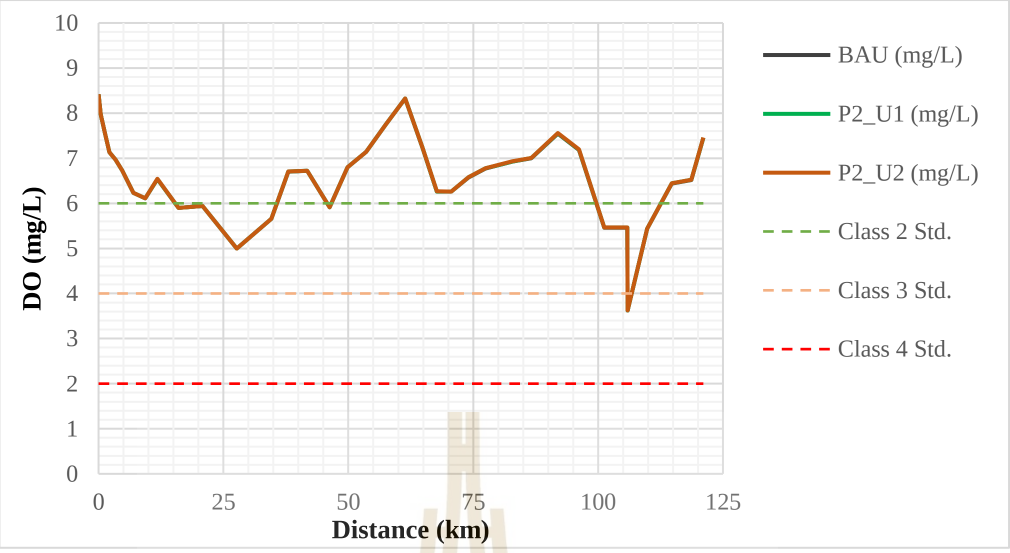


Figure 4.22 DO Profile with BOD reduction of urban scenarios.

Table 4.28 DO concentration in LTK River according to reduction of BOD from urban area

No.	Distance (km)	BAU (mg/L)	P2_U1 (mg/L)	P2_U2 (mg/L)
1	0.00	8.42	8.42	8.42
2	9.37	6.11	6.11	6.11
3	20.83	5.94	5.94	5.94
4	41.76	6.72	6.72	6.72
5	61.41	8.32	8.33	8.33
6	80.64	6.86	6.87	6.87
7	101.24	5.46	5.46	5.47
8	**105.88**	**3.62**	**3.62**	**3.63**
9	109.85	5.43	5.44	5.44
10	114.75	6.44	6.44	6.45
11	118.64	6.52	6.52	6.52
12	122.00	7.45	7.46	7.46

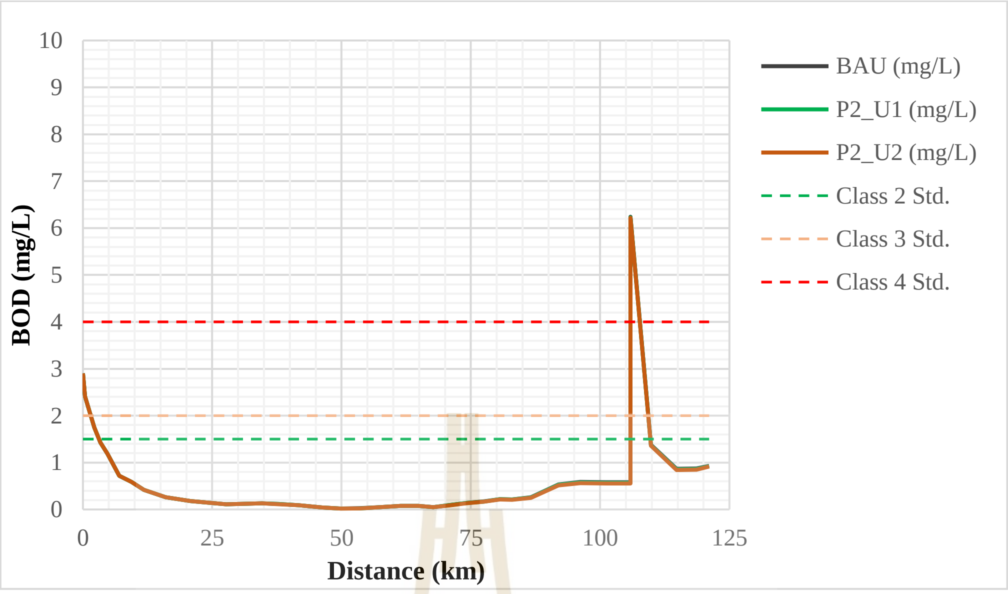


Figure 4.23 BOD Profile with BOD reduction of urban scenarios

Table 4.29 BOD concentration in LTK River according to the reduction of BOD from the urban area

No.	Distance (km)	BAU (mg/L)	P2_U1 (mg/L)	P2_U2 (mg/L)
1	0.00	2.90	2.90	2.90
2	9.37	0.59	0.59	0.58
3	20.83	0.18	0.18	0.18
4	41.76	0.09	0.09	0.09
5	61.41	0.08	0.08	0.07
6	80.64	0.22	0.22	0.21
7	101.24	0.58	0.57	0.55
8	**105.88**	**6.24**	**6.23**	**6.22**
9	109.85	1.38	1.37	1.36
10	114.75	0.87	0.85	0.84
11	118.64	0.87	0.86	0.85
12	122.00	0.93	0.92	0.91

Table 4.28 and Table 4.29 shown that BOD load reduction from the urban area makes a change of DO and BOD value in the Lam Takhong River. The results of these BOD reductions pointed up that BOD from urban sources does not affect the change in DO trend as well as BOD in the Lam Takhong river.

Table 4.30 Water quality date from diffuse resources discharge into LTK River

Up (km)	Down (km)	POP	Q Feb19 (cms)	BOD Feb19 (mg/L)	TN Feb19 (µg/L)	TP Feb19 (µg/L)	NH_4-N Feb19 (µg/l)	OrgN_Feb19 (µg/l)
0.00	15.91	43092	0.47	0.10	329.13	10.62	286.66	42.47
15.91	31.32	33092	0.43	0.08	277.14	8.94	241.38	35.76
31.32	43.19	14856	0.15	0.10	359.16	11.59	312.81	46.34
43.19	51.25	81818	1.07	0.08	273.43	8.82	238.15	35.28
51.25	63.63	16643	0.03	0.55	1890.82	60.99	1646.84	243.98
63.63	69.60	46864	0.34	0.15	499.96	16.13	435.45	64.51
69.60	85.56	97438	0.22	0.46	1584.64	51.12	1380.17	204.47
85.56	101.28	188533	0.08	2.61	9003.76	290.44	7841.98	1161.78
101.28	109.31	125503	0.20	0.67	2306.44	74.40	2008.83	297.60
109.31	117.49	62082	0.06	1.05	3626.53	116.98	3158.59	467.94

4.4.3 Determining of TMDL reduction to meet water quality standard targets in Thailand

BOD values are reduced from 25% to 70% respectively and the TMDL is calculated accordingly. Table 4.31 shows that if a 50% BOD reduction is obtained from WWTPs (10 mg/L), the water quality will change from level 4 to level 3 in the surface water quality standard in Thailand. In addition, the TMDL releases into the river need to be reduced by 44.57% of the total source.

Table 4.31 Estimating TMDL reduction to water quality meet the standard

Scenario (WWTP)	% Reduction	BOD (mg/L)	Load BOD WWTP (kg/d)	Load BOD Industrials (kg/d)	BOD WLA (kg/d)	BOD LA (kg/d)	BOD TMDL (kg/d)	% WLA	% LA	%TMDL Reduction
BAU	100%	20.00	1468	115	1583	64	1647	96.11	3.89	0.00
P2_W1	25%	15.00	1101	115	1216	64	1280	95.00	5.00	22.28
P2_W2	50%	10.00	734	115	849	64	913	92.99	7.01	**44.57**
P2_W3	60%	8.00	587.2	115	702	64	766	91.65	8.35	53.48
P2_W4	70%	7.00	440.4	115	555	64	619	89.67	10.33	62.39

4.5 Scenarios for water quality prediction

The scenarios were run to assess the impact of the point sources and non-point sources loads on the quality water of the Lam Takhong River. Many types of sources are located along the Lam Takhong basin, three types are spread along each reach of the river network, i.e. WWTP, industries, and urban area. Based on those, four groups of model scenarios were conducted to investigate the impact of point and non-point sources on the water quality in terms of DO and BOD. The simulated scenarios and their analysis are as follow:

4.5.1 Land use change in the Lam Takhong watershed

The predicted results of flow and water yield from the subbasin into the Lam Takhong river in 2027 by SWAT are the input data of water quality forecast using the Qual2K water quality model. Streamflow affected DO and BOD both in February and November 2027 (Figure 4.24) when the flow of headwater and flow from subbasin increase in 2027 (Table 4.6 and Table 4.8), F1, and F2 simulated scenario is shown in

Figure 4.24 and 4.25. On the other hand, urban area and population increase in 2027 (F1-LUC and F2-LUC scenarios) (Table 4.23), it is the reason that DO and BOD change in 2027. However, land use change slightly effects on BOD and DO (Table 4.32 and 4.33).

It is determined that land use change does not greatly affect the trend of river water quality, but that the flow from headwater and subbasin have a significant impact on water quality (Figure 4.24 To Figure 4.27).

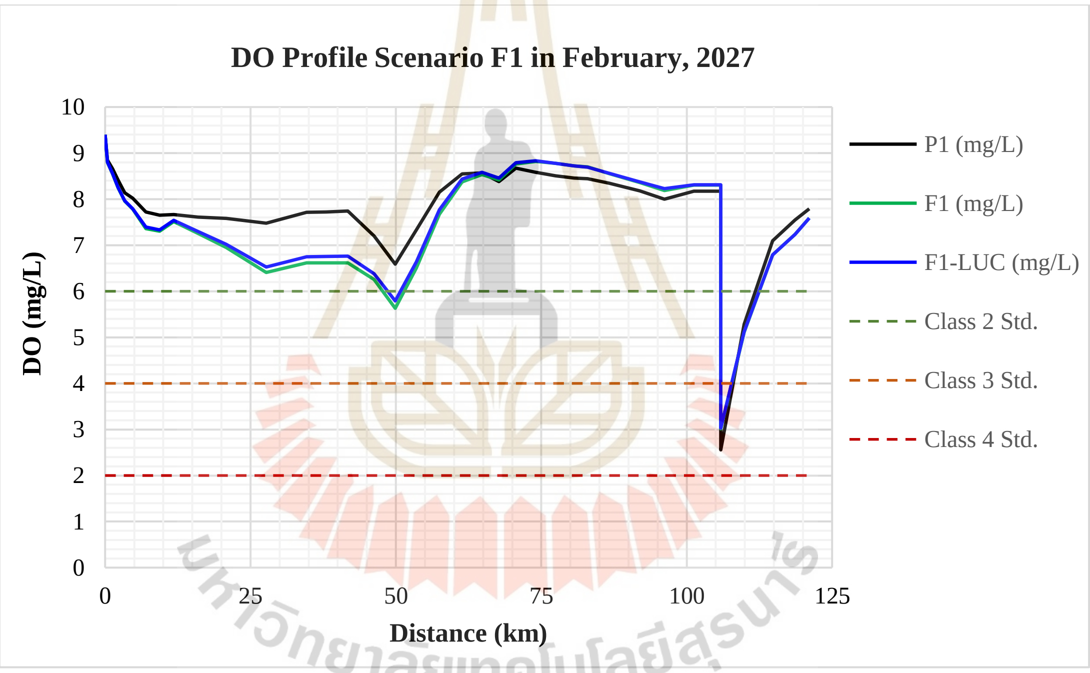


Figure 4.24 Land use change scenarios impact on DO concentration in February 2027.

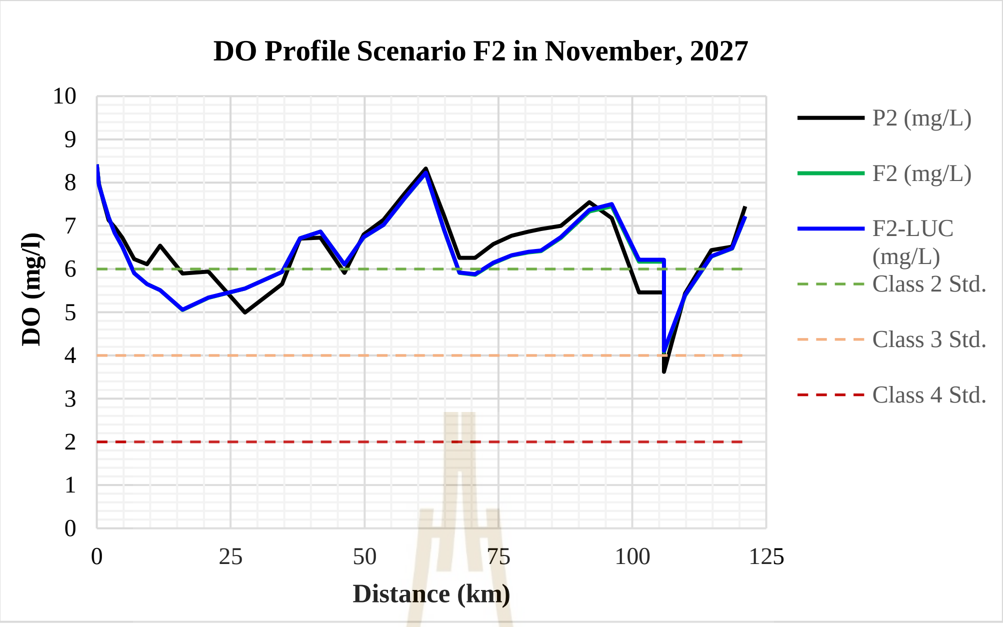


Figure 4.25 Land use change scenarios impact on DO concentration in November 2027.

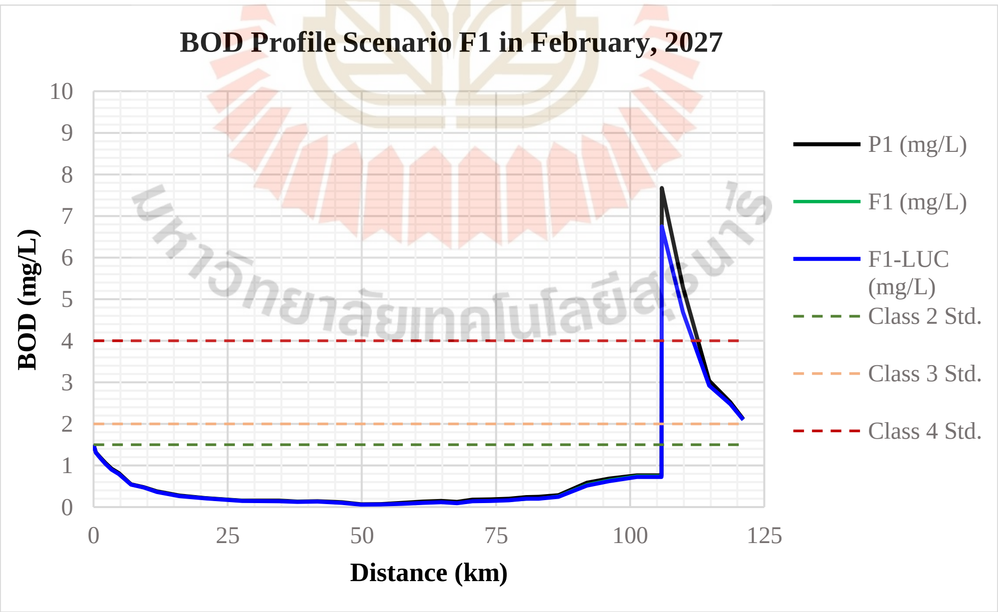


Figure 4.26 Land use change scenarios impact on BOD concentration in February 2027.

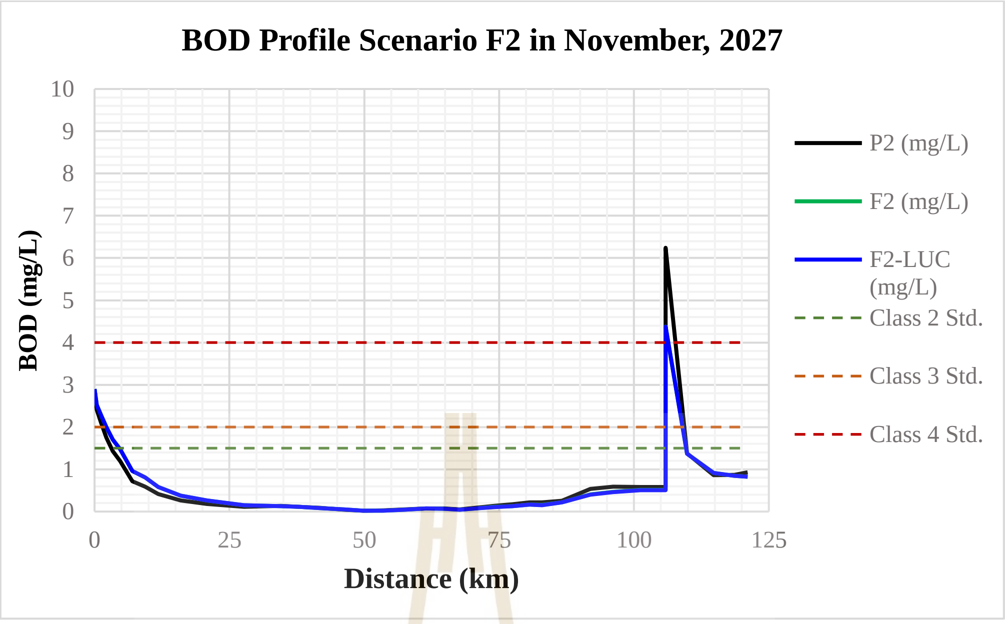


Figure 4.27 Land use change scenarios impact on BOD concentration in November 2027.

Table 4.32 DO and BOD concentration in LTK River with Land use change in February 2027

No.	Distance (km)	DO (mg/L)			BOD (mg/L)		
		P1	F1	F1-LUC	P1	F1	F1-LUC
1	0.00	9.40	9.40	9.40	1.50	1.50	1.50
2	9.37	7.65	7.30	7.33	0.48	0.47	0.47
3	20.83	7.58	6.95	7.02	0.22	0.22	0.21
4	41.76	7.74	6.61	6.76	0.14	0.13	0.13
5	61.41	8.54	8.38	8.44	0.13	0.10	0.10
6	80.64	8.46	8.72	8.72	0.24	0.20	0.20
7	101.24	8.17	8.30	8.31	0.76	0.75	0.72
8	**105.88**	**2.56**	**3.02**	**3.03**	**7.67**	**6.76**	**6.75**
9	109.85	5.28	5.11	5.12	5.29	4.69	4.69
10	114.75	7.09	6.79	6.79	3.04	2.92	2.92
11	118.64	7.55	7.24	7.23	2.52	2.48	2.48
12	122.00	7.79	7.59	7.59	2.12	2.10	2.10

Table 4.33 DO and BOD concentration in LTK River with Land use change in November 2027

No.	Distance (km)	DO (mg/L)			BOD (mg/L)		
		P2	F2	F2_LUC	P2	F2	F2_LUC
1	0.00	8.42	8.42	8.42	2.90	2.90	2.90
2	9.37	6.11	5.65	5.65	0.59	0.81	0.80
3	20.83	5.94	5.34	5.34	0.18	0.26	0.26
4	41.76	6.72	6.86	6.87	0.09	0.09	0.08
5	61.41	8.32	8.22	8.23	0.08	0.07	0.07
6	80.64	6.86	6.39	6.40	0.22	0.16	0.16
7	101.24	5.46	6.17	6.21	0.58	0.51	0.51
8	**105.88**	**3.62**	**4.08**	**4.11**	6.24	**4.38**	**4.38**
9	109.85	5.43	5.39	5.40	1.38	1.37	1.37
10	114.75	6.44	6.29	6.30	0.87	0.92	0.92
11	118.64	6.52	6.47	6.48	0.87	0.85	0.85
12	122.00	7.45	6.47	6.48	0.93	0.85	0.85

Land use change in 2027 (Table 4.32 and 4.33) poses less impact on water quality including DO and BOD concentration in the Lam Takhong River because the loading from diffuse sources discharges into the river accounts for less than 5% of the total load (Table 4.20).

4.5.2 Change the outflow of wastewater treatment plants

The wastewater treatment plants along the Lam Takhong River basin, Korat Municipality WWTP is located in 105 km downstream and has the highest BOD load released into the river. From F1_110%Q, F1_120%Q scenarios and F2_110%Q, F2_120%Q scenarios have respectively been done to detect the impact of discharge from WWTPs, while the other sources remain at the same rates. Figures 4.28 to 4.31 shown the changes in DO and BOD after the outflow of the WWTPs changed and Table

4.34 and 4.35 summarizes the value change in DO and BOD along the Lam Takhong River due to outflow increase in the future.

The simulation of these scenarios causes a decrease in DO and increase on BOD along the Lam Takhong River both in February and November in 2027. However, the rate of change on DO and BOD is more intense in downstream due to City Municipality WWTP discharge. DO value is lower 0.24 mg/L (7.9%) and 0.46 mg/L (15.2%) and BOD value rises 0.38 mg/L (5.6%) and 0.74 mg/L (11%) (Table 4.34) at km 105.88 in February 2027 when outflow from the city municipality WWTP increase 10% and 20% respectively. On other hand, DO value in November reduces less than February 0.06 mg/L (1.5%) and 0.14 mg/L (3.4%) (Table 4.35)., while the BOD value increases more than February 0.27 mg/L (6.2%) and 0.53 mg/L (12.1%) (Table 4.35). In summary, the flow discharge from WWTP has a slight impact on DO and BOD in Lam Takhong River.

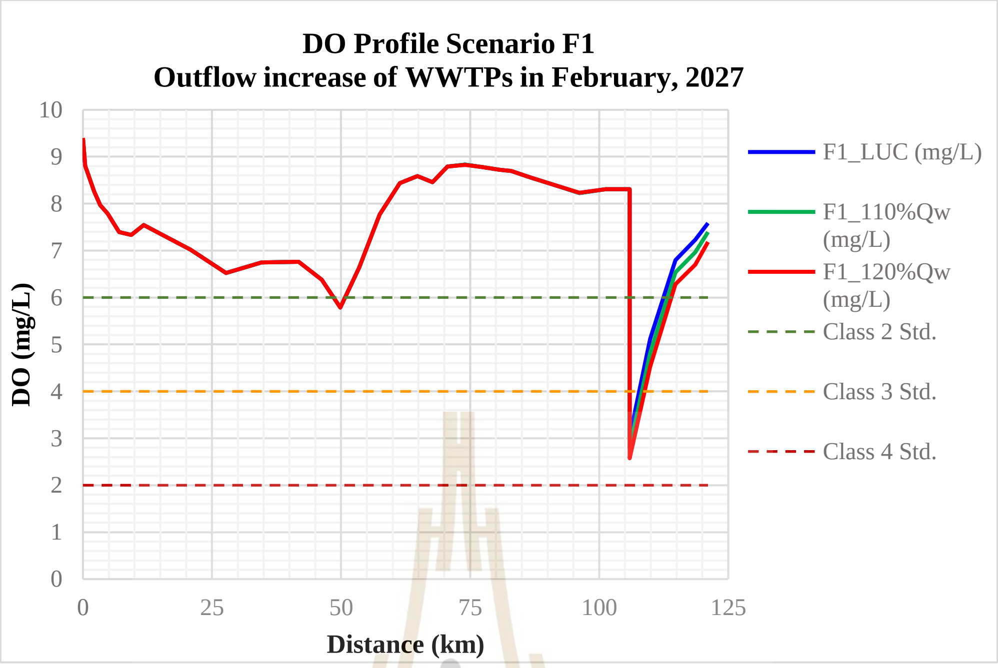


Figure 4.28 DO Profile Scenario F1 Outflow increase of WWTPs in February 2027.

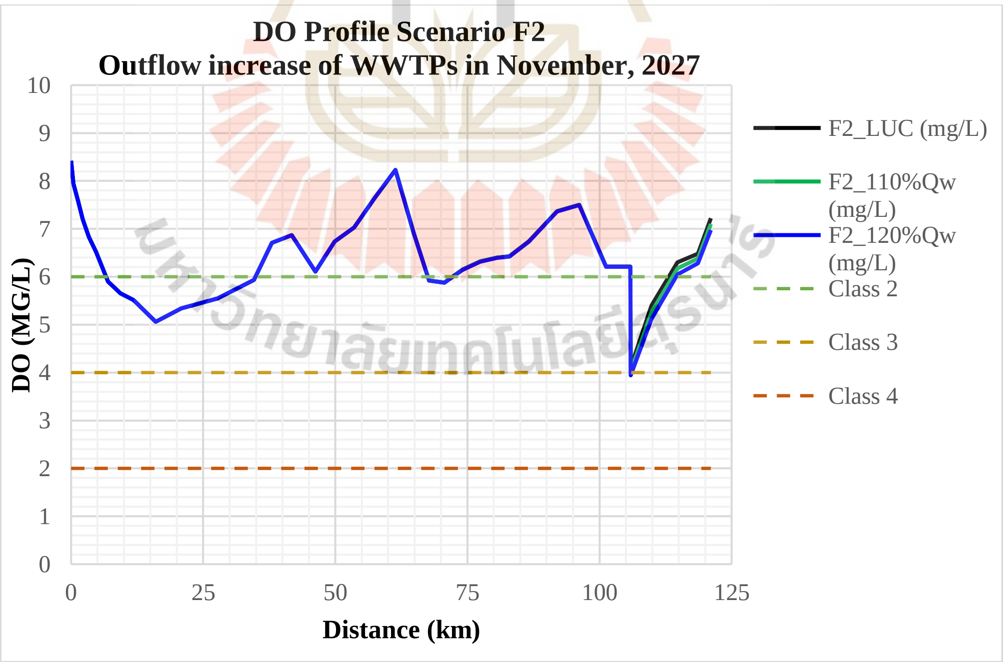


Figure 4.29 DO Profile Scenario F2 Outflow increase of WWTPs in November 2027.

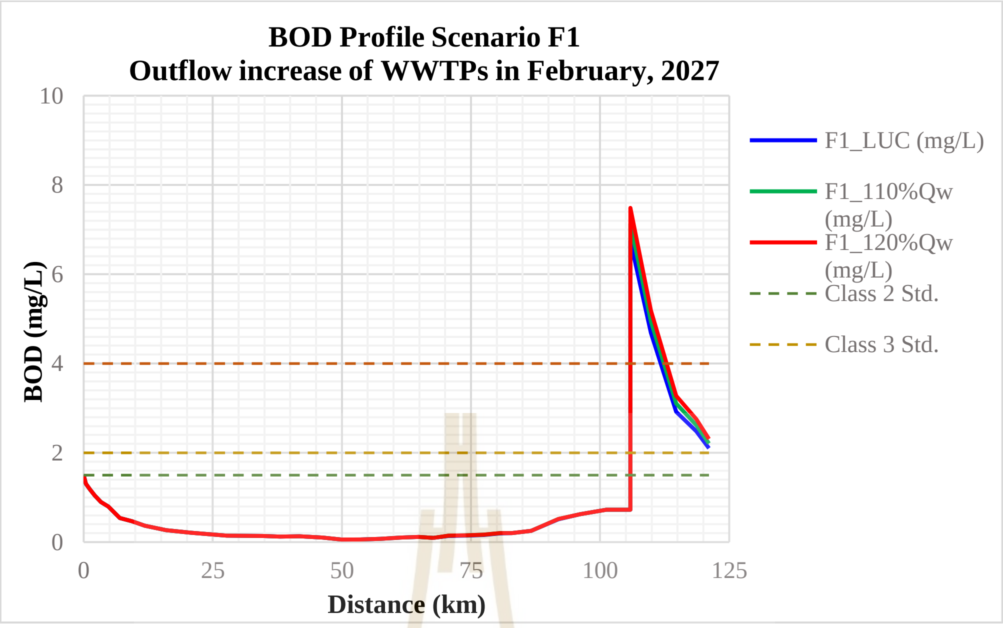


Figure 4.30 BOD Profile Scenario F1 Outflow increase of WWTPs in February 2027.

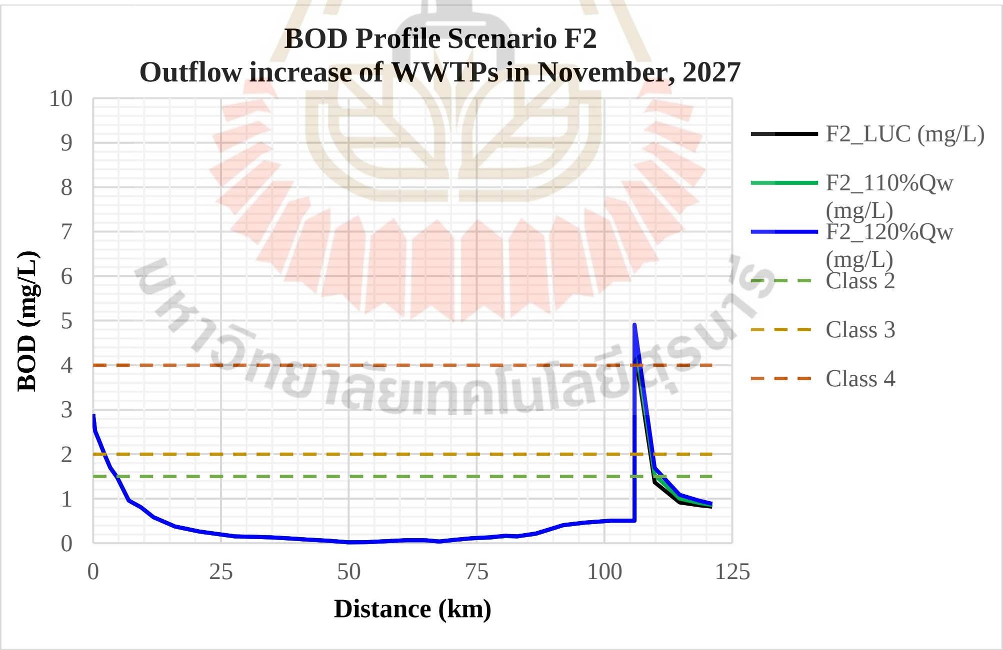


Figure 4.31 BOD Profile Scenario F2 Outflow increase of WWTPs in November 2027.

Table 4.34 DO and BOD concentration in LTK River with the increasing outflow from WWTPs in February 2027

No.	**Distance (km)**	**DO (mg/L)**			**BOD (mg/L)**		
		F1	F1_110%Q	F1_120%Q	F1	F1_110%Q	F1_120%Q
1	0.00	9.40	9.40	9.40	1.50	1.50	1.50
2	9.37	7.33	7.33	7.33	0.47	0.47	0.47
3	20.83	7.02	7.02	7.02	0.21	0.21	0.21
4	41.76	6.76	6.76	6.76	0.13	0.13	0.13
5	61.41	8.44	8.44	8.44	0.10	0.10	0.10
6	80.64	8.72	8.72	8.72	0.20	0.20	0.20
7	101.24	8.31	8.31	8.31	0.72	0.72	0.72
8	**105.88**	**3.03**	**2.79**	**2.57**	**6.75**	**7.13**	**7.49**
9	109.85	5.12	4.82	4.53	4.69	4.95	5.19
10	114.75	6.79	6.54	6.28	2.92	3.10	3.28
11	118.64	7.23	6.97	6.70	2.48	2.62	2.76
12	122.00	7.59	7.39	7.18	2.10	2.21	2.31

Table 4.35 DO and BOD concentration in LTK River with the increasing outflow from WWTPs in November 2027

No.	Distance (km)	DO (mg/L)			BOD (mg/L)		
		F2	F2_110%Qw	F2_120%Qw	F2	F2_110%Qw	F2_120%Qw
1	0.00	8.42	8.42	8.42	2.90	2.90	2.90
2	9.37	5.65	5.65	5.65	0.81	0.80	0.80
3	20.83	5.34	5.34	5.34	0.26	0.26	0.26
4	41.76	6.86	6.87	6.87	0.09	0.08	0.08
5	61.41	8.22	8.23	8.23	0.07	0.07	0.07
6	80.64	6.39	6.40	6.40	0.16	0.16	0.16
7	101.24	6.17	6.21	6.21	0.51	0.51	0.51
8	**105.88**	**4.08**	**4.02**	**3.94**	**4.38**	**4.65**	**4.91**
9	109.85	5.39	5.26	5.12	1.37	1.53	1.69
10	114.75	6.29	6.17	6.05	0.92	1.00	1.09
11	118.64	6.47	6.38	6.28	0.85	0.90	0.95
12	122.00	7.58	7.22	7.22	0.89	0.83	0.82

The outflow of WWTPs are increased up 10% (F2_110%Q scenario) and 20% (F2_120%Q scenario) in November 2027. It is found that DO concentrations are reduced by 0.06 (F2_110%Q) and 0.14 mg/l (F2_120%Q) and BOD concentrations increase slightly by 0.27 (F2_W1) and 0.53 mg/l (F2_120%Q). However, DO value in November 2027 is higher than 2019 in the amount of 0.29 mg/L and at the same time the BOD value also decreased compared to 2019 (1.51 mg/L).

4.5.3 Scenarios of water quality control by BOD discharge reduction from WWTPs

The scenarios in this third group have been hilignted to detect the impact of the WWTP loads on the DO and BOD. These scenarios are simulated to test the reducing WWTP load, while the other point sources remain at their normal rates. It has been assumed that the BOD load reduce by 25% (W1 scenarios) and by 50% (W2 scenarios). Figures 4.32 to 4.35 illustrate the changes in DO and BOD due to reducing the BOD load from WWTPs. However, DO change is not clearly expressed as BOD, BOD value is improved from class four to class three in water quality standard when BOD load is reduced 50% load from WWTP.

Table 4.36 and 4.37 summarize the value change in DO and BOD along the Lam Takhong River due to the simulation of this third scenario group. It can be noticed from Figures 4.32 to 4.35 that the City Municipality WWTP in Lam Takhong River has a very great effect on the water quality in terms of BOD as shown in Table 4.36 and 4.37.

The simulated results of scenarios from Figure 4.32 to Figure 4.35 prove that the most optimal way to control water quality in the Lam Takhong River is to reduce the BOD load from WWTP discharge.

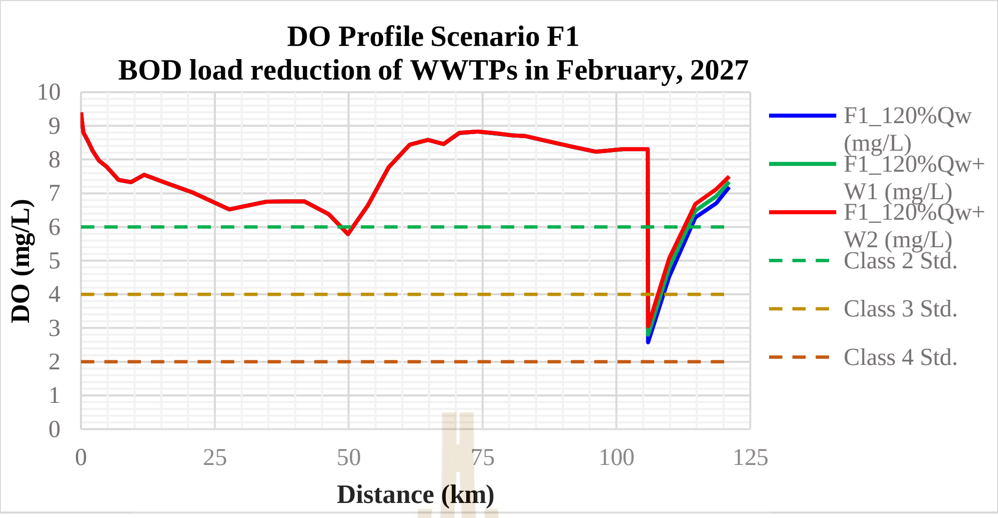


Figure 4.32 The scenarios reduce BOD discharge of WWTPs into Lam Takhong River and change DO concentration in February 2027.

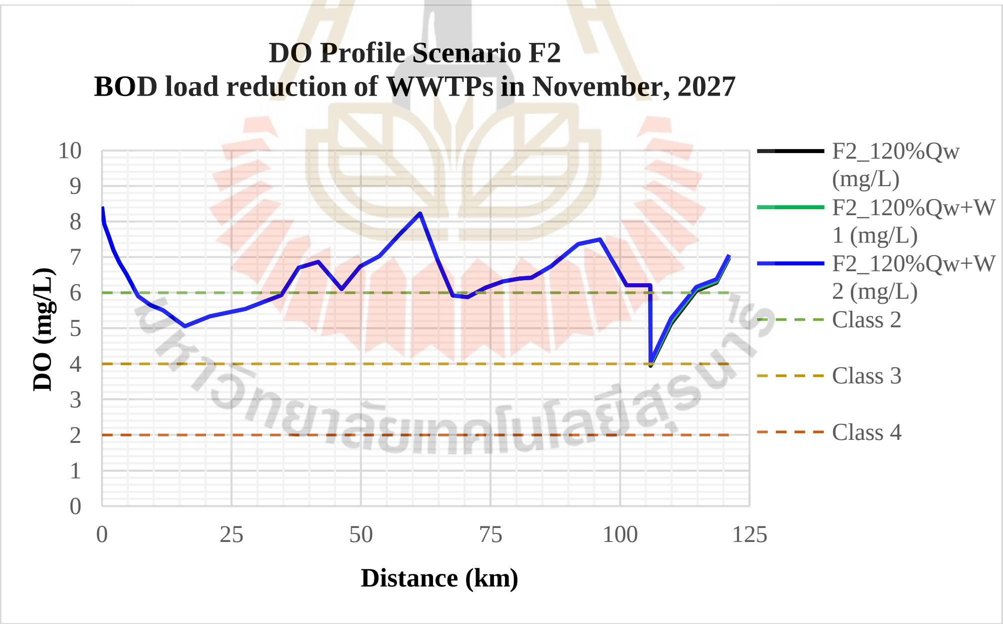


Figure 4.33 The scenarios reduce BOD discharge of WWTP into Lam Takhong River and change DO concentration in November 2027.

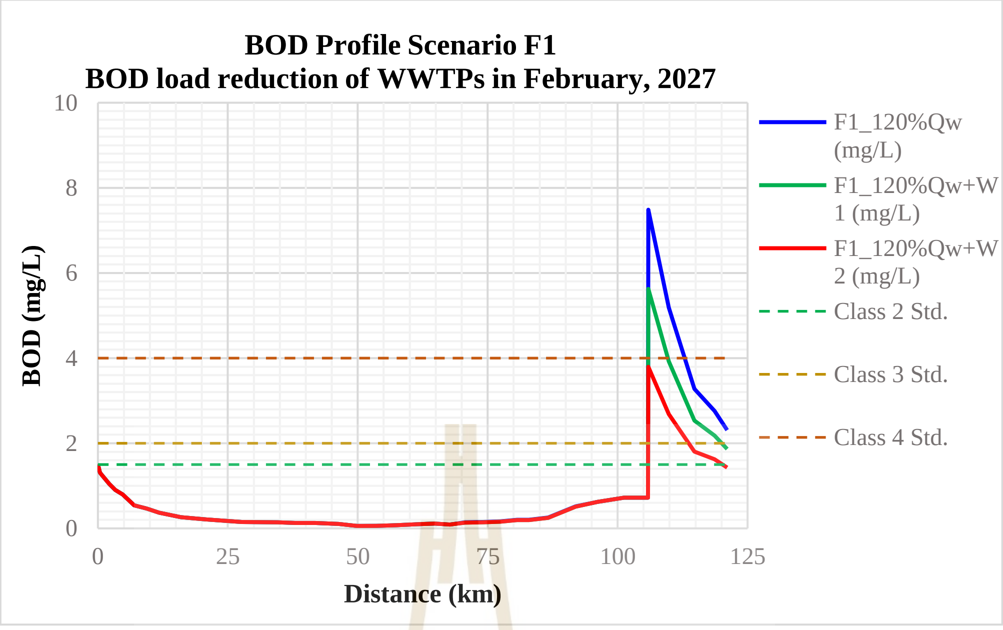


Figure 4.34 The scenarios reduce BOD discharge of WWTPs into Lam Takhong River and change BOD concentration in February 2027.

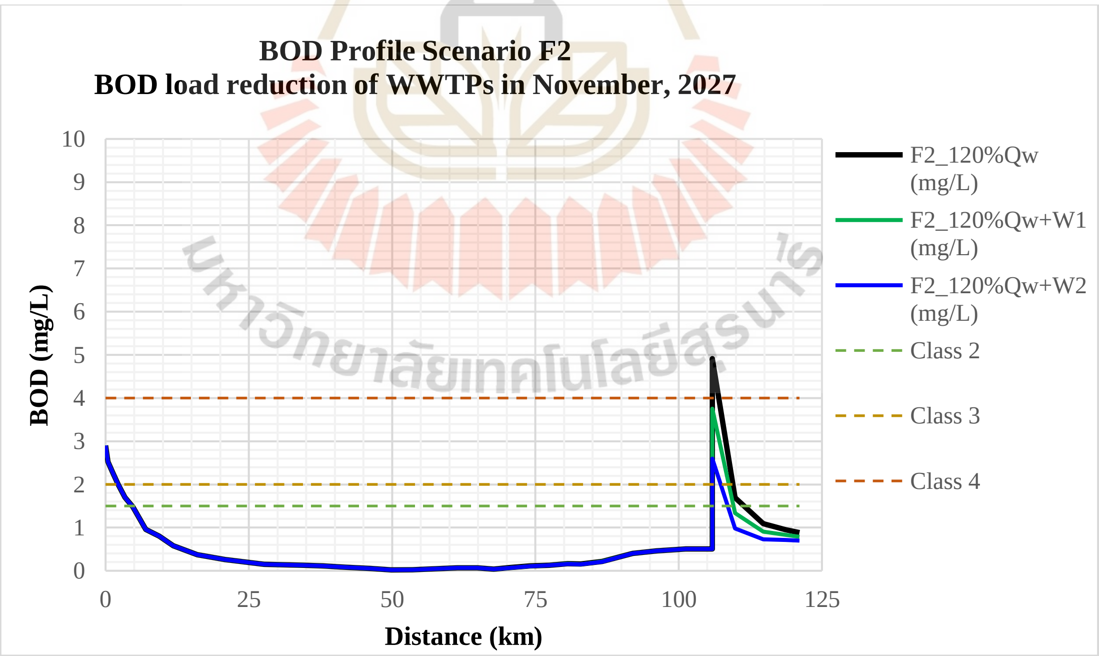


Figure 4.35 The scenarios reduce discharge of WWTP into Lam Takhong River and change BOD concentration in November 2027.

Table 4.36 DO and BOD concentration in LTK River with cutting down the BOD load of WWTPs in February 2027

No.	**Distance (km)**	**DO (mg/L)**			**BOD (mg/L)**		
		F1-120%Qw	F1-120%Qw +W1	F1-120%Qw +W2	F1-120%Qw	F1-120%Qw +W1	F1-120%Qw +W2
1	0.00	9.40	9.40	9.40	1.50	1.50	1.50
2	9.37	7.33	7.33	7.33	0.47	0.47	0.47
3	20.83	7.02	7.02	7.02	0.21	0.21	0.21
4	41.76	6.76	6.76	6.76	0.13	0.13	0.13
5	61.41	8.44	8.44	8.44	0.10	0.10	0.10
6	80.64	8.72	8.72	8.72	0.20	0.20	0.19
7	101.24	8.31	8.31	8.31	0.72	0.72	0.72
8	**105.88**	**2.57**	**2.80**	**3.05**	**7.49**	**5.63**	**3.80**
9	109.85	4.53	4.79	5.06	5.19	3.92	2.69
10	114.75	6.28	6.48	6.68	3.28	2.54	1.81
11	118.64	6.70	6.91	7.12	2.76	2.18	1.62
12	120.00	7.18	7.34	7.50	2.31	1.86	1.43

Table 4.37 DO and BOD concentration in LTK River with cutting down the BOD load of WWTPs in November 2027

No.	**Distance (km)**	**DO (mg/L)**			**BOD (mg/L)**		
		F2-120%Qw	F2-120%Qw +W1	F2-120%Qw +W2	F2-120%Qw	F2-120%Qw +W1	F2-120%Qw +W2
1	0.00	8.42	8.42	8.42	2.90	2.90	2.90
2	9.37	5.65	5.65	5.65	0.80	0.80	0.80
3	20.83	5.34	5.34	5.34	0.26	0.26	0.26
4	41.76	6.87	6.87	6.87	0.08	0.08	0.08
5	61.41	8.23	8.23	8.23	0.07	0.07	0.07
6	80.64	6.40	6.40	6.40	0.16	0.16	0.16
7	101.24	6.21	6.21	6.21	0.51	0.51	0.51
8	**105.88**	**3.94**	**4.00**	**4.06**	**4.91**	**3.75**	**2.60**
9	109.85	5.12	5.20	5.28	1.69	1.33	0.98
10	114.75	6.05	6.11	6.17	1.09	0.91	0.73
11	118.64	6.28	6.33	6.38	0.95	0.83	0.71
12	120.00	6.98	7.02	7.07	0.88	0.79	0.70

4.5.4 The inflow change of headwater scenarios

4.5.4.1 Monthly mean flow of headwater

From the predicted results of the first and second scenario groups shown that flow of headwater and flow out from WWTPs have effected DO and BOD in the Lam Takhong River. Therefore, the study continues to implement a combination of the increase of 20% flow out from WWTP and the mean flow of headwater in the 19 years as shown in Figure 4.8, the February mean flow is 7.87 m^3/s and the November mean flow is 5.99 m^3/s.

Figures 4.36 to 4.39 show that the changes in DO from class three improved to class two in water quality standard in February 2027 because of flow increase in headwater from 5.6 m^3/s up 7.87 m^3/s. In contrast, in November DO lower from class two to class three of water quality standard due to flow reduction in headwater from 6.5 m^3/s down 5.99 m^3/s.

Table 4.38 and 4.39 summarize the value change in DO and BOD along the Lam Takhong River due to simulation of this forth scenario group when the flow of headwater and flow out from WWTPs were changed.

The simulated results of scenarios from Figure 4.36 to Figure 4.39 shown that the flow of headwater in the Lam Takhong river has an impact on the water quality in the downstream.

The flow of headwater is one of the major factors affecting the water quality in the LTK River and then the outflow of WWTPs.

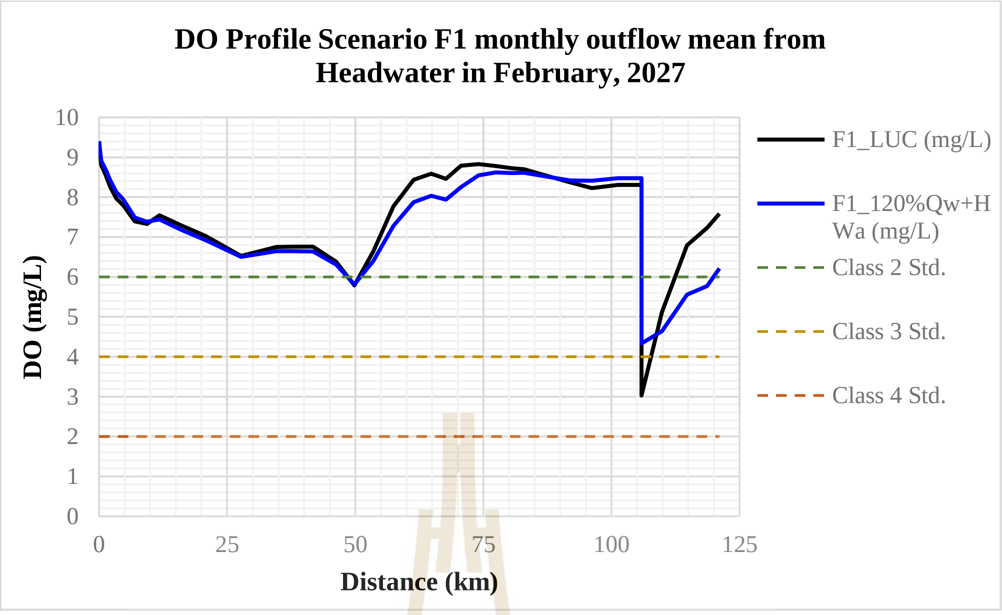


Figure 4.36 DO Profile Scenario F1 monthly mean outflow from Headwater in February 2027.

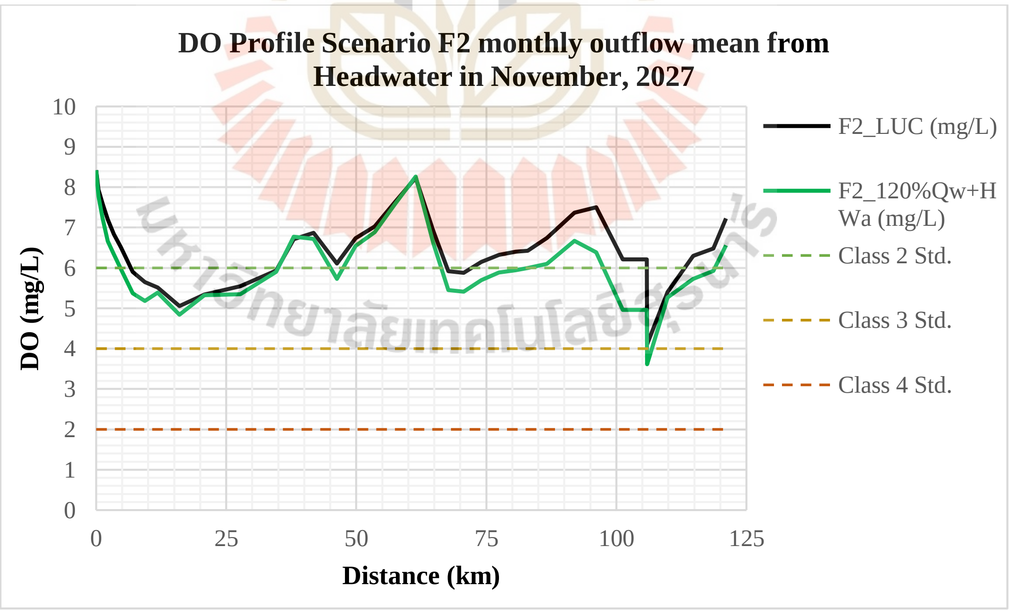


Figure 4.37 DO Profile Scenario F2 monthly mean outflow from Headwater in November 2027.

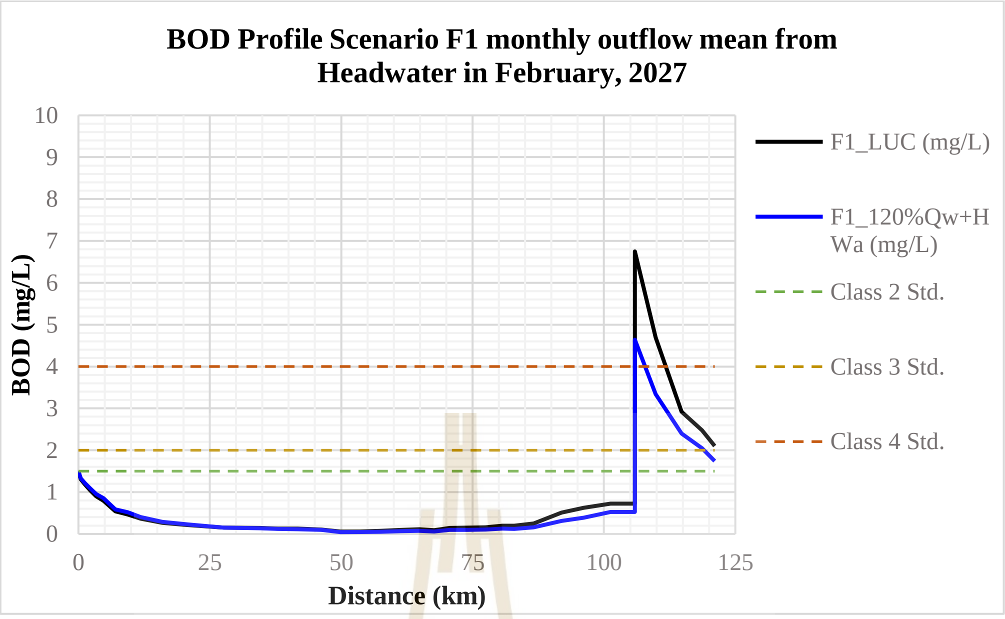


Figure 4.38 BOD Profile Scenario F1 monthly mean outflow from Headwater in February 2027.

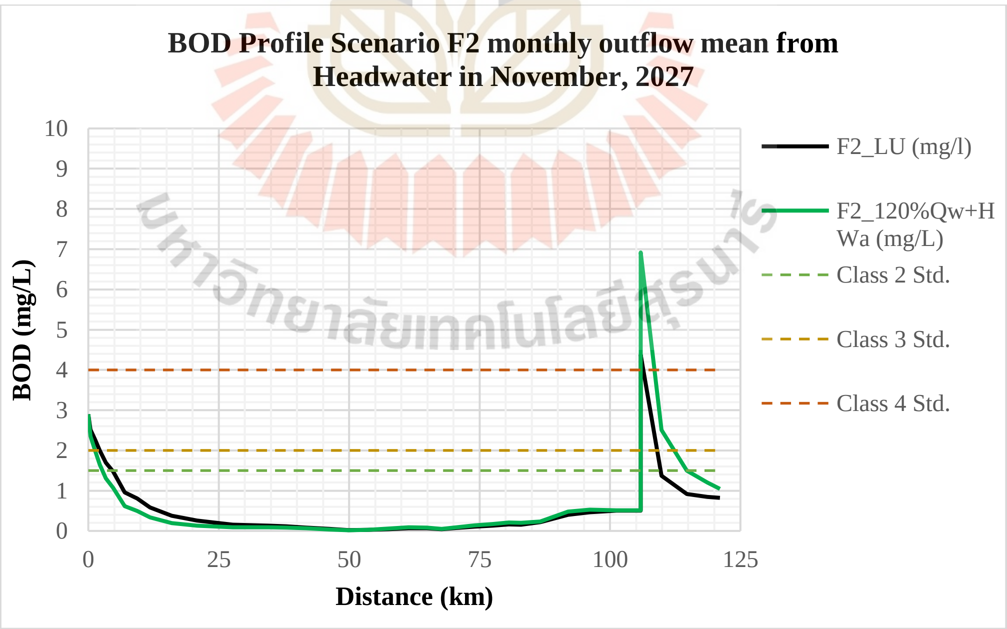


Figure 4.39 BOD Profile Scenario F2 monthly mean outflow from Headwater in November 2027.

Table 4.38 DO and BOD concentration in LTK River with the inflow of headwater change in February 2027

No.	**Distance (km)**	**DO (mg/L)**		**BOD (mg/L)**	
		F1_LUC	F1_120%Qw+HWa	F1_LUC	F1_120%Qw+HWa
1	0.00	9.40	9.40	1.50	1.50
2	9.37	7.33	7.38	0.47	0.52
3	20.83	7.02	6.92	0.21	0.23
4	41.76	6.76	6.64	0.13	0.11
5	61.41	8.44	7.87	0.10	0.07
6	80.64	8.72	8.61	0.20	0.12
7	101.24	8.31	8.48	0.72	0.52
8	**105.88**	**3.03**	**4.33**	**6.75**	**4.64**
9	109.85	5.12	4.64	4.69	3.34
10	114.75	6.79	5.56	2.92	2.40
11	118.64	7.23	5.77	2.48	2.05
12	122.00	7.59	6.21	2.10	1.74

Table 4.39 DO and BOD concentration in LTK River with the inflow of headwater change in November 2027

No.	**Distance (km)**	**DO (mg/L)**		**BOD (mg/L)**	
		F2_LUC	F2_120%Qw+HWa	F2_LUC	F2_120%Qw+HWa
1	0.00	8.42	8.42	2.90	2.90
2	9.37	5.65	5.18	0.80	0.50
3	20.83	5.34	5.32	0.26	0.13
4	41.76	6.87	6.72	0.08	0.07
5	61.41	8.23	8.26	0.07	0.09
6	80.64	6.40	5.94	0.16	0.21
7	101.24	6.21	4.96	0.51	0.51
8	**105.88**	**4.11**	**3.62**	**4.38**	**6.92**
9	109.85	5.40	5.27	1.37	2.51
10	114.75	6.30	5.72	0.92	1.50
11	118.64	6.48	5.93	0.85	1.20
12	122.00	7.22	6.56	0.82	1.04

4.5.4.2 The flow change scenarios from headwater

Flow rate of headwater is the main boundary condition when Qual2K is set up and runs the simulation. Therefore, flow from headwater of the river is one of the major factors impacts on pollutant loading in the river. The four types of various flow rate in headwater were respectively assumed to be by 10%, 20% augmentation, and reduce 10%, 20% reduction in 2027 under HW1, HW2, HW3, HW4 scenarios.

The scenarios have been performed to investigate the impact of the flow of headwater on the DO and BOD in the Lam Takhong river. The scenarios were simulated to test the change of flow in the headwater, while other parameters in headwater and along the river remain at their normal rates. Figures 4.40 and 4.44 show the changes in DO and BOD due to the increasing and reducing the flow of headwater. Value change of DO and BOD in February and November in 2027 was indicated in details in Table 4.40 and Table 4.41 summarizes the percentage change in DO and BOD along the Lam Takhong River due to these simulations of scenarios.

It can be noticed from Figures 4.40 and 4.44 that the flow of headwater in the Lam Takhong River have a great influence on the water quality in term of DO and BOD. As shown in Table 4.40 and 4.41, the greatest reduction of DO and increase BOD were recorded downstream at km 105.88 location, where it reduced by 44% on DO and increase by 69% on BOD in November 2027. While the greatest reduction of DO and increase of BOD were simulated at the same location downstream where the DO decreased by 26.7% and the BOD increased by 31.9% when the flow of headwater was reduced 20% in February 2027 (Table 4.42).

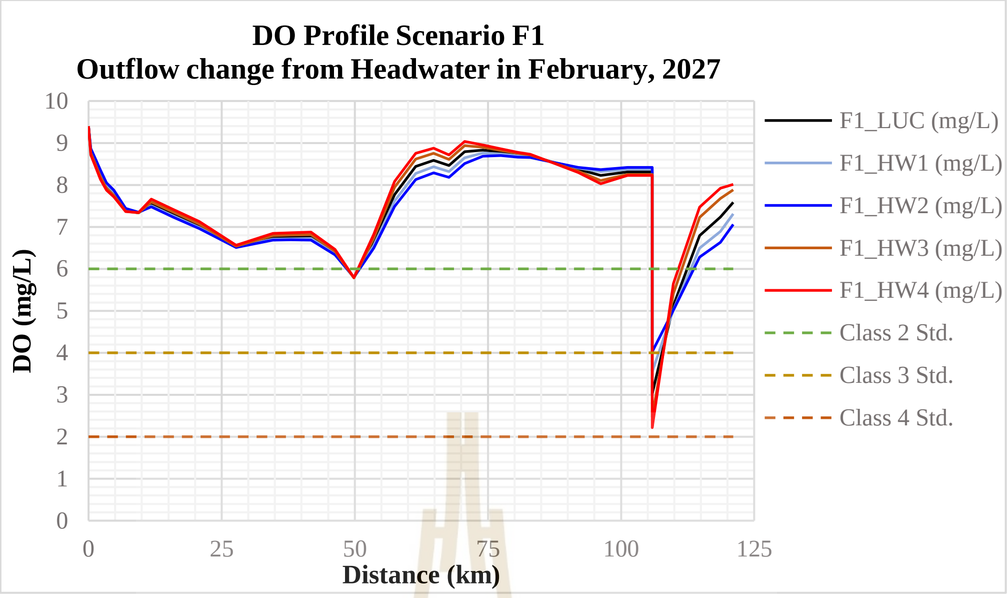


Figure 4.40 DO Profile Scenario F1 Outflow change from headwater in February 2027.

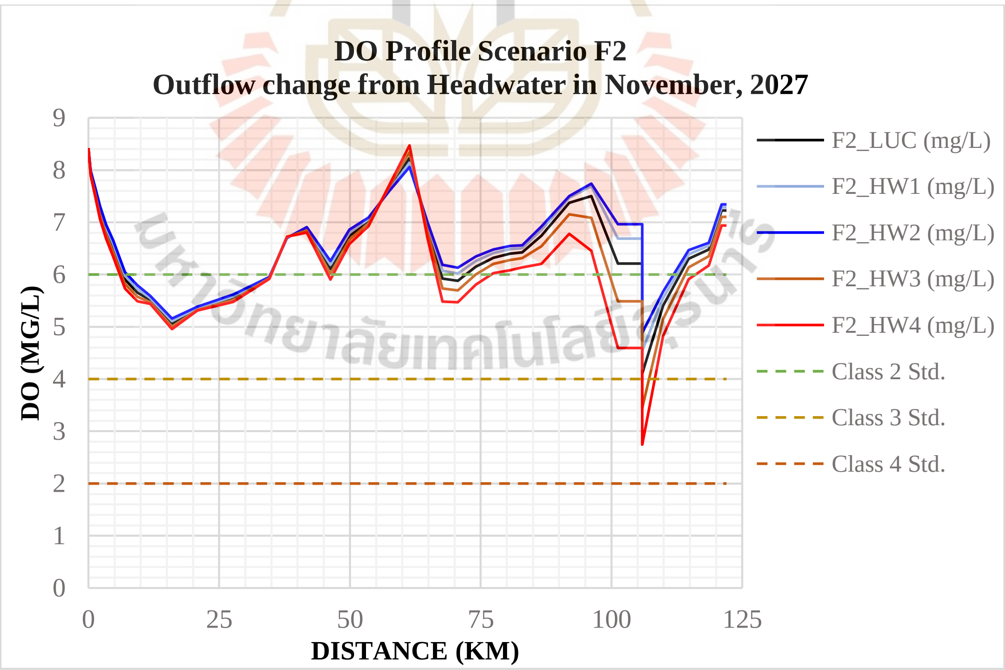


Figure 4.41 DO Profile Scenario F2 Outflow change from headwater in November 2027.

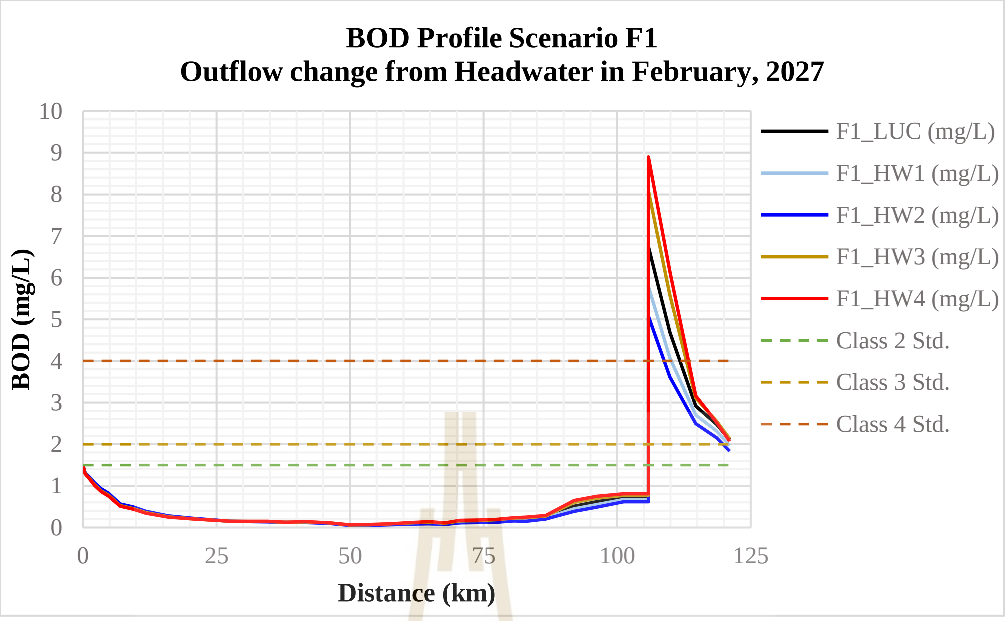


Figure 4.42 BOD Profile Scenario F1 Outflow change from headwater in February 2027

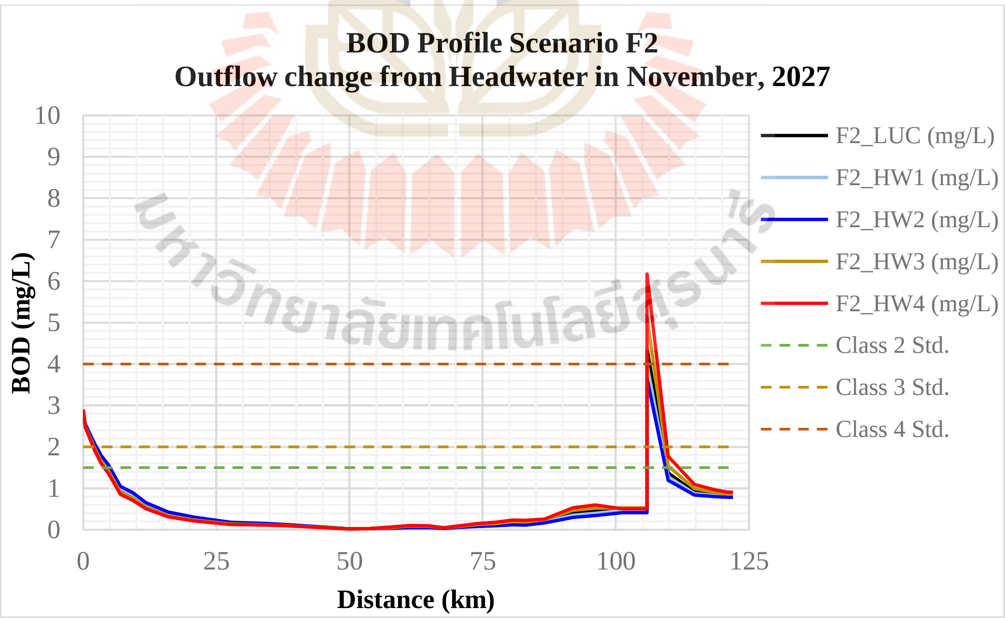


Figure 4.43 BOD Profile Scenario F2 Outflow change from headwater in November 2027.

Table 4.40 DO and BOD concentration in LTK River with change outflow of WWTPs in February 2027

No.	Distance (km)	DO (mg/L)					BOD (mg/L)				
		F1-HW1	F1-HW2	F1-LUC	F1-HW3	F1-HW4	F1-HW1	F1-HW2	F1-LUC	F1-HW3	F1-HW4
1	0.00	9.40	9.40	9.40	9.40	9.40	1.50	1.50	1.50	1.50	1.50
2	9.37	7.34	7.35	7.33	7.33	7.34	0.48	0.49	0.47	0.45	0.44
3	20.83	6.98	6.96	7.02	7.07	7.13	0.21	0.22	0.21	0.20	0.20
4	41.76	6.72	6.69	6.76	6.81	6.87	0.12	0.12	0.13	0.13	0.14
5	61.41	8.27	8.12	8.44	8.62	8.75	0.09	0.08	0.10	0.11	0.12
6	80.64	8.69	8.66	8.72	8.75	8.78	0.17	0.15	0.20	0.22	0.24
7	101.24	8.37	8.42	8.31	8.25	8.23	0.67	0.62	0.72	0.78	0.81
8	**105.88**	**3.55**	**4.02**	**3.03**	**2.47**	**2.22**	**5.79**	**5.08**	**6.75**	**8.09**	**8.90**
9	109.85	5.02	5.01	5.12	5.41	5.65	4.08	3.61	4.69	5.58	6.15
10	114.75	6.49	6.28	6.79	7.23	7.47	2.70	2.50	2.92	3.11	3.17
11	118.64	6.89	6.63	7.23	7.68	7.92	2.32	2.15	2.48	2.56	2.52
12	122.00	7.59	7.31	7.06	7.88	8.01	2.10	1.97	1.83	2.14	2.07

Table 4.41 DO and BOD concentration in LTK River with change outflow of WWTPs in November 2027

No.	Distance (km)	DO (mg/L)					BOD (mg/L)				
		F2-HW1	F2-HW2	F2-LUC	F2-HW3	F2-HW4	F2-HW1	F2-HW2	F2-LUC	F2-HW3	F2-HW4
1	0.00	8.42	8.42	8.42	8.42	8.42	2.90	2.90	2.90	2.90	2.90
2	9.37	5.65	5.73	5.80	5.57	5.49	0.80	0.85	0.89	0.76	0.71
3	20.83	5.34	5.36	5.38	5.32	5.31	0.26	0.28	0.31	0.24	0.21
4	41.76	6.87	6.89	6.91	6.84	6.81	0.08	0.09	0.10	0.08	0.08
5	61.41	8.23	8.14	8.06	8.34	8.47	0.07	0.06	0.05	0.08	0.10
6	80.64	6.40	6.48	6.54	6.28	6.08	0.16	0.14	0.12	0.19	0.23
7	101.24	6.21	6.68	6.96	5.49	4.60	0.51	0.46	0.41	0.53	0.51
8	**105.88**	**4.54**	**4.88**	**4.11**	**3.44**	**2.74**	**3.99**	**3.65**	**4.38**	**5.12**	**6.17**
9	109.85	5.40	5.55	5.67	5.15	4.82	1.37	1.28	1.20	1.54	1.77
10	114.75	6.30	6.39	6.47	6.14	5.91	0.92	0.87	0.84	0.99	1.09
11	118.64	6.48	6.55	6.61	6.35	6.17	0.85	0.82	0.80	0.90	0.96
12	122.00	7.22	7.29	7.34	7.11	6.94	0.82	0.81	0.79	0.86	0.90

Table 4.42 Summary of the percentage change in DO and BOD at km 105.88 due to change of headwater flow scenarios

Change type	DO					BOD				
	F1-HW1	F1-HW2	F1-LUC	F1-HW3	F1-HW4	F1-HW1	F1-HW2	F1-LUC	F1-HW3	F1-HW4
February										
Conc (mg/L)	3.6	4.0	3.0	2.5	2.2	5.8	5.1	6.8	8.1	8.9
Change (mg/L)	0.5	1.0	0.0	-0.6	-0.8	-1.0	-1.7	0.0	1.3	2.2
Change (%)	17.2	32.7	0.0	-18.5	-26.7	-14.2	-24.7	0.0	19.9	31.9
November										
Conc (mg/L)	4.1	4.5	4.9	3.4	2.7	4.4	4.0	3.7	5.1	6.2
Change (mg/L)	-0.8	-0.3	0.0	-1.4	-2.1	0.7	0.3	0.0	1.5	2.5
Change (%)	-15.8	-7.0	0.0	-29.5	-43.9	20.0	9.3	0.0	40.3	69.0

4.5.5 Change outflow and BOD load from WWTP to meet water quality standard targets in Thailand

These scenarios were conducted to find out the way which improves the water quality in Lam Takhong river can meet the class three in surface water quality standard in Thailand by limit the amount of WWTP flow rate.

Figure 4.44 indicated that outflow change from WWTPs significantly impacted on water quality in Lam Takhong River. When 67% flow out reduction from WWTPs is water quality can meet class three in surface water quality standard in Thailand (Table 4.43).

However, the population will increase in the future, this means discharge from WWTP will increase. Therefore, it is very difficult to conduct this way in order to meet the class 3 standard.

And another method was conducted, these scenarios concentrated on BOD load reduction from WWTP release into Lam Takhong River but outflow is not change.

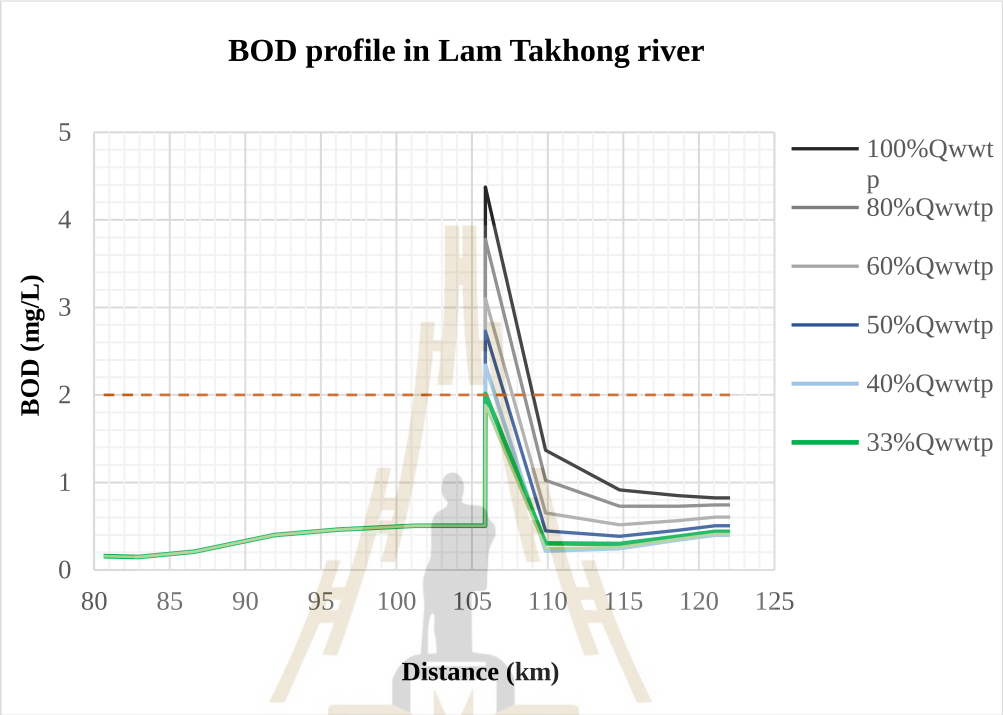


Figure 4.44 BOD in Lam Takhong River when outflow change from WWTPs in 2027

Table 4.43 Outflow reduction scenarios from WWTPs

Qwwtp (m^3/s)	**BODwwtp (mg/L)**	**DO (105.88km)**	**BOD (105.88km)**	**TMDL**
100% (0.8102)	20	4.11	4.38	1653.6
80% (0.6481)	20	4.27	3.78	1360.0
60% (0.4861)	20	4.42	3.10	1066.4
50% (0.4051)	20	4.47	2.73	919.6
40% (0.3241)	20	4.47	2.34	772.8
33% (0.2674)	**20**	**4.63**	**2.00**	**670.0**
30% (0.2431)	20	4.63	1.88	626.0

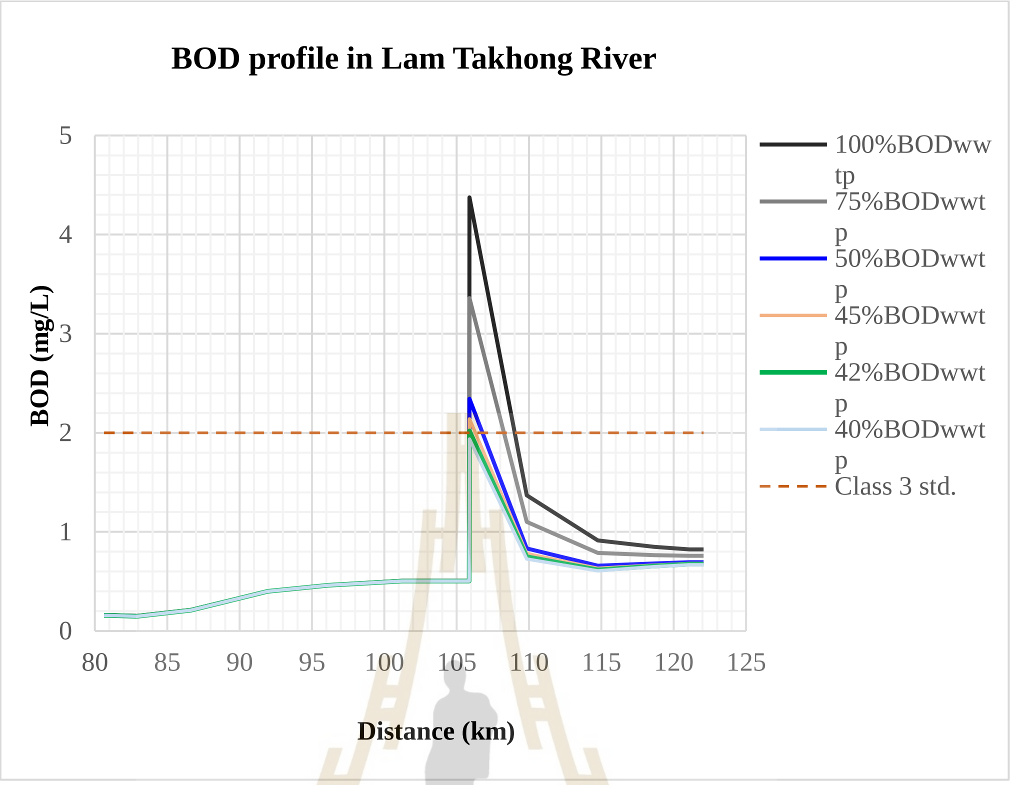


Figure 4.45 BOD in Lam Takhong River when BOD load change from WWTPs in 2027

Table 4.44 BOD load reduction scenarios from WWTPs

Qwwtp (m^3/s)	BODwwtp (mg/L)	DO (105.88km)	BOD (105.88km)	TMDL (kg BOD/day)
100%	20 (100%)	4.11	4.38	1653.6
100%	15 (75%)	4.15	3.36	1286.6
100%	10 (50%)	4.20	2.34	919.6
100%	9 (45%)	4.21	2.14	846.2
100%	**8.4 (42%)**	**4.21**	**2.00**	**802.1**
100%	8 (40%)	4.22	1.94	772.8

The simulated results showed that BOD load reduction from WWTPs also affected water quality in Lam Takhong River (Figure 4.45). When 58% BOD load reduction from WWTPs is BOD and DO concentration can meet class three in surface water quality standard in Thailand (Table 4.44). To reduce 58% BOD load from WWTPs need a novation in wastewater treatment engineering.

In order to achieve optimum water quality improvement, scenarios combining flow out and BOD load change from WWTP were simulated.

The scenarios of combining BOD load and flow out reduction from WWTP pointed out that if 23% flow out and 50% BOD load were reduced, DO (4.36 mg/L) and BOD (2 mg/L) concentration can meet the class three in surface water quality standard in Thailand (Table 4.45).

The following charts (Figure 4.47 and 4.48) show more details about the changes in DO and BOD concentrations in Lam Takhong River when the BOD load and flow out reduction scenario is implemented.

The evolutions of the concentration of DO and BOD in the Lam Takhong river are detailed in the table 4.46 The scenarios show that 58% BOD load reduction or 23% outflow and 50% BOD load were lowered, DO and BOD concentration can meet the class 3 in surface water quality standard in Thailand.

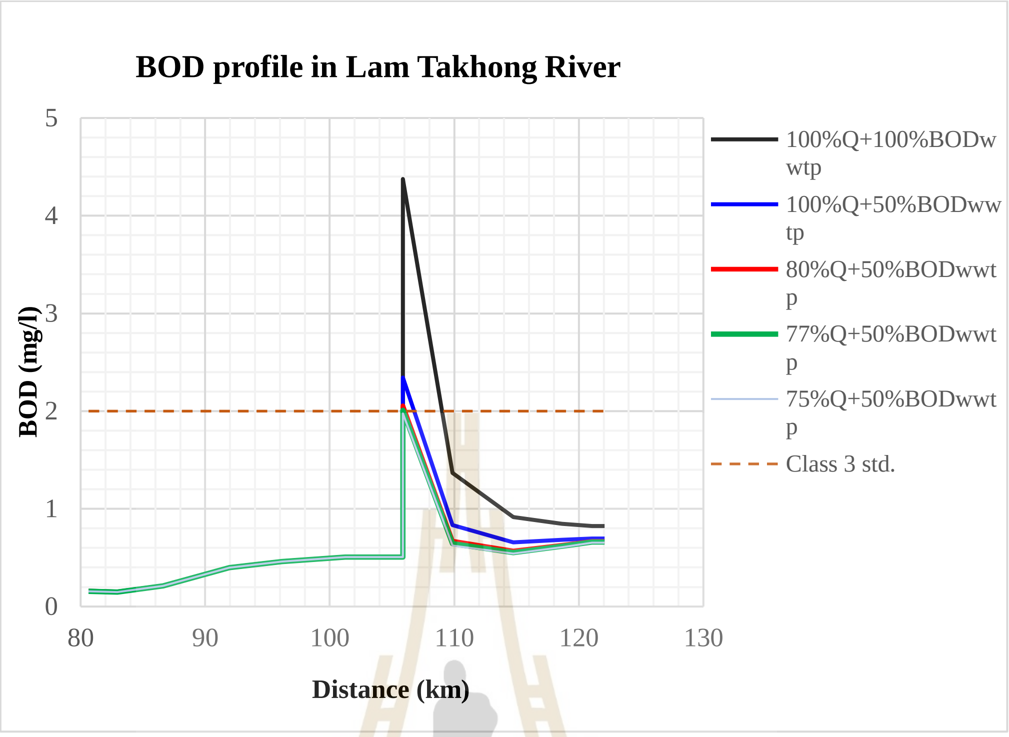


Figure 4.46 BOD in Lam Takhong River combining flow out and BOD load change from WWTP in 2027

Table 4.45 Outflow and BOD load reduction scenarios from WWTPs

Qwwtp (m^3/s)	BODwwtp (mg/L)	DO (105.88km)	BOD (105.88km)	TMDL (kg BOD/day)
100% (0.8102)	10 (50%)	4.20	2.34	919.6
80% (0.6481)	10 (50%)	4.34	2.06	772.8
77% (0.6238)	**10 (50%)**	**4.36**	**2.00**	**750.8**
75% (0.6076)	10 (50%)	4.37	1.98	736.1

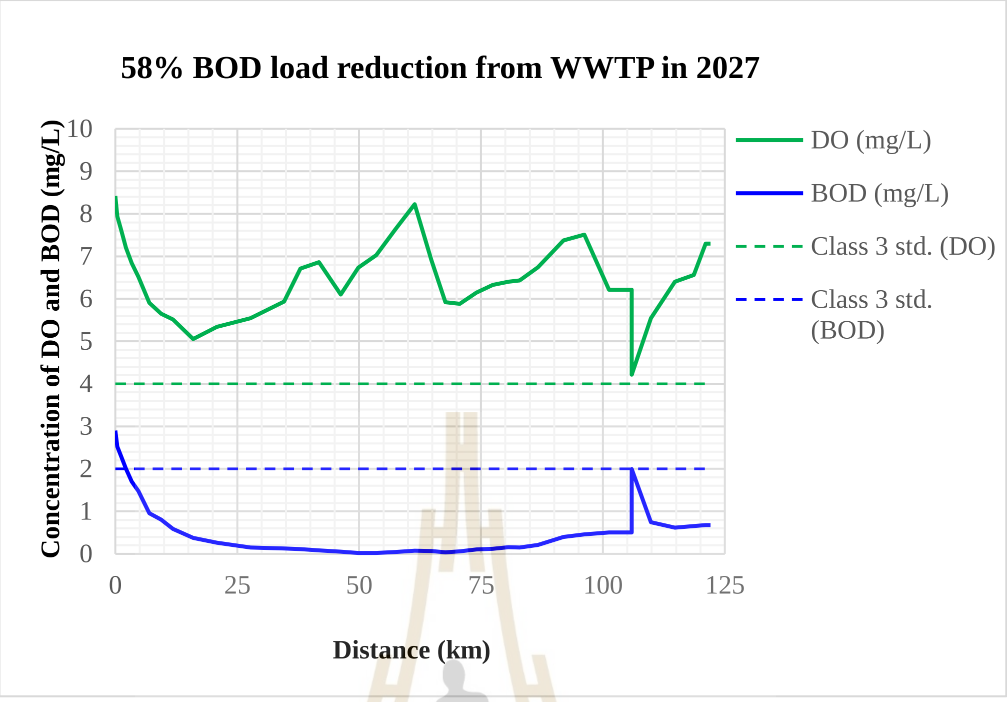


Figure 4.47 BOD in Lam Takhong River when 58% BOD load reduction in 2027

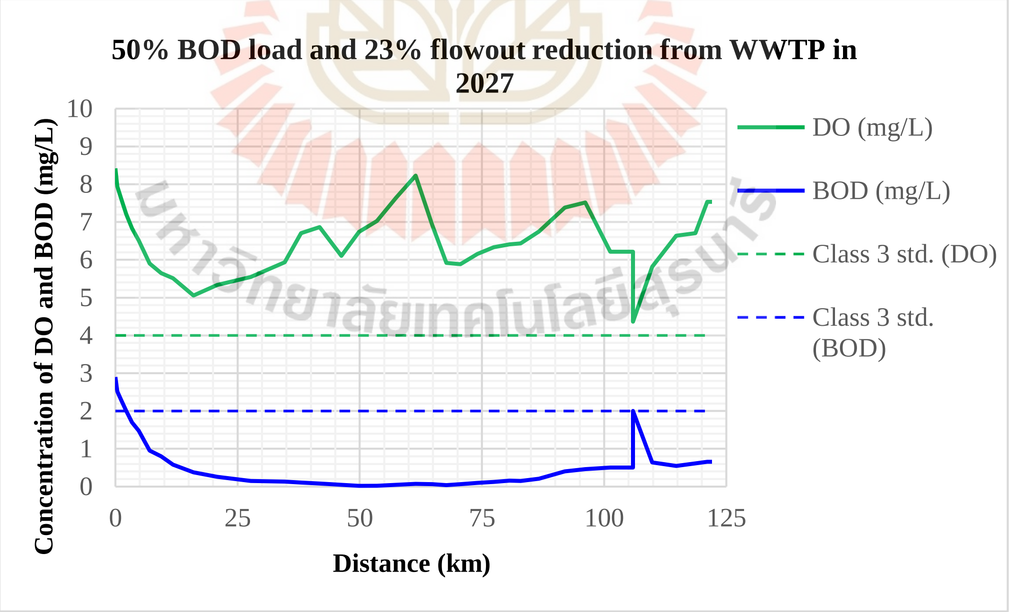


Figure 4.48 BOD in Lam Takhong River when integration of 50% BOD load and 23% flow out reduction from WWTP in 2027

Table 4.46 DO and BOD value when BOD load and outflow reduction from WWTP in 2027

Distance (km)	**58%BOD load reduction**		**50% BOD load+23% flow out reduction**	
	DO (mg/L)	BOD (mg/L)	DO (mg/L)	BOD (mg/L)
0.00	8.42	2.90	8.42	2.90
9.37	5.65	0.80	5.65	0.80
20.83	5.34	0.26	5.34	0.26
41.76	6.87	0.08	6.87	0.08
61.41	8.23	0.07	8.23	0.07
80.64	6.41	0.16	6.41	0.16
101.24	6.21	0.51	6.22	0.51
105.88	**4.21**	**2.00**	**4.36**	**2.00**
109.85	5.55	0.74	5.82	0.64
114.75	6.40	0.62	6.64	0.55
118.64	6.56	0.65	6.71	0.61
122.00	7.30	0.67	7.54	0.66

4.6 Summary

This chapter details the output results and the achievement of the current and predicted study objectives.

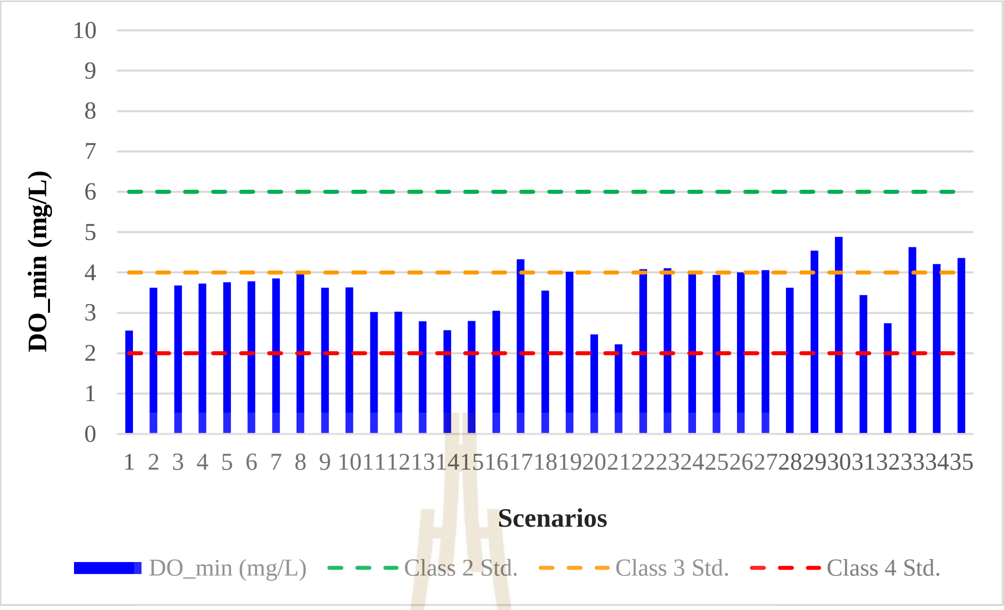
SWAT was used to simulate and forecast flow in Lam Takhong River and flow from subbasin into the river in 2019 and 2027. The results from SWAT were input data of the QUAL2K water quality model.

QUAL2K model was simulated to assess the current water quality status of the Lam Takhong River. The hydraulic parameter (flow) together with the water quality parameters (DO, BOD, TN, and TP) were chosen for model simulation. The model was calibrated in February 2019 and validated in November 2019. The simulation of the current condition indicated that the water quality at upstream of the Lam Takhong river derived from the outlet of Lam Takhong Dam is initially good, but it gradually deteriorates toward downstream. This is due to the pollutant amount of sources that may contribute pollution along the stream.

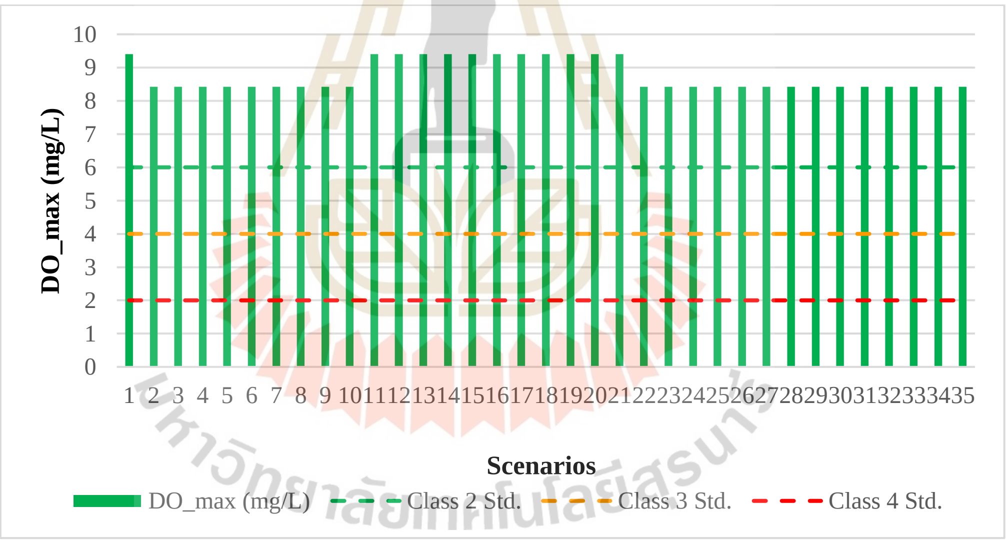
Furthermore, four future scenario groups were simulated to assess the impact of the sources on the river water quality. The first scenario group investigated that change of flow in headwater and from subbasin in the river combine with land use change in 2019 and the result showed that land use change (urban area) has little effect on the quality of the river water. The second scenario group was set up to investigate the effect of outflow increasing at the WWTP, the results indicated that the changes in DO and BOD after the outflow of the WWTP has changed, however, the rate of change on DO and BOD is more intense in the downstream due to Korat Municipality WWTP. Similarly, the third scenario group simulated the BOD reduction release into the river from WWTPs and found out this is a praising method to improve water quality in the Lam Takhong River. The simulated scenarios proved that WWTP is the main point source contributors on the Lam Takhong River. Finally, the fourth scenario group conducted change flow in the headwater of the river, and the simulated shown that DO and BOD values significantly changed under the impact of flow in headwater, both the augmentation and reduction.

From 32 simulated scenarios, the results pointed up that location which had the lowest DO value (Figure 4.44a) is the same location had the highest BOD value (Figure 4.45a) where is away from the Korat Municipality WWTP about 880m toward downstream. The highest DO value is always located in the headwater of Lam Takhong River (Figure 4.44b), while the lowest BOD value is from km 49 to km 54 of Lam Takhong River (Figure 4.45b).

The 21st scenario (F1_HW4) which flow change at headwater was set up, it is shown that DO value (2.2 mg/L) is lowest among 35 scenarios when the inflow of headwater is reduced by 20%, the 2.2 mg/L value is very close to the boundary value of class four of surface water quality standard. Besides, the 30th scenario (F2_HW2) has the maximum DO value (4.88 mg/L) when the inflow of headwater is increased by 20%, and DO value meet class three of standard (Table 4.43). Corresponding to the minimum DO value, the maximum BOD value (8.9 mg/L) is also obtained from scenario 21, which exceeds the standard of class four (4 mg/L). Only scenario 6 has BOD value meets class four of standard when BOD load is released from WWTP reduced by 70%, it means that concentration of BOD from WWTP discharges into the Lam Takhong River is 6 mg/L (Table 4.44).



(a)

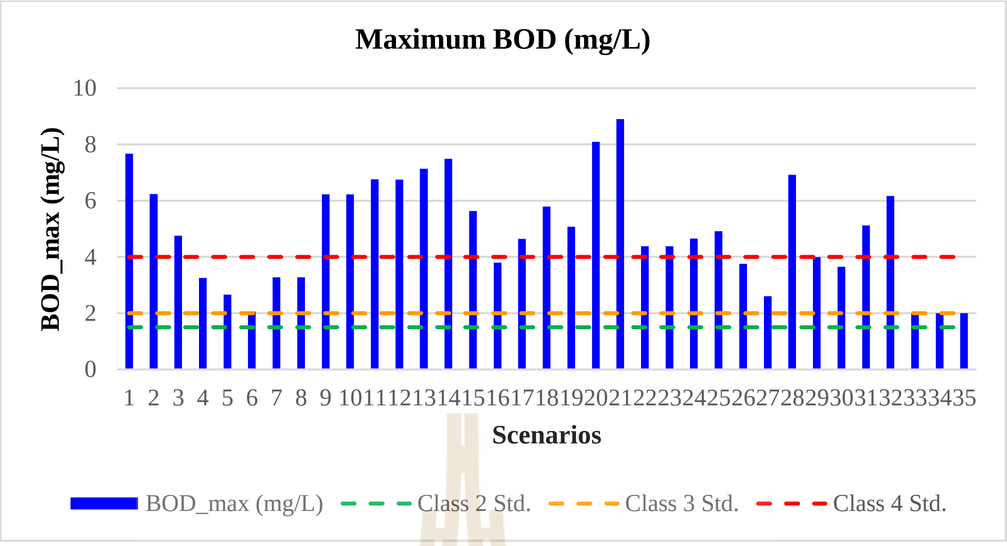


(b)

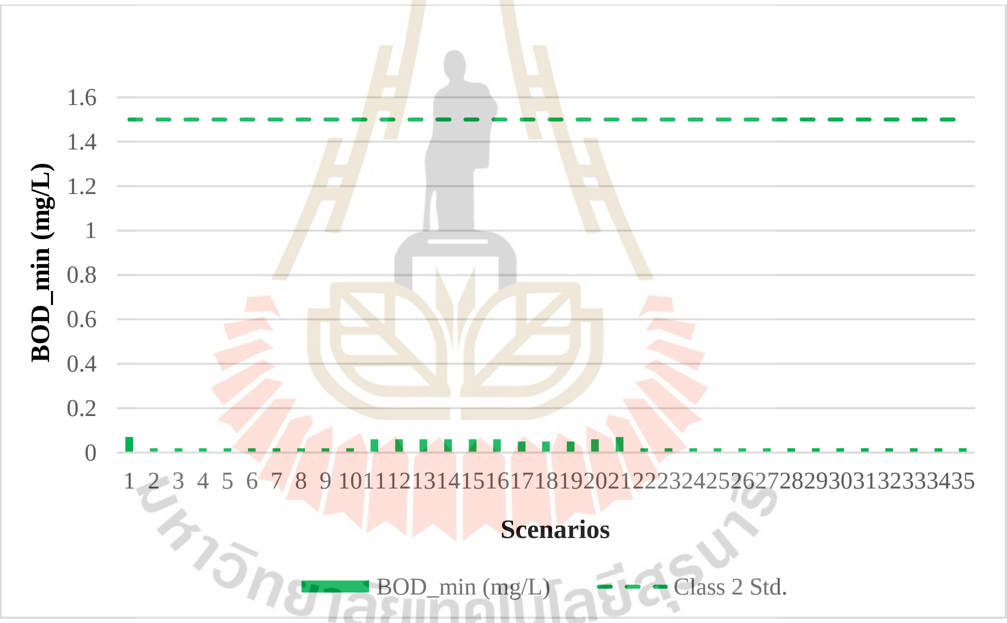
Figure 4.49 (a) and (b) Minimum and maximum DO value in Lam Takhong River from simulated scenarios.

Table 4.47 Minimum and maximum DO value in Lam Takhong River according to spatial and temporal distribution

NO.	Scenarios	DO_min		DO_max		When
		Value (mg/L)	Location (km)	Value (mg/L)	Location (km)	
1	P1	2.56	105.88	9.4	0	Feb-19
2	P2	3.62	105.88	8.42	0	Nov-19
3	P2_W1	3.68	105.88	8.42	0	Nov-2019, ↓25%BOD (wwtp)
4	P2_W2	3.73	105.88	8.42	0	Nov-2019, ↓50%BOD (wwtp)
5	P2_W3	3.76	105.88	8.42	0	Nov-2019, ↓60%BOD (wwtp)
6	P2_W4	3.78	105.88	8.42	0	Nov-2019, ↓70%BOD (wwtp)
7	P2_W2+N1	3.85	105.88	8.42	0	Nov- 2019, ↓50%BOD +↓25% nutrient (wwtp)
8	P2_W2+N2	3.98	105.88	8.42	0	Nov- 2019, ↓50%BOD +↓50% nutrient (wwtp)
9	P2_U1	3.62	105.88	8.42	0	Nov- 2019, ↓25% BOD (Urban)
10	P2_U2	3.63	105.88	8.42	0	Nov- 2019, ↓50% BOD (Urban)
11	F1	3.02	105.88	9.4	0	Feb-27
12	F1_LUC	3.03	105.88	9.4	0	Feb-2027, Land use change
13	F1_110%Qw	2.79	105.88	9.4	0	Feb-2027, 110%Qwwtp
14	F1_120%Qw	2.57	105.88	9.4	0	Feb-2027, 120% Qwwtp
15	F1_120%Qw+W1	2.80	105.88	9.4	0	Feb-2027, 120%Qwwtp + ↓25%BOD
16	F1_120%Qw+W2	3.05	105.88	9.4	0	Feb-2027, 120%Qwwtp + ↓50%BOD
17	F1_120%Qw+HWa	4.33	105.88	9.4	0	Feb-2027, 120%Qwwtp + QmeanHW
18	F1_HW1	3.55	105.88	9.4	0	Feb-2027, 110%Qhw
19	F1_HW2	4.02	105.88	9.4	0	Feb-2027, 120%Qhw
20	F1_HW3	2.47	105.88	9.4	0	Feb-2027, 90%Qhw
21	F1_HW4	2.22	105.88	9.4	0	Feb-2027, 80%Qhw
22	F2	4.08	105.88	8.42	0	Nov-27
23	F2-LUC	4.11	105.88	8.42	0	Nov-2027, Land use change
24	F2_110%Qw	4.02	105.88	8.42	0	Nov-2027, 110%Qwwtp
25	F2_120%Qw	3.94	105.88	8.42	0	Nov-2027, 120%Qwwtp
26	F2_120%Qw+W1	4.00	105.88	8.42	0	Nov-2027, 120%Qwwtp + ↓25%BOD
27	F2_120%Qw+W2	4.06	105.88	8.42	0	Nov-2027, 120%Qwwtp + ↓50%BOD
28	F2_120%Qw+HWa	3.62	105.88	8.42	0	Nov-2027, 120%Qwwtp + QmeanHW
29	F2_HW1	4.54	105.88	8.42	0	Nov-2027, 110%Qhw
30	F2_HW2	4.88	105.88	8.42	0	Nov-2027, 120%Qhw
31	F2_HW3	3.44	105.88	8.42	0	Nov-2027, 90%Qhw
32	F2_HW4	2.74	105.88	8.42	0	Nov-2027, 80%Qhw
33	F2_33%Qw	4.63	105.88	8.42	0	Nov-2027, 33%Qwwtp
34	F2_42%BODw	4.21	105.88	8.42	0	Nov-2027, 42%BODwwtp
35	F2_77%Qw+ 50%BODw	4.36	105.88	8.42	0	Nov-2027, 77%Q+50%BODwwtp



(a)



(b)

Figure 4.50 (a) and (b) Maximum and minimum BOD value in Lam Takhong River from simulated scenarios.

Table 4.48 Maximum and Minimum BOD value in Lam Takhong River according to spatial and temporal distribution

NO.	Scenarios	BOD_max		BOD_min		When
		Value (mg/L)	Location (km)	Value (mg/L)	Location (km)	
1	P1	7.67	105.88	0.07	49-54	Feb-19
2	P2	6.24	105.88	0.02	49-50	Nov-19
3	P2_W1	4.75	105.88	0.02	49-50	Nov-2019, ↓25%BOD (wwtp)
4	P2_W2	3.25	105.88	0.02	49-50	Nov-2019, ↓50%BOD (wwtp)
5	P2_W3	2.66	105.88	0.02	49-50	Nov-2019, ↓60%BOD (wwtp)
6	P2_W4	2.06	105.88	0.02	49-50	Nov-2019, ↓70%BOD (wwtp)
7	P2_W2+N1	3.27	105.88	0.02	49-50	Nov- 2019, ↓50%BOD +↓25% nutrient (wwtp)
8	P2_W2+N2	3.28	105.88	0.02	49-50	Nov- 2019, ↓50%BOD +↓50% nutrient (wwtp)
9	P2_U1	6.22	105.88	0.02	49-50	Nov- 2019, ↓25% BOD (Urban)
10	P2_U2	6.23	105.88	0.02	49-50	Nov- 2019, ↓50% BOD (Urban)
11	F1	6.76	105.88	0.06	49-54	Feb-27
12	F1_LUC	6.75	105.88	0.06	49-54	Feb-2027, Land use change
13	F1_110%Qw	7.13	105.88	0.06	49-54	Feb-2027, 110%Qwwtp
14	F1_120%Qw	7.49	105.88	0.06	49-54	Feb-2027, 120% Qwwtp
15	F1_120%Qw+W1	5.63	105.88	0.06	49-54	Feb-2027, 120%Qwwtp + ↓25%BOD
16	F1_120%Qw+W2	3.80	105.88	0.06	49-54	Feb-2027, 120%Qwwtp + ↓50%BOD
17	F1_120%Qw+HWa	4.64	105.88	0.05	49-57	Feb-2027, 120%Qwwtp + QmeanHW
18	F1_HW1	5.79	105.88	0.05	49-54	Feb-2027, 110%Qhw
19	F1_HW2	5.08	105.88	0.05	49-54	Feb-2027, 120%Qhw
20	F1_HW3	8.09	105.88	0.06	49-54	Feb-2027, 90%Qhw
21	F1_HW4	8.90	105.88	0.07	49-54	Feb-2027, 80%Qhw
22	F2	4.38	105.88	0.02	49-54	Nov-27
23	F2-LUC	4.38	105.88	0.02	49-54	Nov-2027, Land use change
24	F2_110%Qw	4.65	105.88	0.02	49-54	Nov-2027, 110%Qwwtp
25	F2_120%Qw	4.91	105.88	0.02	49-54	Nov-2027, 120%Qwwtp
26	F2_120%Qw+W1	3.75	105.88	0.02	49-54	Nov-2027, 120%Qwwtp + ↓25%BOD
27	F2_120%Qw+W2	2.60	105.88	0.02	49-54	Nov-2027, 120%Qwwtp + ↓50%BOD
28	F2_120%Qw+HWa	6.92	105.88	0.02	49-54	Nov-2027, 120%Qwwtp + QmeanHW
29	F2_HW1	3.99	105.88	0.02	49-54	Nov-2027, 110%Qhw
30	F2_HW2	3.65	105.88	0.02	49-54	Nov-2027, 120%Qhw
31	F2_HW3	5.12	105.88	0.02	49-50	Nov-2027, 90%Qhw
32	F2_HW4	6.17	105.88	0.02	49-50	Nov-2027, 80%Qhw
33	F2_33%Qw	2.00	105.88	0.02	49-50	Nov-2027, 33%Qwwtp
34	F2_42%BODw	2.00	105.88	0.02	49-50	Nov-2027, 42%BODwwtp
35	F2_77%Qw+ 50%BODw	2.00	105.88	0.02	49-50	Nov-2027, 77%Q+50%BODwwtp

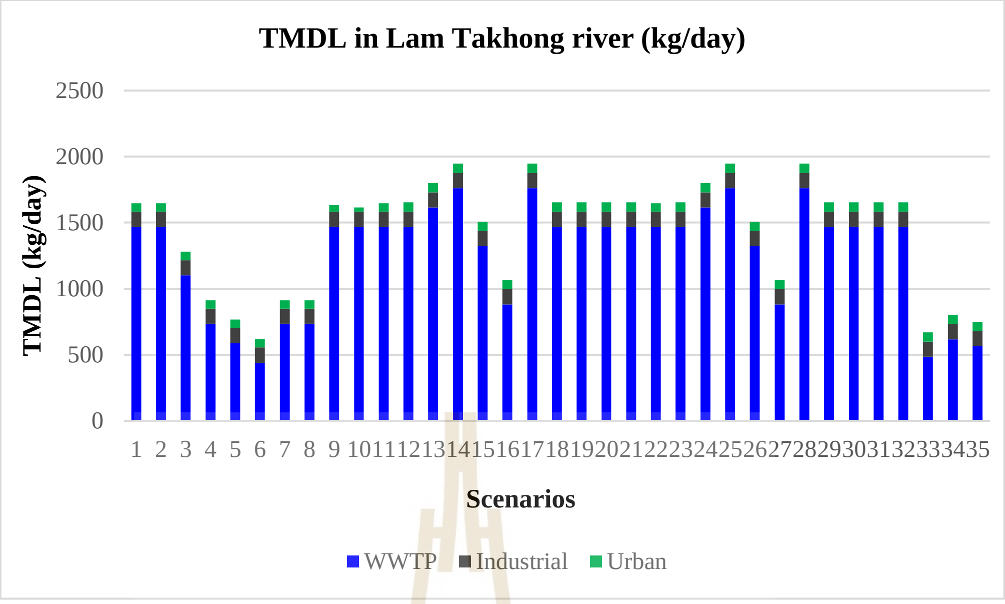


Figure 4.51 Total maximum daily load in Lam Takhong River from simulated scenarios.

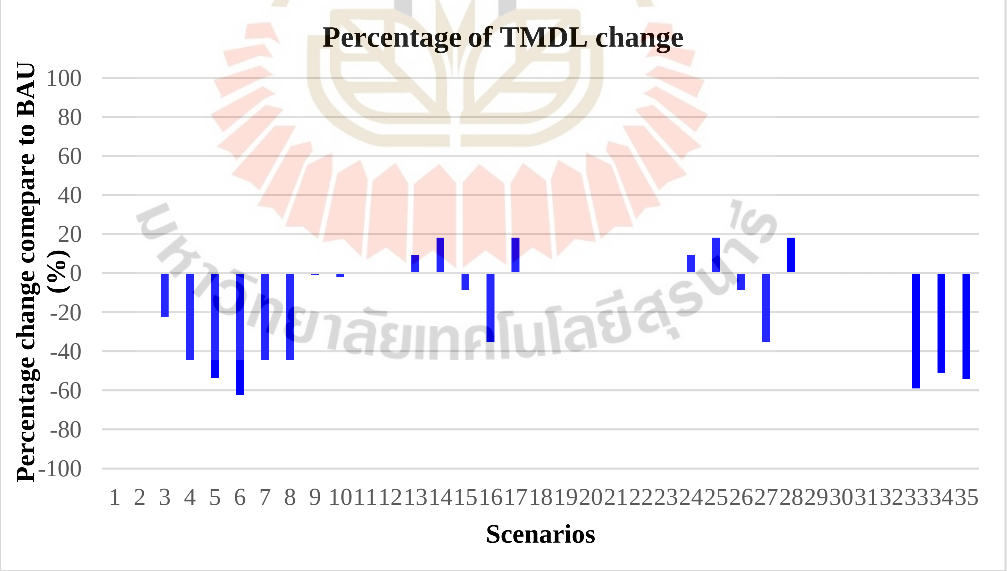


Figure 4.52 Percentage of TMDL change in Lam Takhong River from simulated scenarios compare to BAU scenario.

Table 4.49 Total maximum daily load and Percentage of TMDL change in Lam Takhong River from simulated scenarios.

NO.	Scenarios	BOD Load (kg/day)			TMDL (kg BOD/d)	%TMDL change	When
		WWTP	Industrial	Urban			
1	P1	1468	115	64	1647.0	0.0	Feb-19
2	P2	1468	115	64	1647.0	0.0	Nov-19
3	P2_W1	1101	115	64	1280.0	-22.3	Nov-2019, ↓25%BOD (wwtp)
4	P2_W2	734	115	64	913.0	**-44.6**	Nov-2019, ↓50%BOD (wwtp)
5	P2_W3	587.2	115	64	766.2	**-53.5**	Nov-2019, ↓60%BOD (wwtp)
6	P2_W4	440.4	115	64	619.4	**-62.4**	Nov-2019, ↓70%BOD (wwtp)
7	P2_W2+N1	734	115	64	913.0	-44.6	Nov- 2019, ↓50%BOD +↓25% nutrient (wwtp)
8	P2_W2+N2	734	115	64	913.0	-44.6	Nov- 2019, ↓50%BOD +↓50% nutrient (wwtp)
9	P2_U1	1468	115	48	1631.0	-1.0	Nov- 2019, ↓25% BOD (Urban)
10	P2_U2	1468	115	32	1615.0	-1.9	Nov- 2019, ↓50% BOD (Urban)
11	F1	1468	115	64	1647.0	0.0	Feb-27
12	F1_LUC	1468	115	70.57	1653.6	0.4	Feb-2027, Land use change
13	F1_110%Qw	1614.7	115	70.57	1800.3	9.3	Feb-2027, 110%Qwwtp
14	F1_120%Qw	1761.5	115	70.57	1947.1	**18.2**	Feb-2027, 120% Qwwtp
15	F1_120%Qw+W1	1321.1	115	70.57	1506.7	-8.5	Feb-2027, 120%Qwwtp + ↓25%BOD
16	F1_120%Qw+W2	880.8	115	70.57	1066.4	-35.3	Feb-2027, 120%Qwwtp + ↓50%BOD
17	F1_120%Qw+HWa	1761.5	115	70.57	1947.1	18.2	Feb-2027, 120%Qwwtp + QmeanHW
18	F1_HW1	1468	115	70.57	1653.6	0.4	Feb-2027, 110%Qhw
19	F1_HW2	1468	115	70.57	1653.6	0.4	Feb-2027, 120%Qhw
20	F1_HW3	1468	115	70.57	1653.6	0.4	Feb-2027, 90%Qhw
21	F1_HW4	1468	115	70.57	1653.6	0.4	Feb-2027, 80%Qhw
22	F2	1468	115	64	1647.0	0.0	Nov-27
23	F2-LUC	1468	115	70.57	1653.6	0.4	Nov-2027, Land use change
24	F2_110%Qw	1614.7	115	70.57	1800.3	9.3	Nov-2027, 110%Qwwtp
25	F2_120%Qw	1761.5	115	70.57	1947.1	18.2	Nov-2027, 120%Qwwtp
26	F2_120%Qw+W1	1321.1	115	70.57	1506.7	-8.5	Nov-2027, 120%Qwwtp + ↓25%BOD
27	F2_120%Qw+W2	880.8	115	70.57	1066.4	-35.3	Nov-2027, 120%Qwwtp + ↓50%BOD
28	F2_120%Qw+HWa	1761.5	115	70.57	1947.1	18.2	Nov-2027, 120%Qwwtp + QmeanHW
29	F2_HW1	1468	115	70.57	1653.6	0.4	Nov-2027, 110%Qhw
30	F2_HW2	1468	115	70.57	1653.6	0.4	Nov-2027, 120%Qhw
31	F2_HW3	1468	115	70.57	1653.6	0.4	Nov-2027, 90%Qhw
32	F2_HW4	1468	115	70.57	1653.6	0.4	Nov-2027, 80%Qhw
33	F2_33%Qw	484.4	115	70.57	670.0	-0.59	Nov-2027, 33%Qwwtp
34	F2_42%BODw	616.6	115	70.57	802.1	-0.51	Nov-2027, 42%BODwwtp
35	F2_77%Qw+ 50%BODw	565.2	115	70.57	750.8	-0.54	Nov-2027, 77%Q+50%BODwwtp

BOD TMDL is calculated for 35 scenarios, which is the lowest value of 619.4 kgBOD/day when 70% BOD load reduction is from WWTP, and TMDL value decreases 62.4% (scenario six) compare to BAU scenario. While the highest value is 1947.1 kgBOD/day when increasing 20% of waste discharge from the WWTP, and TMDL value rises 18.2% compare to BAU scenario Table (4.45).

In general, only a 50% BOD reduction in February (scenarios 16) and 25% BOD reduction in November in 2027 (scenarios 26) from WWTPs will result in the highest BOD value (km 105.88) that meets class three of surface water quality standard in Thailand.

The final and possibly important summary is that 58% BOD load reduction or 23% outflow and 50% BOD load were reduced, DO and BOD concentration can meet the class three in surface water quality standard in Thailand. Beside, the results prove that there are two possible management techniques including headwater flow augmentation and WWTP load reduction to improve water quality in Lam Takhong river can meet the class three of surface water quality standard.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

This study aimed to assess the river water quality modeling by integrating the SWAT model and the Qual2K model.

5.1.1 Models application

- Monthly calibration and validation of SWAT model showed that both M89 and M164 simulated flows were in reasonable agreement with measured values (objective one), coefficient of determination (R^2) and Nash-Sutcliffe model efficiency coefficient (NSE) were greater than 0.70 and the percent bias (PBIAS) less than 15% expected M164 validation PBIAS 23.8%.
- Water quality calibration and validation of the QUAL2K model had R^2 range and NSE higher than 0.7 all variables expected BOD validation NSE equal to 0.65. The correlation between simulated and observed values for DO, BOD showed a high R^2 and NSE. Thus the QUAL2K model can be used to simulate and predict the effect of point and non-point diffusion on river water quality in the Lam Takhong River (objective two).
- In general, the SWAT model is suitable for flow simulation and the QUAL2K model can be used to simulate water quality in Lam Takhong river. The integration of the SWAT model and the QUAL2K model is a useful tool for water resources management in Lam Takhong watershed or other river watershed with similar conditions (topographic or weather).

5.1.2 Simulation results and water quality assessment in Lam Takhong river

- The simulated results for the current condition indicate that DO and BOD upstream to km 102 of the Lam Takhong river is always good (class two of standard), while the DO decreased from km 102 toward downstream (km 115) where it recorded a class four. The BOD was recorded as class four from km 104 to km 112.5 (February 2019) and from km 104 to km 107.5 improved BOD downstream to class two (objective two).

- Three current model scenario groups were simulated to assess the impact of the point sources and nonpoint sources on current water quality including if 50% BOD load from WWTPs is reduced, DO and BOD would be improved from class four to class three of the standard; if the 50% BOD load reduction combining 25%, and 50% nutrient reduction from WWTP has a slight influence on DO and BOD changes; BOD load reduction from the urban area has a trivial influence on DO and BOD changes. The simulated scenarios proved that WWTP is the main pollutant source contributor to the Lam Takhong River (objective three).

- Four future model scenario groups were simulated to assess the impact of the sources on the river water quality pointed up following results
    - The location had the minimum DO value is the same location had the maximum BOD value (km 105.88). The highest DO value is always located in the headwater of Lam Takhong River, while the lowest BOD value is from km 49 to km 54 km from upstream of Lam Takhong River (objective two).
    - Land use change (urban area) has minimal impact on the quality of the river water in 2027 including DO and BOD concentration because the loading

from diffuse sources discharge into the river accounts for less than 5% of the total load (objective three).

- Scenario 21 has the 2.2 mg/L lowest DO value among 32 scenarios when the inflow of headwater is reduced by 20%. Besides, scenario 30 has the maximum DO value (4.88 mg/L) when the inflow of headwater is increased by 20%. At that time, the maximum BOD value (8.9 mg/L) is also obtained from scenario 21, which exceeds the standard of class four (4 mg/L). Only scenario 6 has a BOD value that meets class four of standard when the BOD load is released from WWTP is reducted to 70% (objective two).
- The 619.4 kgBOD/day TMDL value is the lowest value among 32 scenarios when 70% BOD load is reduced from WWTP, and TMDL value decreases 62.4% (scenario 6) compared to BAU scenario. While the highest value is 1947.1kgBOD/day when increasing 20% of waste discharge from the WWTP, and TMDL value increases 18.2% (objective four).
- In short, a 50% BOD reduction in February (scenarios 16) and 25% BOD reduction in November in 2027 (scenarios 26) from WWTP will obtain the highest BOD value (km 105.88) that can meet class three of surface water quality standard in Thailand (objective four).

- In general, there are possible two ways to improve water quality in Lam Takhong river in the future is flow augmentation from headwater and BOD load reduction from WWTP (or combining outflow adjuration and BOD load reduction). This will help DO and BOD concentration can meet the class three in surface water quality standard in Thailand.

5.1.3 The use of study results

- Identifying WWTP as a major source of pollution for the river help environmental managers and technicians find ways to reduce BOD discharge into the Lam Takhong river.

- Knowing the distribution of pollutant discharge sources in different locations helps managers to plan both the location and the emission load of each source. As a result, it is possible to redeploy easy-to-control waste sources.

- It is possible to combine SWAT and QUAL2K models to study in other river basins in Thailand or countries with similar conditions, especially in the absence of flow monitoring data.

5.1.4 Scholary contribution

- There is no study in Thailand using TMDL to calculate the discharge load reduction into the Lam Takhong river to meet the surface water quality standard in Thailand by the combination of SWAT model and QUAL2K model in the water resource management.

- The collaboration in the research team of the environmental engineering school in Suranaree University of Technology has resulted in an integration between future land use changes and the impact on river water quality.

- The research in the land use change and BOD loading reduction from the polluted sources can impact the media that have not been carried out in Lamtakong river watershed.

- The study is carried out on all polluted sources (point source and diffuse source) in the whole Lam Takhong river basin at present and in the future that no researcher had done before.

5.2 Recommendations

5.2.1 Policy recommendation

- Identification of water area need to be protected, then policy issues related to the use of surface water are linked with pollution need to be considered or dilution requirements during periods of low flow.
- The urban area also is a source that can impact on the water quality, therefore the industrial and urban rainwater runoff in the area needs to be thoroughly collected and treated.
- Consideration of step-wise, time-targeted implementation of industrial effluent standards and wastewater treatment plants, so industrial factories should apply cleaner technology for safe disposal of waste.
- The economic and social goal of effluent standards and water quality objectives need to be considered, so financing issues and implementation of municipal waste treatment to suitable standards.
- Fertilizer management needs to be improved, particularly from the efficient use of animal wastes and the environment, pesticide management and control are conducted in the manufacture, sales, application, and disposal.
- At present, the water quality at downstream of the Lam Takhong River is classified as polluted in terms of DO and BOD in class four of standard, meaning that pollution may become more critical in the far future. Several cleanup campaign programs will be conducted to improve the water quality of the River.
- There are two main management techniques that need to be considered including headwater flow augmentation and WWTP load reduction. These

will improve water quality to a class three standard, therefore there is a necessity for policy support that performs increase headwater flow and reduce the load from WWTP.

5.2.2 Future research activities recommendation

- The spatial digital map of the Lam Takhong river is more convenient, interactive, and efficient than the traditional paper map. However, the layers used to develop this map are for the year 2015 based on the data obtained. Therefore, for future work, up-to-date data is recommended for developing the map since the natural changes day by day.
- QUAL2K proved that it may be a useful model for simulating and evaluating the quality of the river water in Lam Takhong river. However, parameters were simulated in this study due to the limited time, frequency, and quantity. Therefore, in future work, it is recommended that more parameters should be analyzed for a long period (many times in the year), and more refined calibration and validation for better simulation of the water quality in Lam Takhong River. Data collection is recommended following Table 5.1.

Table 5.1 The addition of data collection for the QUAL2K water quality model

Type of data	Description
Parameters of water quality (additionally analyzed)	Inorganic Solids, CBODslow, Organic Nitrogen, Organic Phosphorus, Inorganic Phosphorus, Phytoplankton, Pathogen, COD, Bottom algae.
Parameters at headwater location (additionally analyzed)	Inorganic Solids, CBODslow, Organic Nitrogen, Organic Phosphorus, Inorganic Phosphorus, Phytoplankton, Pathogen.
Location of collected samples	Increasing collected samples (every 1km) from 100 km to 122km location
Frequency of collected samples	Water samples are collected at least twice a day (day and night), preferably every hour
Hydraulics Data	Flow and velocity: measured at least every 10 km

- Integrating SWAT and Qual2k is potentially an effective tool for water quality simulation in Lam Takhong River, and to develop water quality models as well as assess and manage river water quality. Thus, a highly recommended future works is a new integration of models, it is possible that there are several couples including MIKE-SHE and Qual2k, or SWAT and MIKE11.

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APPENDIX

LIST OF PUBBLICATIONS

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Journals

Tran, C., Yossapol, C., Kosa, P., Tantemsapya, N., and Kongkhiaw, P. (2020). Use of Swat Model for Hydrological Simulation in Lam Takhong Watershed in Thailand. **Test engineering management**. 83: 8113-8120.

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BIOGRAPHY

Miss TRAN NGOC CHAU was born on 20 December 1985 in An Giang Province, Vietnam. She obtained a bachelor's degree in Engineering in 2008 and a master's degree in Engineering in 2012 in the Faculty of Environment and Natural Resources from Ho Chi Minh City University of Technology, Vietnam under the support of JICA scholarship. Besides, she won a scholarship program for the ASEAN Ph.D. student in Environmental Engineering School, Institute of Engineering, Suranaree University of Technology, Thailand from 2016 to 2019. While she conducted her research, she published two scientific research articles in international journals in Scopus index and another under revised status regarding water quality modeling and load allocation. In addition, she won many the awards and honors including an advanced training course on statistical models for Ecological conservation in 2017 (ERAMUS+ scholarship, Royal University of Phnom Penh, Cambodia), a renewable energy and energy efficiency in 2018 (GIZ internship Program, University of Rostock, Mecklenburg-Vorpommern, Germany), the short course on River Basin Modelling in 2019 (OKP scholarship, IHE Delft Institute for Water Education, The Netherlands), and ASEA UNINET Students Week 2019 on Sustainable Development Fellowship (Universitas Indonesia, Indonesia), and the short course on Water Resources Assessment and Modelling in 2020 (OKP scholarship, IHE Delft Institute for Water Education, The Netherlands), etc.