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นางสาวกิตติยา ลิมปีผลไพบูลย์

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CARRYING CAPACITY OF PAK PHANANG RIVER ON ORGANIC WASTE LOADING

Miss Kittiya Limpiponpaiboon

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การศึกษาครั้งนี้ได้ประยุกต์ใช้แบบจำลองทางคณิตศาสตร์ WASP 6.0 (EUTRO) ในการประเมินศักยภาพการรองรับปริมาณสารอินทรีย์ของแม่น้ำปากพนัง เพื่อรักษาระดับออกซิเจนละลายให้มีค่าไม่ต่ำกว่า 4.0 มิลลิกรัมต่อลิตร ตามมาตรฐานคุณภาพน้ำผิวดินสำหรับแหล่งน้ำชั้น 3 ที่กฎหมายกำหนด โดยทำการประเมินภาระมลพิษจากข้อมูลทุติยภูมิในช่วงปี พ.ศ. 2545 ถึง พ.ศ. 2546 พบว่ามีค่าเฉลี่ยของปริมาณสารอินทรีย์ทั้งหมดประมาณ 2,978 กิโลกรัมต่อวัน ผลการศึกษาพบว่าช่วงของแม่น้ำตั้งแต่ฝายไม้เสียบจนถึงพรุควนเคร็ง มีศักยภาพในการรองรับปริมาณสารอินทรีย์ประมาณ 1,175 กิโลกรัมต่อวัน ซึ่งสามารถรองรับปริมาณสารอินทรีย์ได้ประมาณ 7 เท่าของภาระในปัจจุบัน ช่วงของแม่น้ำตั้งแต่พรุควนเคร็งจนถึงคลองเชียรใหญ่ มีศักยภาพในการรองรับปริมาณสารอินทรีย์ประมาณ 130 กิโลกรัมต่อวัน ซึ่งควรมีการบำบัดภาระมลพิษให้ได้ร้อยละ 80 ของภาระในปัจจุบัน และช่วงของแม่น้ำตั้งแต่คลองเชียรใหญ่จนถึงประตูระบายน้ำอุทกวิภาชประสิทธิ มีศักยภาพในการรองรับปริมาณสารอินทรีย์ประมาณ 874 กิโลกรัมต่อวัน ซึ่งควรมีการบำบัดภาระมลพิษให้ได้ร้อยละ 60 ของภาระในปัจจุบัน ดังนั้น ศักยภาพในการรองรับปริมาณสารอินทรีย์ของแม่น้ำปากพนังมีค่ารวมประมาณ 2,179 กิโลกรัมต่อวัน

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ลายมือชื่อนิสิต กิตติยา ลิมปิผลไพบูลย์
ลายมือชื่ออาจารย์ที่ปรึกษา
ลายมือชื่ออาจารย์ที่ปรึกษาร่วม

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WASP 6.0 (EUTRO) was applied to estimate the carrying capacity of Pak Phanang River on organic waste loading. The achievement of water quality goal was set to maintaining a DO concentration of 4.0 mg/L according to the river class 3 of Thailand's surface water quality standard. The average annual organic waste loads was estimated from secondary data collected in 2002 to 2003, as 2,978 kg/day. The results showed that loading capacity of the river from Mai Siap weir to Kuan Kreng swamp forest was 1,175 kg/day which can receive additional load about 7 times of the existing loads. Loading capacity of the river from Kuan Kreng swamp forest to Klong Chian Yai was 130 kg/day which requires 80 percents treatment of the existing loads. Loading capacity of the river from Klong Chian Yai to Uthokvibhajaprasid Gate was 874 kg/day which requires 60 percents treatment of the existing loads. Consequently, it was calculated that total loading capacity of Pak Phanang River was 2,179 kg/day.

Field of study Environmental Science (Inter-department)
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CHAPTER I

INTRODUCTION

1.1 Background

Pak Phanang River Basin is an important agricultural area in Nakhon Si Thammarat Province on the South-East coast of Thailand. In years gone by, the paddy farming was successful until the shrimp farms were introduced to this area in the 1990's. As a result, land use patterns have changed rapidly as mangrove forests and rice paddies were uncontrolly converted to shrimp ponds. The increasing of organic waste without any treatment from highly intensive shrimp farming activity has been released into the land, river and the sea. It results in poor water quality of Pak Phanang River and coastal area.

In 1995, Royal Irrigation Department constructed drainage gates in Pak Phanang River and its tributaries. This activity aimed to separate saline and fresh water of Pak Phanang River and also to protect flood problems. Since the main gate (Uthokvibhajaprasid) has been operated in October 1999, the salinity of Pak Phanang River decreased while BOD level increased. If the organic waste is rising continuously in the river, the ecological systems will be dammaged. However, the major cause of wastewater is not only from shrimp farm but also from municipals, industries and other agricultures. Besides, the water body has an ecological carrying capacity to handle the organic pollutants. Therefore, the balance point between organic waste loading and natural water-purification system would be the answer to the question about the maximum level of pollutant loading.

An effective management of water resources is to determine the carrying capacity of an existing pollutant on the river. Since the carrying capacity is strongly depending on the hydrodynamic characteristics of water body and the transport characteristics of pollutant, mathematical models are tools for estimating and determining water quality impacts. They are useful for allocating loads, evaluating management practices and understanding the basic mechanisms for the transport and fate of water quality with regards to water resources management.

1.2 Objective

To determine organic waste loading capacity of Pak Phanang River based on water quality standard.

1.3 Scope of the Study

1.3.1 Location

Pak Phanang River Basin located in Nakhon Si Thammarat Province on the South-East coast of Thailand with the catchment area of approximately 3000 square kilometers and total length of 110 kilometers.

1.3.2 Computation Framework

WASP 6.0 (EUTRO 6.0) will be used to simulate water quality constituents.

1.3.3 Target Water Quality Goal

Water quality standard level for river class 3 (DO ≥ 4 mg/l) will be used as the water quality goal.

1.4 Expected Outcome

Findings of this research could support the decision making processes of environmental management in Pak Phanang River Basin.

CHAPTER II

LITERATURE REVIEW

2.1 Overview of Pak Phanang River Basin

2.1.1 General Information

Pak Phanang River and its tributaries are located along the eastern coast of Nakhon Si Thammarat Province, peninsula of Thailand. It is situated at latitude 8^0 22' North and longitude 100^0 22' East. The river originates from the Bun Tud mountain range, passes through Cha-uat, Chian Yai, joins with the tributary from Hua Sai at Pak Phraek to form Pak Phanang River which flows to Pak Phanang Bay. Total length of the river is approximately 110 kilometers and the Pak Phanang River basin is about 3000 square kilometers (Figure 2.1).

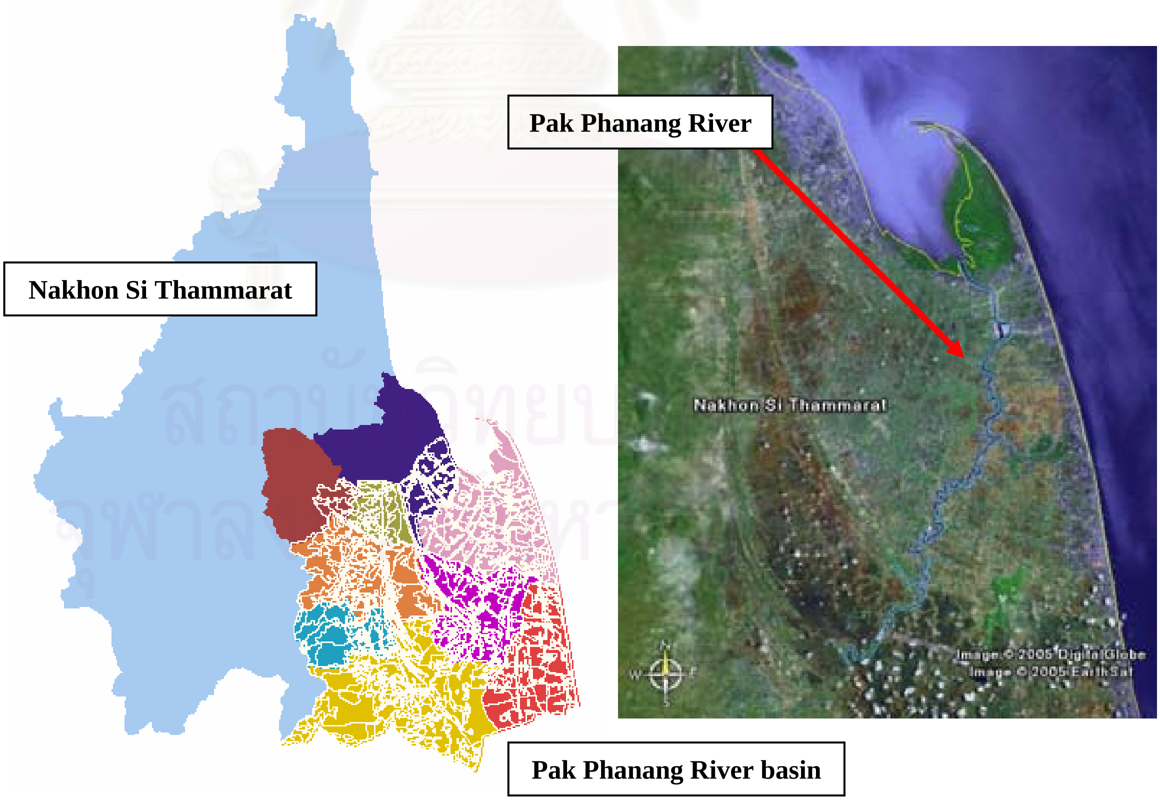


Figure 2.1: Map of Pak Phanang River basin

The basin area consists of 9 districts; Cha-uat, Chian Yai, Pak Phanang, Mueang, Ron Phibun, Lan Saka, Chulabhorn, Hua Sai and King Amphoe Phra Phrom. The general data of Pak Phanang River basin was shown in Table 2.1.

Table 2.1: General data of Pak Phanang River basin

Data Types	Characteristics
Topography	Coastal plain (less than 10 meters above MSL)
Climate	Classified as Tropical Monsoon. The rains are affected by the North-East Monsoon in November to January and change to South-East Monsoon in May to October. Hot and dry season are in February to April.
Meteorology*(1)*	Annual temperature (^{0}C): 27.3 Range of monthly temperature (^{0}C): 25.8-28.5 Annual relative humidity (%): 79.0 Range of monthly relative humidity (%): 75.0-86.0 Annual wind speed (knot): 2.6 Range of monthly wind speed (knot): 1.7-3.7 Annual evaporation (mm): 141.40 Range of monthly evaporation (mm): 84.7-145.7 (average for 10 years)
Population and Community*(2)*	Totally population of basin area is about 760,000 (end of December 2003). Mostly settlement in Mueang, Cha-uat, Pak Phanang and Hua Sai districts.
Land use*(3)*	Agricultures: 1,229,124 rai (61.767 %) Forests: 384,850 rai (19.34 %) Aquacultures: 106,295 rai (5.342 %) Municipal area: 67,341 rai (3.384 %) Water sources: 12,197 rai (0.613 %) Others: 190,125 rai (9.554 %)

Sources: *(1) Royal Irrigation Department, 1994*

(2) Administration Office of Nakonh Si Thammarat, 2004

(3) Surveyed by Land Development Department in 1997 (Land Development Department, 1999)

During the past, the economy of this area is based on agriculture and fisheries. Paddy farm was the most important agricultural crop. Because of higher prices of the shrimp farming, paddy farm area has been rapidly converted to shrimp farm. In addition, mangrove forest has been rehabilitated by shrimp farm too (Table 2.2).

Table 2.2: Land use changes in Pak Phanang River basin

Land Use Types	**Area (km^2)**			**Change (km^2) 1988-1999**	**%**
	1988	**1995**	**1999**		
Forest	163.10	67.69	65.02	-98.08	-60.13
Rubber	443.22	627.52	624.92	181.70	41.00
Paddy field	1,554.81	1,329.95	1,306.11	-248.70	-16.00
Shrimp-Fish farming	20.86	175.54	205.73	184.87	886.24
Mangrove	101.80	84.82	86.11	-15.69	-15.41
Rubber-Mixed orchards-Village	45.26	19.61	19.57	-25.69	-56.76
Mixed orchards-Rubber-Village	77.91	90.71	90.79	12.88	16.53
Coconut-Mixed orchards-Village	175.63	210.90	205.31	29.68	16.90
Swamp area-Nipa palm	479.01	448.16	441.47	-37.54	-7.84
Tin mine	5.26	8.70	9.66	4.40	83.65
Town-Village	30.42	31.73	32.35	1.93	6.34
River	16.37	16.07	17.50	1.13	6.90
Reservoir-Pond	-	3.09	8.95	8.95	-
Sand beach	0.15	7.87	7.25	-	-
Other	-	-	1.79	-	-
Total	3,113.80	3,122.36	3,122.53		

Source: *Yongchalermchai et al., 2004*

Remarks: *(1) Areas estimated by Department of Land Development in 1988*

(2) and (3) Areas derived from satellite images in 1995 and 1999 by visual interpretation, the difference in total area between 1995 and 1999 due to increasing of mangrove area around the Pak Phanang Bay

This condition was affected to ecosystems and the environment. Especially, the releasing of untreated shrimp waste into water sources was results in low water quality. Besides, shrimp waste is including with nutrients, organic waste, and salt that causing saltwater intrusion along Pak Phanang River.

2.1.2 Pak Phanang River Basin Royal Development Project

The Royally-initiated Pak Phanang River basin Development Project was created to mitigate the chronic socio-economic problems and improve the inhabitants' standard of living in a sustainable development.

The various development activities have progressed as follows;

1) Development of Irrigation Systems and Basic Infrastructures

1.1) Drainage and Saline-water Obstruction System

The work involved has been partly carried out. The entire system was planted to complete and start operating in 2003, with all components supporting each other effectively. The system consists of;

- The Uthokvibhajaprasid regulator and the emergency drainage canal, completed and operated since 1 October 1999
- Cha-uat - Phraek Mueang canal, with regulator
- Bang Do - Tha Phaya canal, with regulator
- Na Got canal, with regulator

1.2) Irrigation System for Agriculture

- Improvement of the irrigation system of the Pak Phanang Water Distribution and Maintenance Project, covering an area of 480,000 rai (192,000 acres)
- Mai Siap weir irrigation system, 24,000 rai (9,600 acres)
- Huay Nam Sai reservoir irrigation system, 17,500 rai (7,000 acres)

1.3) Separation of Fresh-water and Saline-water Zones

A ninety-one kilometers stretch of the original Accelerated Rural Development Office road along the coast serves as a dyke dividing the fresh and salt water zones.

2) Development of Saline-water Irrigation

The activity aims to promote and develop sustainable sea-shrimp farming for an area of 60,000 rai (24,000 acres) in the saline-water zone, without harmful impact on the environment. The principles governing this activity are outlined hereunder.

- Locating the water source and conveying to the people's shrimp ponds, through saline-water irrigation systems, sea water of suitable quality for sea-shrimp farming.
- Laying out systems to drain waste water from shrimp ponds without affecting the environment.
- Setting up waste-water treatment systems to safeguard the environment.

So far, work has progressed to the stage where saline-water irrigation systems are being established for shrimp farming in the following areas;

- Na Got village, 1,200 rai (480 acres)
- Tha Phaya village, 2,412 rai (964.8 acres)
- Bo Khonthi village, 2,335 rai (934 acres)
- Na Saton village, 1,906 rai (762.4 acres)

In addition, for the promotion of sustainable sea-shrimp farming, a plan has been prepared for the subsequent development of the remaining 50,000 rai (20,000 acres) of the saline-water zone.

3) Occupational Promotion and Income Raising

The activities include;

- Adjusting the crop production system
- Increasing crop production efficiency

- Promoting farmers' association
- Extending technical knowledge and technologies in the field of agriculture
- Developing and promoting off-farm occupations
- Planning for Ecotourism development
- Developing agricultural products processing
- Planning agricultural marketing system development
- Planning for human and social development

4) Rehabilitation of Natural Resources and the Environment

This activity aims at making possible the effective and sustainable conservation of the environment and natural resources in the project area, with emphasis being placed on the participatory method of management;

- Determination of environmental protection zones and pollution control zones, as well as legal measures to penalize offenders seriously.
- Conservation of forest and watershed areas to ensure their existence in at least 25 percents of the river basin area.
- Planning of water quality improvement and soil improvement.
- Public relations efforts to promote people's understanding and awareness of conservation.

2.1.3 Hydrological System

In order to determine the stream flow, it is important to identify the relation between rainfall and catchments characteristic. The upstream are Huay Nam Sai and Mai Siap canal pass on to Cha-uat, Chian Yai (named Cha-uat canal), Pak Phanang (named Pak Phanang River) and go through Pak Phanang Bay. As a result of direction flow from South to North.

Pak Phanang River basin is a dendritic system. The compactness coefficient (Kc), form factor (FF), and relief ratio are 1.68, 0.96 and 22.36 respectively. The highest point is 1,365 meters above MSL at Khao Luang mountain range on the West side, while the lowest point is 1.0 meter above MSL at Hua Sai on the South-West side. The basin has not well drainage (drainage density = 0.64 km/sq km), so frequently causing flood problem in rain season.

With a view to understand and organize the watershed system, many concerned departments are separated Pak Phanang River basin into 8 parts as follows; Klong Sao Thong, Klong Rak Mai, Klong Thum Pra, Klong Mai Siap Upper Weir, Klong Mai Siap Lower Weir, Plain, Coastal and Outside watershed, as well as the gates that constructed along the river to control water level.

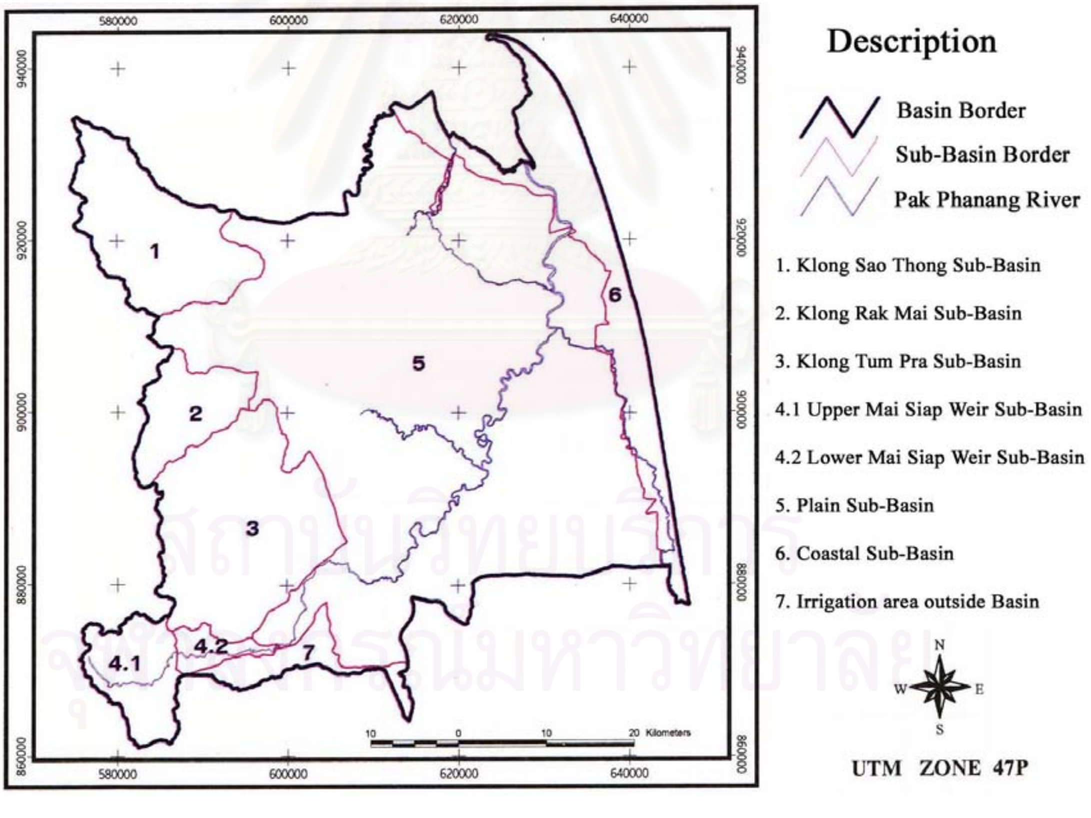
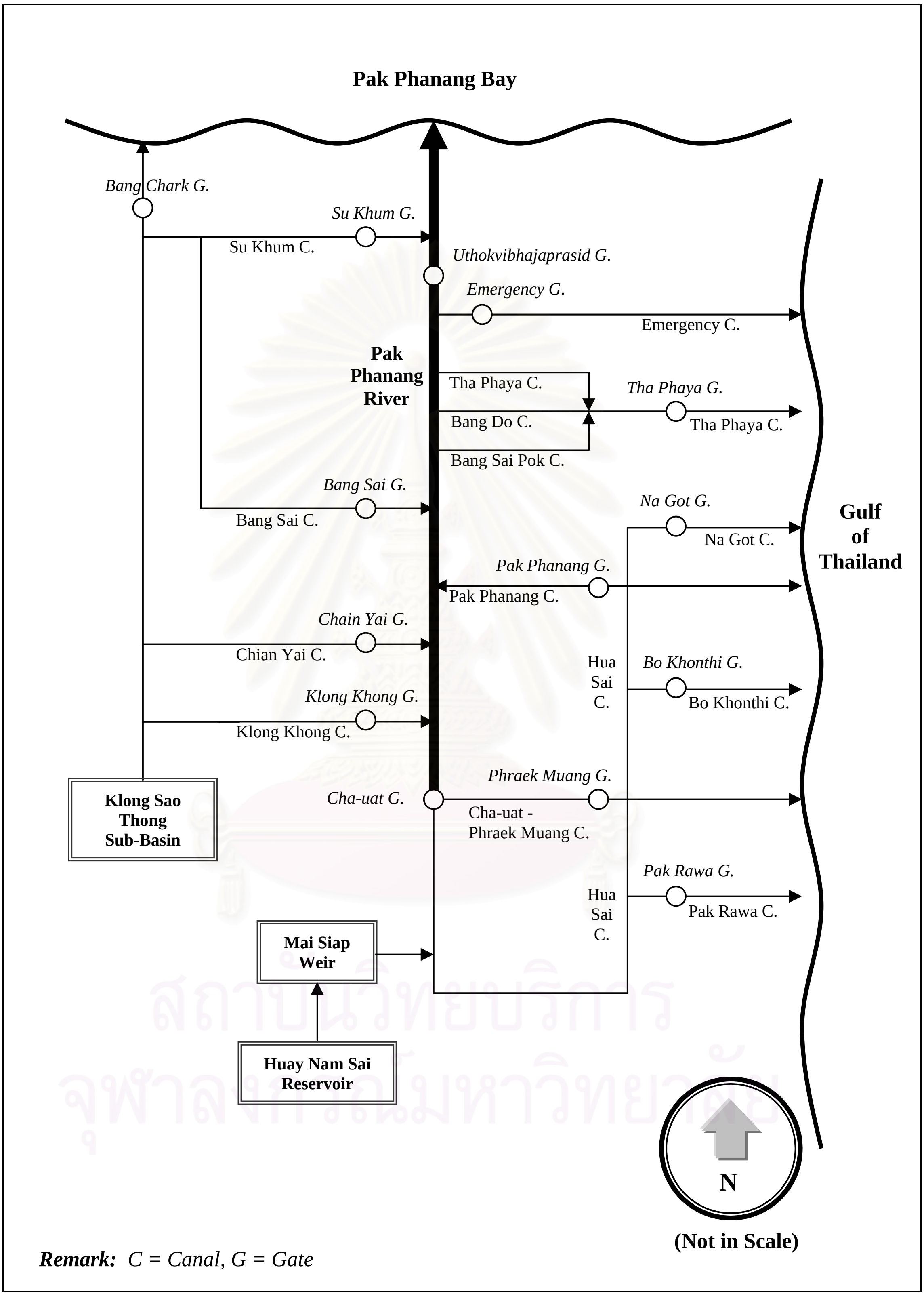


Figure 2.2: Map of sub-basins of Pak Phanang River basin

Source: *Applied from Land Development Department, 1999*



Remark: *C = Canal, G = Gate*

Figure 2.3: Pak Phanang River and its tributaries system

The average runoff can be estimated from hydrological 2 stations in Pak Phanang River basin, Klong Sao Thong (X. 167) and Klong Mai Siap (X. 105). Rainfall data are also used for determining the runoff land catchments area for each basin. The relation between rainfall and runoff is shown in Figure 2.4.

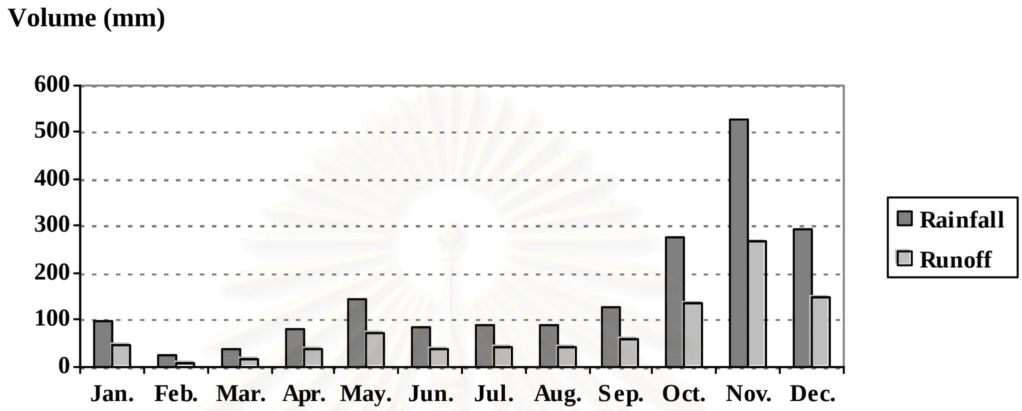


Figure 2.4: Comparison of monthly average rainfall and runoff during 1952-1996

Source: *Applied from Land Development Department, 1994*

Remark: *Computed with the equation as follows;*

$Qm = -1.1823 + 0.1096\,R \ (r = 0.9024)$

where; Qm *= quantity of monthly runoff (million cubic meter)*

R *= quantity of monthly rain fall (mm)*

2.1.4 Water Quality Characterization

The majority source of pollutant in Pak Phanang River can be classified as point and non-point sources. Point sources include municipal and industrial wastewater, and any other sources that can be identified with specific points of entry. The non-point sources include general land runoff and other dispersion that does not have specific point of entry into the river such as overland flow of polluted water from agriculture.

Although the regulators are benefit to reduce flood and salt water intrusion problems, they are not help to reduce water quality problems. National Institute of Coastal Aquaculture (NICA, 2001) reported that after the drainage gates have been operated in 1999, some parameters were rose up obviously (BOD and DO for instance) and more water hyacinth was found along the river. These results are same as water quality monitoring data, compare between before and after the year 1999, from Pollution Control Department (PCD). Figure 2.5 was shown the comparisons of water quality monitored by NICA and PCD between before and after the gates were installed.

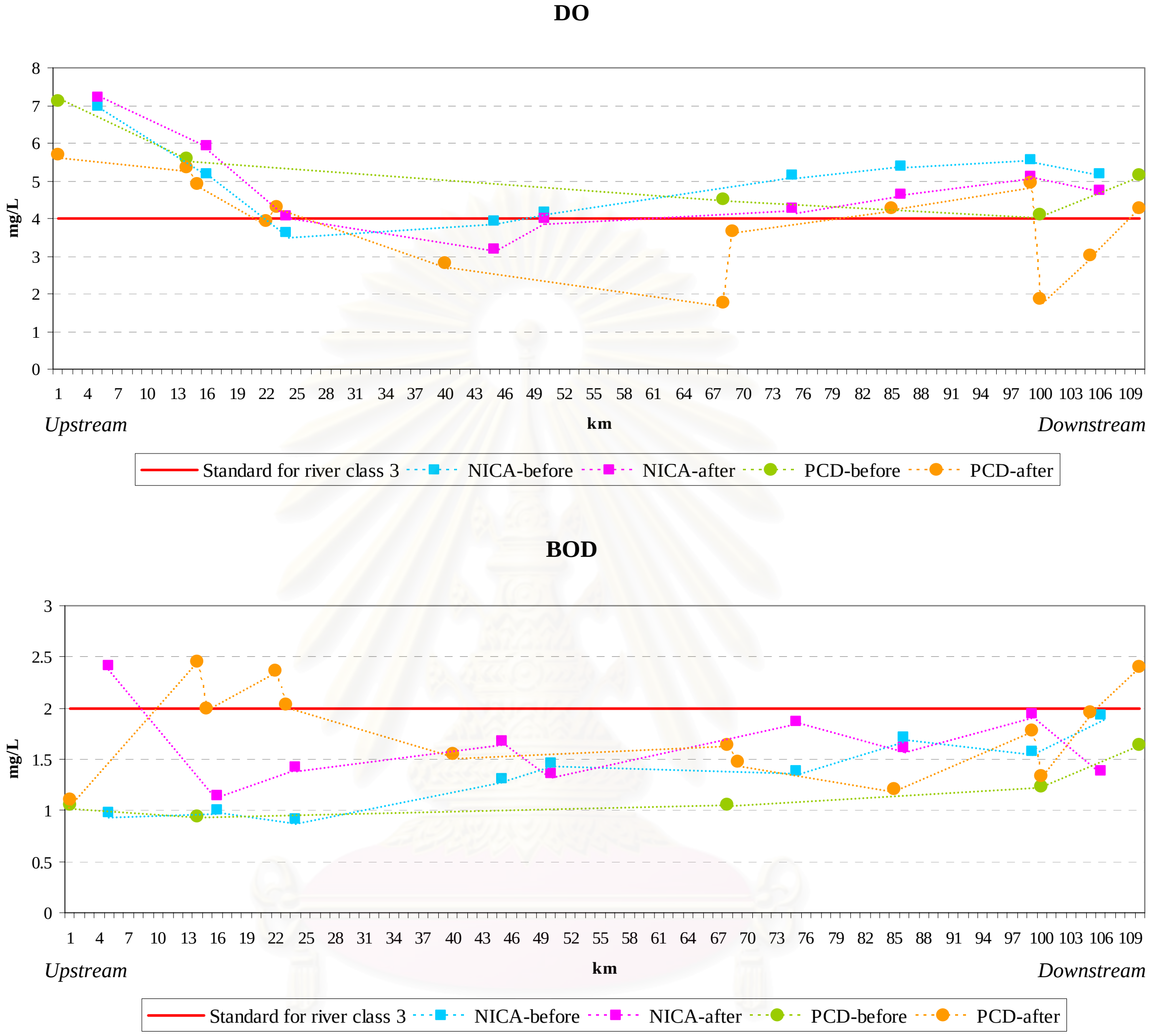


Figure 2.5: The comparisons of water quality monitored by NICA and PCD between before and after the gates were installed.

Sources: *Applied from NICA, 2001 and water quality data from Pollution Control Department (PCD), 1991–2004*

Remark: *For NICA, average in October 1996 to September 1999 (before) and October 1999 to September 2001 (after). For PCD, average in April 1991 to June 1999 (before) and January 2000 to June 2004 (after).*

From Figure 2.5, the trends of water quality from both departments are not slightly different. However, loading estimation of point and non-point sources will be discusses in chapter 3.

2.2 Concepts in Biochemical Oxygen Demand (BOD), Dissolved Oxygen (DO), and Nutrient Analysis

In addition to being major sources of water supply, rivers are used as the principal disposal pathways for waste materials. In order to manage a river system and maintain adequate water quality it is essential, therefore; to understand the mechanisms governing pollution and self-purification processes. The interactions between physical, chemical and biological processes ensure that forecasting the impact of an effluent on a river system is particularly difficult. Figure 2.6 indicates the effects of an organic effluent on a river and the changes occurring downstream from the outfall. Self-purification processes depend on a wide range of parameters and the physical, chemical and biological mechanisms governing water quality in river systems are considered.

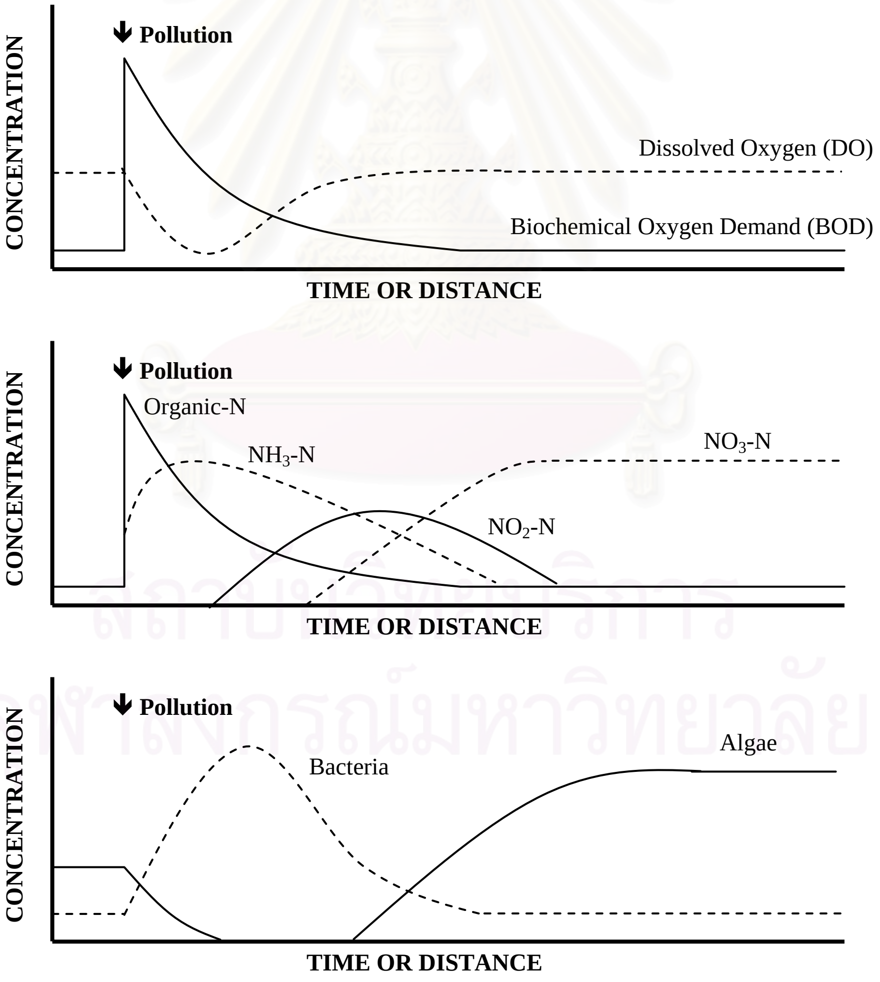


Figure 2.6: Change in stream quality downstream of a waste outfall

Source: *Whitehead and Lack, 1982*

The content of biodegradable organics in waste discharges (from both point and non-point sources) is commonly expressed as the biochemical oxygen demand (BOD). When waste discharge containing biodegradable organics is introduced into receiving waters, decomposer begin immediately to decompose the biodegradable organic matter and then convert it, ultimately, to carbon dioxide (alkalinity), water and mineral and organic non-biodegradable residues. And dissolved oxygen is used in this biochemical reaction.

2.2.1 In-stream Fate and Transport of Pollutants

When a pollutant load is discharged into a flowing stream or river, it is subject to fate and transport processes that modify stream concentrations. The principle factors determining stream concentrations are advection, dispersion, and reaction.

Advection

Advection represents the primary transport process of pollutant inflow in the downstream direction. Lateral advective transport across a stream is typically neglected. Usually complete mixing between the pollutant load and the ambient stream flow in the vertical and lateral direction has been achieved within a relatively short distance downstream of the outfall.

Dispersion

If all water elements in a stream were traveling at a uniform speed over each cross-section of the river, they would arrive at a given location at the same time. In reality, however, lateral velocity differences cause each element to arrive at a different time, resulting in an apparent mixing due to vertical and lateral velocity gradients. For example, the center of the stream near the surface moves faster than the flow near the banks and streambed. This phenomenon is called longitudinal dispersion. When analyzing the effects of a continuous pollutant load, the effects of dispersion may be ignored since the contribution of dispersion to the resulting in-stream pollutant concentration is usually small in comparison to the contribution from advection. On the other hand, when analyzing transport of storm-driven loadings during wet-weather periods, longitudinal dispersion also must be considered since the pollutant loading is represented as a single “pulse” input rather than a continuous series of “pulse” inputs.

When a water quality-analysis is conducted over a “long” distance with a short time “pulse” interval of discharge, then longitudinal dispersion must be considered in the analysis (Thomann and Mueller, 1987).

Reaction

The biodegradable materials discharged to a stream or river (e.g., oxygen-demanding organics) undergoes decomposition by bacteria in the water column. In the presence of dissolved oxygen, bacteria convert organic materials to end products such as CO_2, NO_3, and H_2O, stabilizing the pollutant load. In addition, algae take up nutrients such as inorganic phosphorus and nitrogen during photosynthesis and reduce the nutrient concentrations in the stream. Algal biomass is then recycled back into inorganic nutrients. A number of chemical, biological, and biochemical reactions contribute to the flux and attenuation of waste material concentrations.

The interactions of these factors are shown schematically in Figure 2.6, which presents what would be observed if a single slug of waste load were injected and could be followed downstream over a period of time. Conservative materials in the waste (those not subject to reaction and decay, such as chloride) would track as shown in the sketch of advection, or advection and dispersion. Reactive materials, such as oxygen-consuming materials, would behave as shown in the sketches that include reaction. Thus, the behavior of a dissolved substance in the stream is the result of the velocity and mixing action of the water and the resulting transformation from biological and chemical reactions.

2.2.2 Biochemical Oxygen Demand and Dissolved Oxygen Reaction Kinetics

Figure 2.7 shows the interrelationship of the following major BOD/DO kinetic processes for a water column as commonly represented by water quality models:

- Carbonaceous deoxygenation
- Nitrogenous deoxygenation (nitrification)
- Reaeration
- Sediment oxygen demand
- Photosynthesis and respiration

BOD is a measure of the amount of oxygen required to stabilize organic matter in the wastewater. As such, BOD is an equivalent indicator rather than a true physical or chemical substance. It measures the total concentration of dissolved oxygen that would eventually be demanded as wastewater degrades in stream.

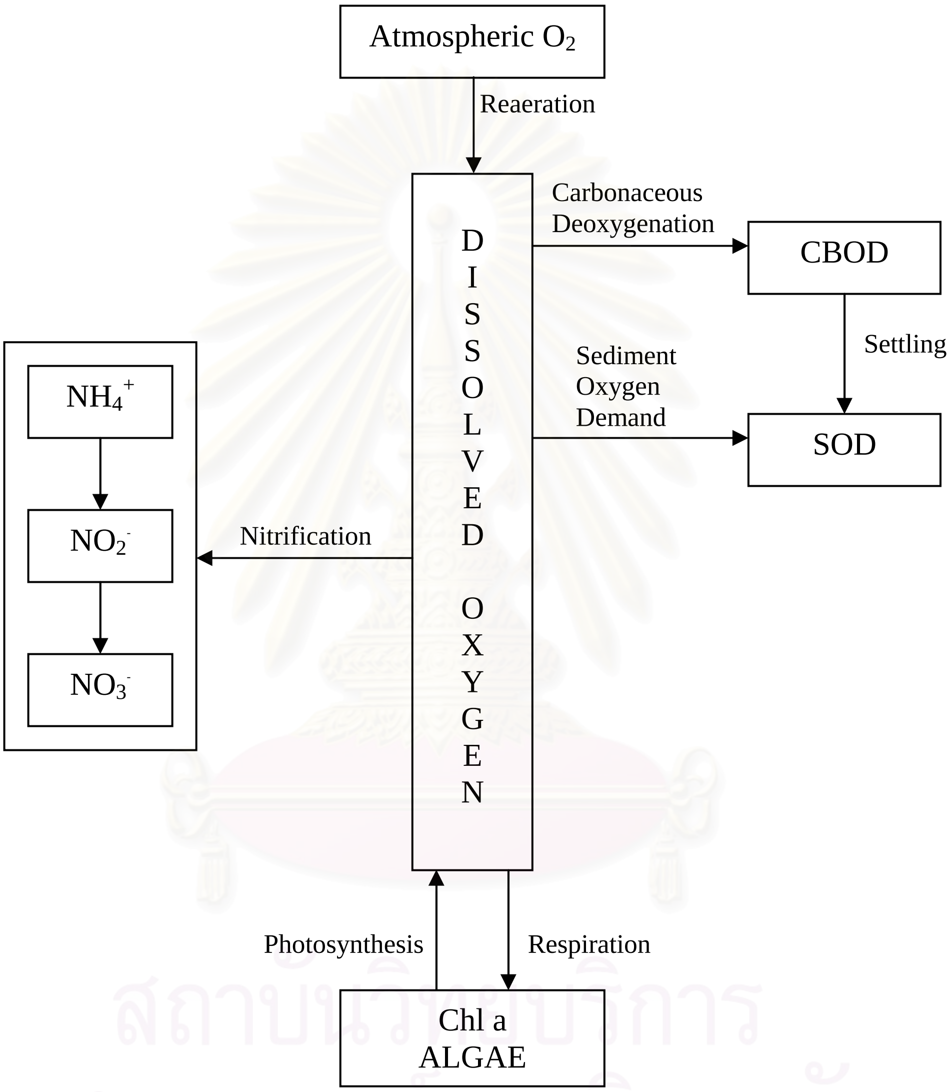


Figure 2.7: Interrelationship of major kinetic processes for BOD and DO as represented by water quality models

Source: *McCutcheon, 1989 cited in U.S. EPA, 1997*

BOD is determined from a standardized test measuring the amount of oxygen available after incubation of the sample at 20 ^{0}C for a specific length of time, usually 5 days. The oxidation process is usually carried out in two stages: carbonaceous and nitrogenous (nitrification). The first stage is accomplished by saprophytic organisms, which derive their energy from the breakdown of organic carbon compounds; the second stage, by autotrophic bacteria, which require simple inorganic nitrogen compounds.

Each stage is characterized by two steps: synthesis and respiration. In the carbonaceous stage, the energy required for synthesis is obtained from the destruction of complex organic carbon compounds, liberating carbon dioxide and water. After the organic matter has been converted to bacterial cells, the endogenous respiration of the synthesized organisms occurs, also yielding carbon dioxide, water, and usually ammonia. In streams, the two stages frequently proceed simultaneously; although there may be lags I the nitrification stage for highly polluted streams or those with low dissolved oxygen.

Carbonaceous Deoxygenation

The first phase of the BOD reaction involves the oxidation of the carbonaceous organic material. The reaction is approximated by a first-order reaction. The oxygen required, y, approaches the total demand of the overall process, L_0, and the rate is assumed to be proportional to the amount of oxygen-demanding material (L_0-y), either substrate or cells:

$$\frac{dy}{dt} = K_1 (L_0 - y) \qquad \text{-------(2-1)}$$

Integration of this expression yields;

$$y = L_0 (1 - e^{-K_1 t}) \qquad \text{-------(2-2)}$$

or, if the relationship is put in terms of the organic matter remaining,

$$L = L_0 e^{-K_1 t} \qquad \text{-------(2-3)}$$

where

K_1 = BOD reaction rate coefficient (day^{-1})

y = oxygen consumed

L = oxygen equivalence of the organic matter remaining

L_0 = total oxygen demand

t = time (day)

Equation 2-1 indicates that the rate at which the oxygen is consumed (dy/dt) is proportional to the concentration of biologically degradable organic material, as well as chemically oxidizable substances. The coefficient, K_1, depends on the state of the material and the degree of treatment.

Another important concept for stream BOD is show in Figure 2.8. When water samples are taken from a stream to the laboratory for analysis of their biochemical oxygen demand, the results may be represented by a family of curves (Equation 2-2) of oxygen consumed vs. time of incubation (Figure 2.8-b). Each of these curves has a different K_1 value decreases in the downstream direction. If $CBOD_5$ values are plotted against the longitudinal stream distance (Figure 2.8-a), a decreasing trend for $CBOD_5$ is obtained. This trend follows an exponential decay and usually can be approximated by the following equation in terms of ultimate CBOD:

$$L\ (CBOD_U) = L_0\ (CBOD_U)\ e^{-K_r \frac{x}{U}} \qquad \text{-------(2-4)}$$

where

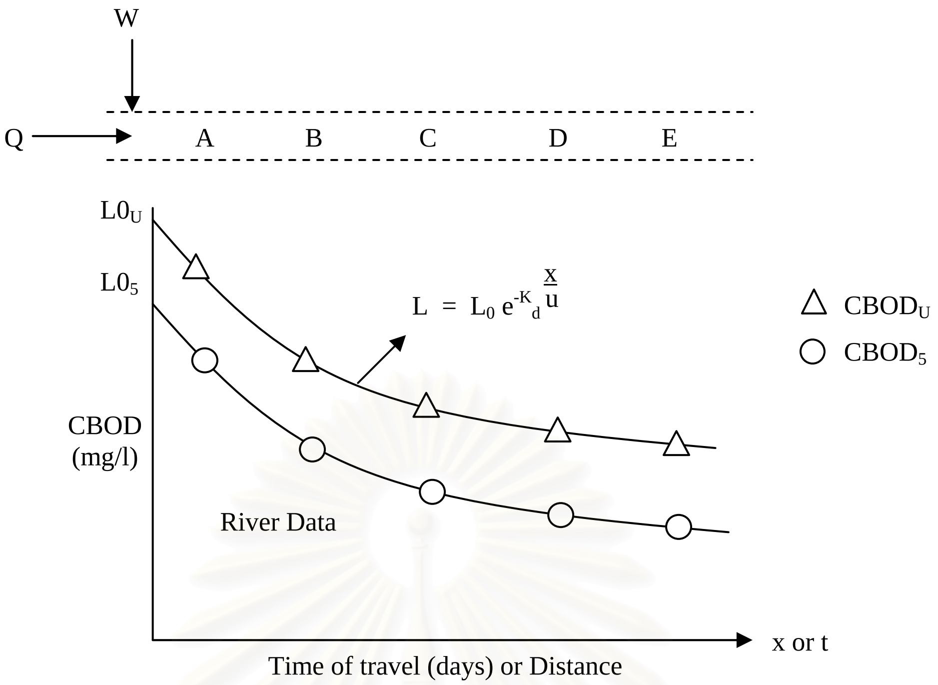
$L\ (CBOD_U)$ = oxygen equivalence of the organic matter at any given location in the stream (measured as $CBOD_U$)

$L_0\ (CBOD_U)$ = total oxygen demand measured at the source of waste load following complete mixing (measured as $CBOD_U$)

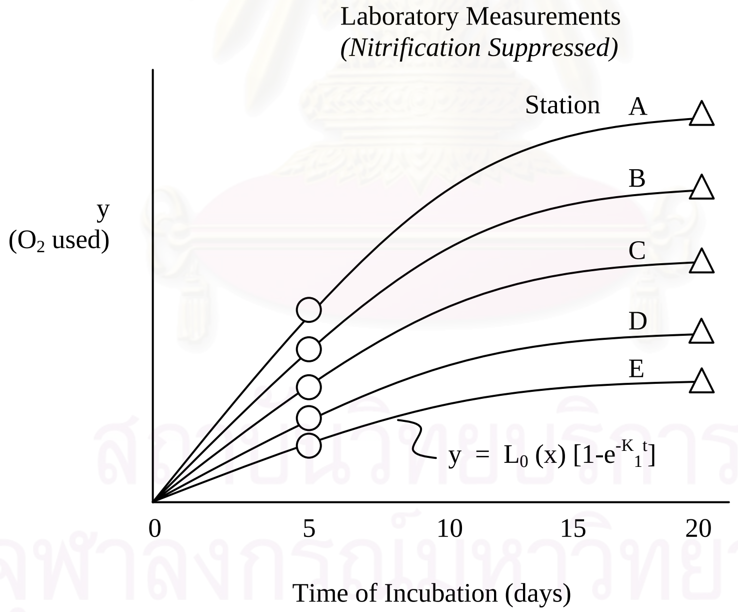
K_r = $CBOD_U$ removal rate in the stream (day^{-1})

x = distance below the wastewater discharge

U = average stream velocity



(Figure 2.8-a)



(Figure 2.8-b)

Figure 2.8: Comparison of stream BOD and laboratory BOD for various incubation times

Source: *Manhattan College, 1983 cited in U.S. EPA, 1997*

The time of travel, t, is equal to x/U. The meaning of Equation 2-4 is that the oxygen-consuming materials are removed from the water column at an overall loss rate of K_r. It should be noted that K_r is used to characterize the overall loss of dissolved organic materials in the water column due to biochemical oxygen and settling. It is highly empirical and therefore, is usually quantified by fitting an exponential decay curve through the field data.

Both of $CBOD_5$ and $CBOD_U$ can be used to describe the decay of CBOD in streams when the ratio of the two remains relatively constant in the downstream direction. However, only $CBOD_U$ can be used to simulate the loss of dissolved oxygen in stream TMDL studies. For this reason, it is necessary to employ $CBOD_U$ measurements for model calibration. If measurements of $CBOD_5$ are to be used, it is necessary to determine the relationship between $CBOD_5$ and $CBOD_U$. One purpose of evaluating K_1 (in Equation 2-2; $CBOD_5$ = y, $CBOD_U$ = L_0; and t = 5 days) is to convert $CBOD_5$, as usually reported to $CBOD_U$, which is required for the dissolved oxygen modeling analysis (e.g. QUAL or WASP) (Thomann and Mueller, 1987).

Nitrogenous Deoxygenation (Nitrification)

The nitrogenous stage of the BOD test includes conversion of organic nitrogen to ammonia and the subsequent oxidation of ammonia. Many wastewaters contain organic nitrogen, such as urea, and/or ammonia. The former is hydrolyzed to ammonia, under aerobic or anaerobic conditions, without the use of oxygen. Ammonia is successively oxidized through nitrite to nitrate by the organisms *Nitrosomonas* and *Nitrobacter*, respectively.

$$NH_4^+ + 1.5\,O_2 \rightarrow NO_2^- + H_2O + 2H^+ \qquad \text{-------(2-5)}$$

$$NO_2^- + 1.5\,O_2 \rightarrow NO_3^- \qquad \text{-------(2-6)}$$

The most common approach to modeling nitrification is to use first-order kinetics to characterize Equation 2-5 and 2-6. That is, the rate of accumulation or depletion is linearly dependent on the amount of nitrogen available in a specific pool. Factors affecting the rate of nitrification include temperature, pH, nitrogen concentrations, dissolved oxygen, suspended solids, and organic and inorganic compound.

Because of the ease of measuring organic nitrogen, ammonia, nitrite, and nitrate, waste load allocation modeling of nitrification involves a mass balance and a description each of species decay. Nitrification is best simulated as a cascade process involving hydrolysis of organic nitrogen, oxidation of ammonia, and oxidation of nitrite. In some models, the intermediate step of nitrite oxidation is combined with the overall oxidation of ammonia to nitrate, but only little computational efficiency is gained. Furthermore, the conversion of nitrite to nitrate is very rapid; therefore, the combination of the corresponding rates is not unreasonable.

Reaeration

In general, oxygen may be removed from or added to water by various physical, chemical, or biological reactions. If oxygen is removed from the water column and the concentration drops below the saturation level, there is a tendency to make up this deficit by the transfer of the gas from the atmosphere through the surface into the stream at a certain rate. If oxygen is added and the water column concentration is greater than the saturation level, the super saturation is reduced by the transfer of oxygen from the stream to the air. Such interactions between the gas phase and liquid phase are driven by the partial pressure gradient in the gas phase and the concentration gradient in the liquid phase (Thomann and Mueller, 1987).

Generally, oxygen transfer in natural waters depends on:

- Internal mixing and turbulence due to velocity gradients and fluctuation
- Temperature
- Wind mixing
- Waterfalls, dams, and rapids
- Surface film
- Water column depth

The rate of transfer to be quantified in stream BOD/DO modeling analyses is expressed as:

$$\frac{dC}{dt} = K_a (C_s - C) \qquad \text{-------(2-7)}$$

where

dC/dt = rate of change of oxygen concentration

C_s = saturation concentration of dissolved oxygen

C = dissolved oxygen concentration in stream

K_a = stream reaeration rate coefficient (day^{-1})

Sediment Oxygen Demand

Benthic decomposition of organic material is defined as the stabilization of the volatile suspended solids that have settled to the streambed. These deposits are stabilized by the biological activity of many different organisms including bacteria. As these organic materials are associated with suspended solids, the discharge of settleable waste components may from a sludge blanket below a wastewater outfall. After a period of time, organic materials may accumulate, since the deposition rate of particulate material is greater than the decomposition and physical loss rate.

The demand of oxygen by sediment and benthic organisms can, in some instances, is a significant fraction of the total oxygen demand. This is particularly true in small streams. The effects may be particularly acute during low-flow and high-temperature conditions. Decomposition of organic matter and respiration of resident invertebrates from the major oxygen demands from the sediment. In addition to biological decomposition and respiration of benthic invertebrates, net photosynthetic oxygen production of attached benthic algae can also be a significant component of the total SOD. The oxygen balance of shallow streams, in particular, can be influenced by this process since attached algae are frequently present in shallow streams. Although these processes are distinct, they are typically quantified together because in situ measurements combine oxygen uptake and separation of the processes would result in added model complexity.

Because its complexity. It is difficult to estimate SOD analytically and independently. In situ measurements of SOD are usually conducted using a chamber at the bottom of the stream. Continuous measurement of oxygen uptake over a certain period of time provides data to derive the oxygen consumption rate. In a modeling analysis, SOD is typically formulated as a zero-order process:

$$\frac{dC}{dt} = -SOD/H \qquad \text{-------(2-8)}$$

where

dC/dt = rate change of oxygen concentration (g O_2/m^3-day)

SOD = sediment oxygen demand (g O_2/m^2-day)

H = average river depth (m)

Like many other reaction rate coefficients, the SOD values can be determined by model calibration if direct measurements from the field are not available.

Photosynthesis and Respiration

Through photosynthesis and respiration, phytoplankton, epiphyte, and rooted aquatic plants could significantly affect the dissolved oxygen levels in the water column. Because phytoplankton growth requires sunlight and nutrients, quantifying photosynthetic oxygen production would need to address phytoplankton-nutrient dynamics. That is, phytoplankton and nutrient should be modeled concurrently to address this problem. In many simple stream BOD/DO models, however, the oxygen production rate due to photosynthesis and consumption rate due to respiration are assigned, thereby uncoupling the calculation from the phytoplankton-nutrient dynamics.

In a stream water quality model, the daily average oxygen production due to photosynthesis and reduction due to respiration is formulated as follows:

$$\frac{dC}{dt} = P - R \qquad \text{-------(2-9)}$$

where

dC/dt = rate of change of oxygen concentration (mg O_2/L-day)

P = average gross photosynthesis production (mg O_2/L-day)

R = average respiration (mg O_2/L-day)

Note that R is considered to be plant respiration only, excluding microbial respiration for carbonaceous deoxygenation in nitrification.

2.2.3 Eutrophication Kinetics

Figure 2.9 shows the major kinetic processes usually considered in a complete DO, BOD, and nutrient analysis. The following processes are discusses in this section:

- Algal growth and nutrient uptake
- Algal death and settling
- Nutrient mineralization
- Sediment nutrient release

Algal Growth and Nutrient Uptake

Phytoplankton growth is directly related to temperature in moderate climates, nutrient effect, and light intensity up to a saturating condition:

$$G_p = G_T \, r_L \, r_n \qquad \text{------(2-10)}$$

where

G_p = phytoplankton growth rate (day^{-1})
G_T = temperature dependent growth rate (day^{-1})
r_L = light effect (dimensionless)
r_n = nutrient effect (dimensionless)

Temperature dependence, G_T, is approximated by:

$$G_T = G_{max} (1.066)^{T-20} \qquad \text{-----(2-10a)}$$

where

G_{max} = maximum growth rate (day^{-1})
T = temperature (^0C)

The value suggested for G_{max} under average conditions for a mixed phytoplankton population is approximately 1.8 day^{-1} (Thomann and Mueller, 1987).

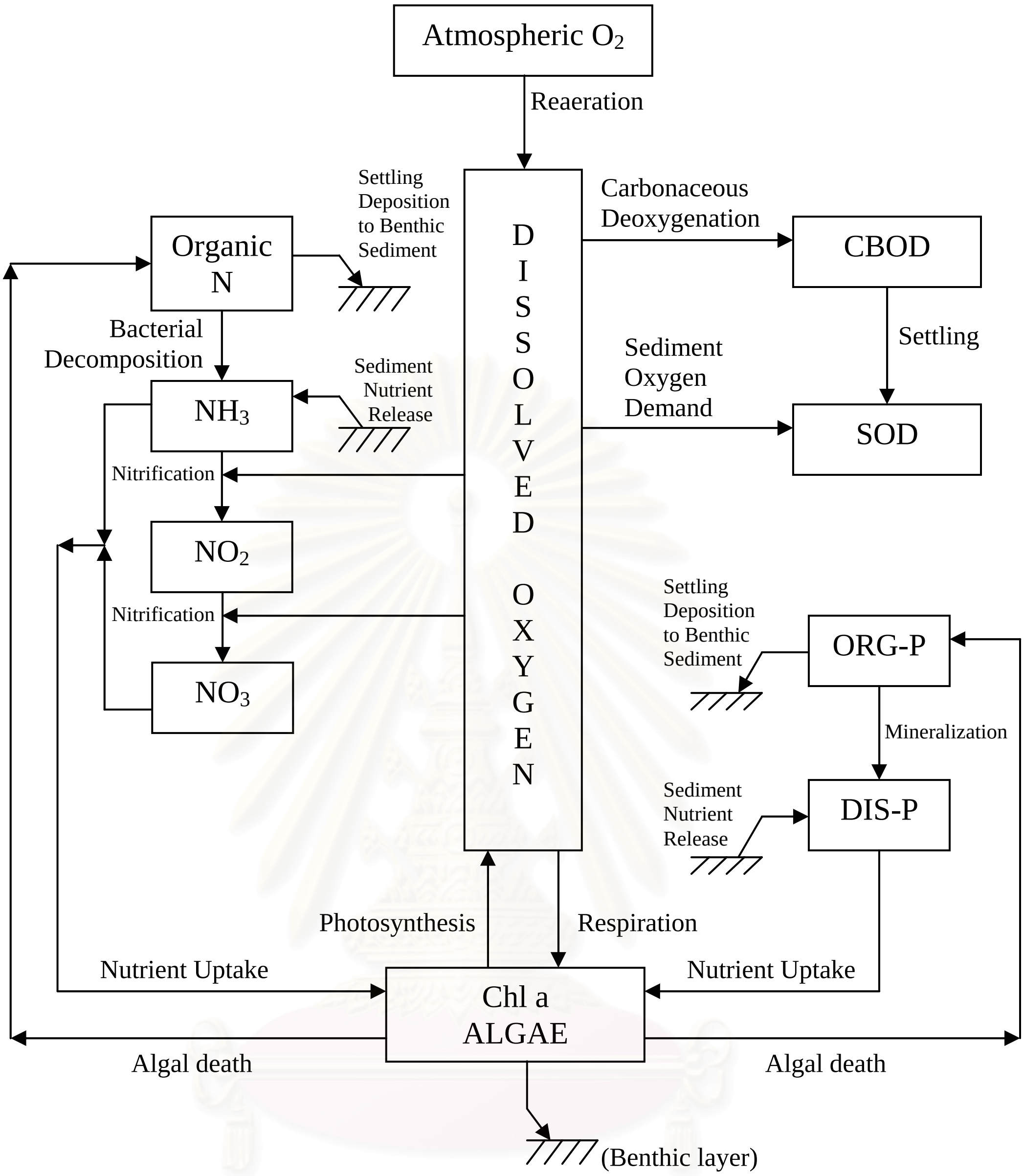


Figure 2.9: Interrelationship of major kinetic processes for BOD, DO, and nutrient analyses as represented by water quality models

Source: *McCutcheon, 1989 cited in U.S. EPA, 1997*

Averaging relative photosynthesis as a function of light intensity over a given depth of water and over a fixed interval of time yields

$$r_L = \frac{2.718\, f}{K_e H T}\left[e^{-\alpha_1} - e^{-\alpha_2}\right] \qquad \text{------(2-11)}$$

$$\alpha_1 = \frac{lT}{l_s f} e^{-K_e H} \qquad \text{-----(2-11a)}$$

$$\alpha_2 = \frac{lT}{l_s f} \qquad \text{----(2-11b)}$$

where

r_L = light effect

l_s = saturating light intensity (ly/day)

l_T = total daily solar radiation (ly)

f = photoperiod (day)

K_e = extinction coefficient (m^{-1})

H = depth (m)

T = average period (day)

The extinction coefficient, K_e, is dependant on inorganic solids, detrital particles, and phytoplankton biomass in the water body. Values of K_e in natural water bodies typically vary from 0.05 to 6.9 m^{-1}. Typical values for l_T range from 250 to 500 ly. The corresponding range of values for r_L is 0.1 to 0.5, so the overall daily effect of light extinction with depth is to reduce the growth rate by about 50-90 percents (Thomann and Mueller, 1987).

The phytoplankton growth rate is also a function of nutrient concentrations up to a saturating condition, greater than which it remains constant with nutrient concentration (Figure 2.10). At zero nutrient concentration, there is no growth. As the nutrient level is increased, the growth rate is linearly proportional to the availability of nutrients. However, as nutrient levels continue to increase, the effect on the growth rate of the phytoplankton is saturated. Such a relationship is described by a Michaelis-Menton formulation where the nutrient reduction factor, or nutrient effect, for algal growth, r_n, is:

$$r_n = \frac{Nut}{K_m + Nut} \qquad \text{------(2-12)}$$

where

Nut = the nutrient concentration (μg/L)

K_m = half saturation (Michaelis) constant (μg/L)

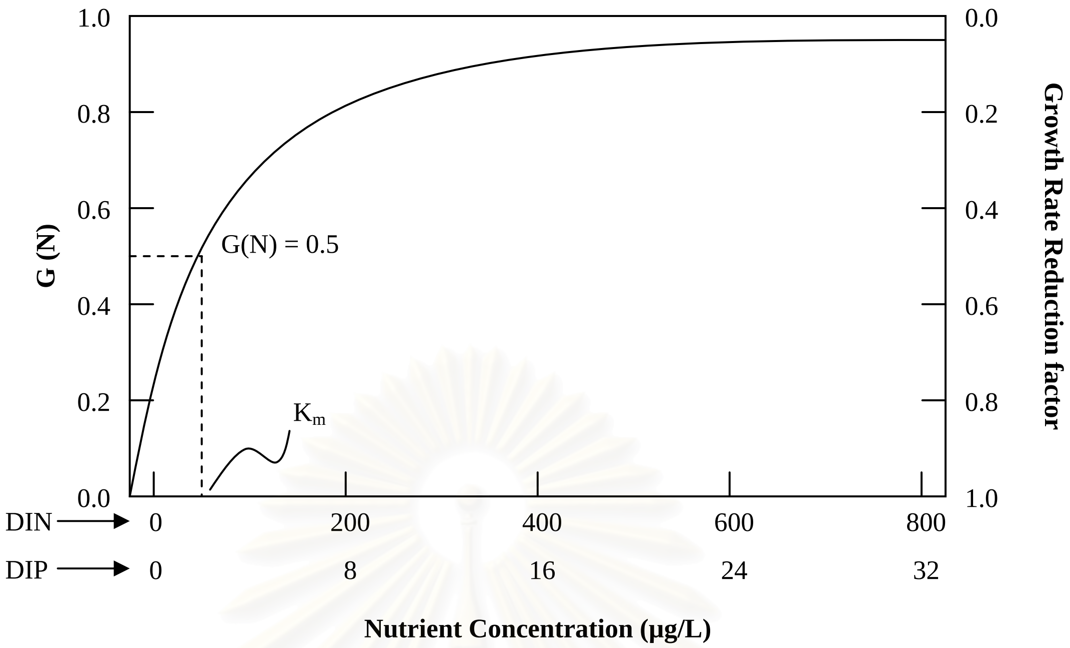


Figure 2.10: Effect of nutrients on algal growth

Source: *Ambrose, Wool, and Martin, 1993 cited in U.S. EPA, 1997*

The Michaelis half-saturation constant, a function of the algal species group, is the nutrient concentration for which the nutrient reduction factor is 0.5 or half the maximum growth rate. The value usually ranges from 5 µg/L to 25 µg/L for nitrogen and from 1 µg/L to 5 µg/L for phosphorus, depending on the species.

When more than one nutrient accounted for in the model (i.e., nitrogen, phosphorus, silica), the nutrient effect is given by:

$$r_n = \min\left(\frac{DIN}{K_{mn} + DIN}\ ;\ \frac{DIP}{K_{mp} + DIP}\ ;\ \frac{Si}{K_{Si} + S_i}\ ;\ ...\right) \quad \text{----(2-13)}$$

where

r_n = limiting nutrient reduction factor

DIN = inorganic nitrogen concentration (sum of ammonia, nitrate, and nitrite)

DIP = dissolved inorganic phosphorus concentration (µg/L)

K_{mn} = Michaelis-Menton constant for nitrogen (µg/L)

K_{mp} = Michaelis-Menton constant for phosphorus (µg/L)

S_i = dissolved inorganic silica concentration (µg/L)

K_{Si} = Michaelis-Menton constant for silica (µg/L)

The minimum ratio of the nutrients considered in the model thus controls the computation of the nutrient reduction factor and is described as the nutrient limiting algal growth. Nitrogen and phosphorus are required by all algal species while silica is required only diatoms.

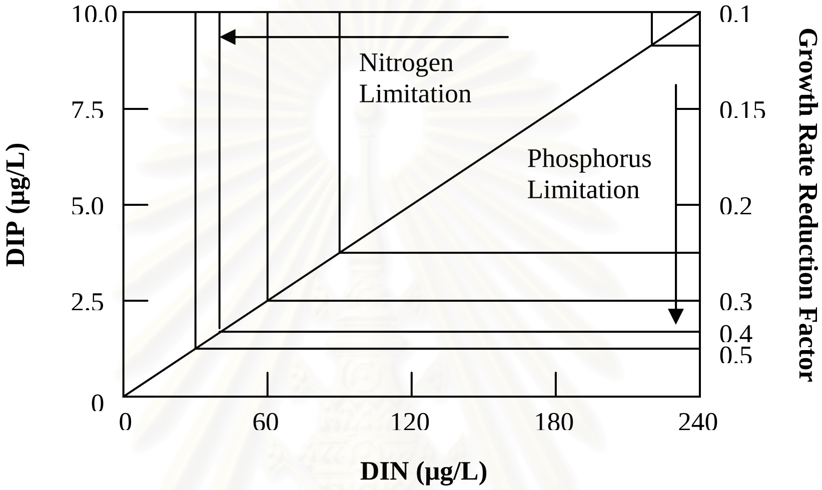


Figure 2.11: Effect of nutrient limitation on algal growth

Source: *Ambrose, Wool, and Martin, 1993 cited in U.S. EPA, 1997*

Figure 2.11 shows the Michaelis-Menton formulation in a slightly different format. In this figure, K_{mn} = 25 µg/L are used. For a stream with a DIN concentration of 100 µg/L, this corresponds to a 20 percent reduction in the growth rate (r_n = 0.8). For phosphorus to become the limiting nutrient in the stream, dissolved inorganic phosphorus must reach a level of 4 µg/L or less. It should also be pointed out that if upstream nitrogen controls were instituted such that Din was reduced to 60 µg/L for the same stream reach, a further reduction in DIP to 2.5 µg/L would be required to keep phosphorus as the limiting nutrient. In other words, as the water column concentrations of DIP begin to approach growth-limiting levels due to continued reduction in point source phosphorus effluents, any nitrogen control strategies that might be instituted would require additional levels of phosphorus removal to keep phosphorus as the limiting nutrient by keeping an upstream N/P ratio below 10.

Algal Death

Decreases in algal biomass are brought about by two processes: algal respiration is caused by endogenous respiration, in which algal biomass is oxidized to generate CO_2. Algal death includes grazing by zooplankton (for diatoms and greens only) and cell destruction through bacterial attack, disease, physical damage, the natural aging process, or other mechanisms. The distinction between phytoplankton reductions through death and reductions through respiration, grazing by zooplankton, or settling is that upon death all the carbon, nitrogen, and phosphorus contained in the algal biomass is returned to the carbonaceous BOD (CBOD), organic nitrogen, and organic phosphorus pools, respectively. During respiration, carbon is given off as CO_2 rather than CBOD; through grazing, only a portion of the organic contents of the algal cells is returned to the respective organic pools. (The remaining portion is lost from the phytoplankton mass balance as zooplankton biomass.)

The algal reduction rate, D_p, can be expressed as:

$$D_p = D_{pt}(T) + D_z \qquad \text{------(2-14)}$$

where

$D_{pt}(T)$ = temperature-dependent endogenous respiration rate (day^{-1})

D_z = death rate (day^{-1}) (grazing and natural mortality)

The phytoplankton death rate, D_z, is a function of zooplankton population and zooplankton grazing rate.

Algal Settling

Phytoplankton is lost from the water column through settling. In a vertically mixed water column, the net settling rate (i.e., settling to the bottom less resuspension from the bottom) is expressed as:

$$S = \frac{V_s}{H} \qquad \text{------(2-15)}$$

where

S = net settling rate (day^{-1})

V_s = phytoplankton settling velocity (m/day)

H = average depth (m)

Nitrogen Components

The major components of the nitrogen system are detrital organic nitrogen, ammonia, nitrite and nitrate. In natural waters, there is a stepwise transformation from organic nitrogen to ammonia, nitrite and nitrate, yielding nutrients for phytoplankton growth as shown in Figure 2.9. The kinetics of the transformations is temperature dependent.

During algal respiration and death, the cellular nitrogen is returned to the organic nitrogen pool. Organic nitrogen undergoes a bacterial decomposition whose end product is ammonia. Ammonia, in the presence of nitrifying bacteria and oxygen, is oxidized to nitrite and to nitrate (nitrification). Both ammonia and nitrate are available for uptake and use in algal growth; however, for physiological reasons the preferred form of nitrogen is ammonia (Conway, 1977; Garside, 1981 cited in U.S. EPA, 1997). The ammonia preference term is characterized in Figure 2.12. As the available nitrate increases above approximately the Michaelis limitation, for given ammonia concentration the preference for ammonia reaches a plateau. Also, as the concentration of available ammonia increases, the plateau levels off at values closer to unity, i.e., total preference for ammonia.

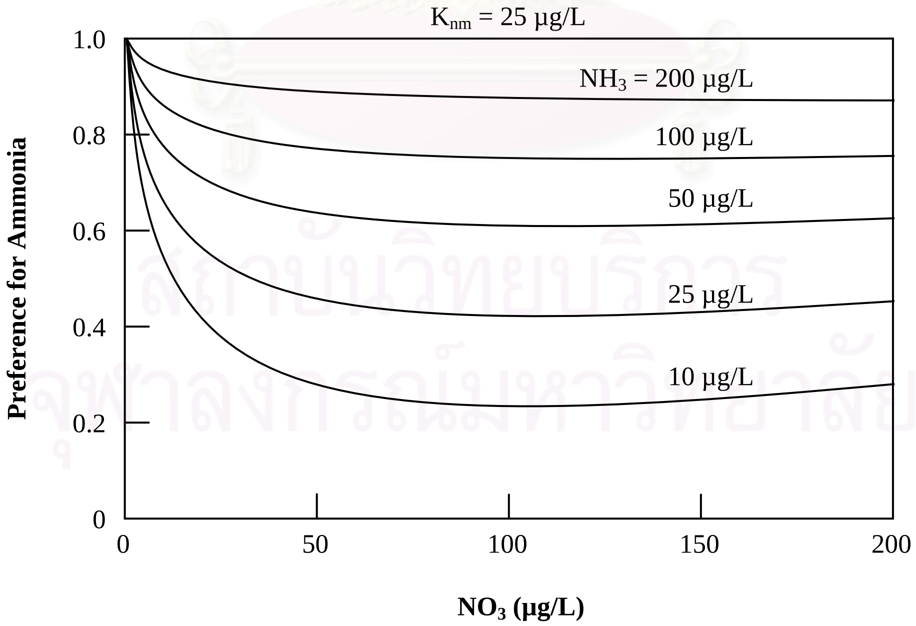


Figure 2.12: Ammonia preference structure for algal growth

Source: *Thomann and Fitzpatrick, 1982 cited in U.S. EPA, 1997*

Phosphorus Component

In many stream water quality models, phosphorus is accounted for in two forms: dissolved and particulate. A fraction of the phosphorus released during phytoplankton respiration and death is in the organic form and readily available for uptake by other viable algal cells. The remaining fraction released is in the organic form and must undergo a mineralization or bacterial decomposition into inorganic phosphorus before it can be used by phytoplankton.

There is an adsorption-desorption interaction between dissolved inorganic phosphorus and suspended particulate matter in the water column. The subsequent settling of the suspended solids together with sorbed inorganic phosphorus can act as a significant loss mechanism in the water column and is a source of phosphorus to the sediment. Compared with the reaction rates for the algal and biological kinetics, which are on the order of days, the adsorption-desorption rates are much faster, permitting an instantaneous equilibrium assumption for the calculation. In the model formulation, the concentrations of dissolved and particulate phosphorus need to be repartitioned at every time step.

Sediment Nutrient Release

In addition to the external sources of nutrients, the release of nutrients from the sediments may also be important. Such releases occur as a result of gradient in nutrient concentration between the overlying water and the interstitial water of the sediment. In some systems, the impact of sediment nutrient release can be significant and can result in continuing eutrophication problems even after point sources have been substantially reduced through control measures. Sediment nutrient release can be treated as nutrient sources to the stream in waste load allocation modeling studies. In the absence of site-specific field data describing sediment nutrient release, approximations can be made on the basis of sediment oxygen demand estimate.

2.3 Basic Equations in Water Quality Models

2.3.1 Mass Balance Principle

The basic principle used to formulate a stream water quality model is mass balance. That is, for a given segment of the stream, the accumulation of a water quality constituent over a finite period of time is equal to the mass entering the segment plus the mass added to the segment, less the mass leaving the segment and the mass lost within the segment (Figure 2.13)

$$\text{Accumulation} = \text{Mass in} - \text{Mass out} + \text{Source} - \text{Sink} \qquad \text{------(2-16)}$$

Applying the mass balance principle and considering a small segment of a stream, one may develop:

$$dV\Delta C = QC\Delta t - [Q + \Delta Q]\left[C + \frac{\partial C}{\partial x}\Delta x\right]\Delta t + W\Delta t - dV\,KC\,\Delta t \qquad \text{------(2-17)}$$

where

dV = volume of the segment and is equal to $A\Delta x$ (L^3)

ΔC = change of concentration (M/L^3)

Q = flow rate (L^3/t)

C = concentration (M/L^3)

Δt = small increment of time (t)

ΔQ = change of flow rate over the length

$\frac{\partial C}{\partial x}$ = concentration gradient over Δx (M/L^4)

W = direct loading rate (Mt^{-1})

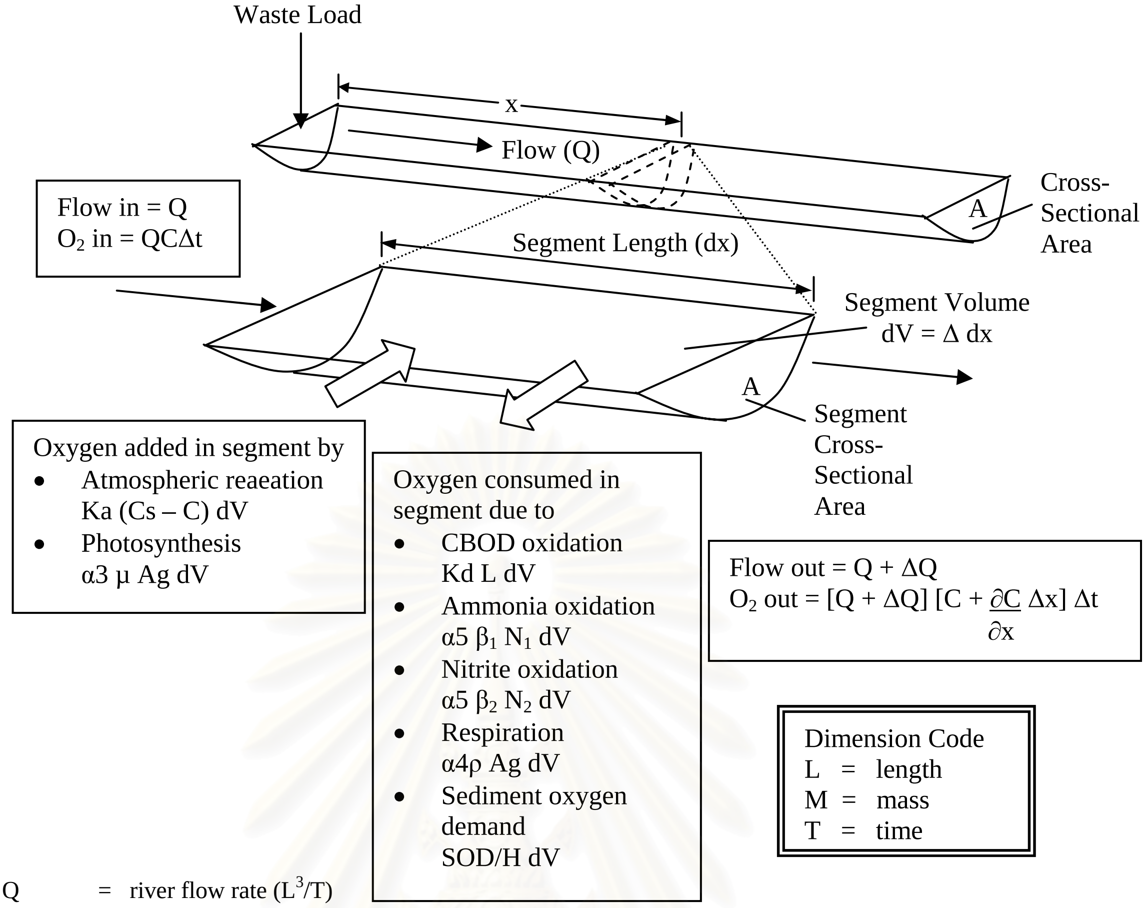
K = first-order reaction rate (t^{-1})

Dividing Equation 2-17 by $dV\Delta t$ results in

$$\frac{\partial C}{\partial t} = \frac{-Q}{A}\frac{\partial C}{\partial x} - \frac{C}{A}\frac{\partial Q}{\partial x} + \frac{W}{dV} - KC \qquad \text{------(2-18)}$$

Assuming steady-state conditions and neglecting the flow gradient, the above equation becomes

$$0 = -\frac{Q}{A}\frac{\partial C}{\partial x} + \frac{W}{dV} - KC \qquad \text{------(2-19)}$$



Q = river flow rate (L^3/T)

C = concentration of dissolved oxygen (M/L^3)

Cs = saturation concentration of dissolved oxygen (M/L^3)

L = CBOD concentration (M/L^3)

H = mean water depth (L)

dV = segment volume AΔx (L^3)

α3 = the stoichiometric ratio of oxygen production per unit of algal photosynthesis (M/M)

α4 = the stoichiometric ratio of oxygen uptake per unit of algal respired (M/M)

α5, α6 = the stoichiometric ratio of oxygen uptake per unit of ammonia and nitrite-nitrogen oxidation, respectively (M/M)

β1, β2 = ammonia and nitrite oxidation rate coefficient, respectively (T^{-1})

μ = algal growth rate coefficient (T^{-1})

ρ = algal respiration rate coefficient (T^{-1})

N_1, N_2 = ammonia and nitrite-nitrogen concentration, respectively (M/L^3)

Ag = algal biomass concentration (M/L^3)

SOD = temperature-adjusted rate constant for SOD (M/L^2T)

Ka = atmospheric reaeration rate; reflect first order reaction whereby a fraction of oxygen deficit is satisfied

Ka (Cs – C) = change in dissolved oxygen concentration in a segment that when, multiplied by segment volume (dV), yields change in dissolved oxygen mass in segment (M/L^3T)

Kd = BOD oxidation rate where oxidation accounts for all CBOD removal (T^{-1})

Figure 2.13: Mass balance equations for dissolved oxygen

Source: *U.S. EPA, 1997*

Note that the reaction term KC may represent formulations for carbonaceous deoxygenation, nitrogenous deoxygenation, reaeration, or any other first-order reactions.

2.3.2 Dissolved Oxygen Equation

Using the notation in Figure 2.13, the distribution of dissolved oxygen may be formulated by including all dissolved oxygen sources and sinks.

$$\begin{aligned} 0 \;=\; & -\frac{Q\,dC}{A\,\partial x} + K_a\,(C_s - C) - K_d\,L \\ & - \alpha_5\,\beta_1\,N_1 - \alpha_6\,\beta_2\,N_2 \\ & + (\alpha_3\,\mu - \alpha_4\,\rho)\,Ag - \frac{SOD}{H} \qquad \text{------(2-20)} \end{aligned}$$

The terms on the right side of Equation 2-20 represent, respectively; the downstream transport of oxygen with the stream flow, atmospheric reaeration, biological oxidation of CBOD, biological oxidation of ammonia, biological oxidation of nitrite photosynthesis less respiration, and the biological oxidation of sediment materials. If CBOD is removed only by direct oxidation, the deoxygenation rate coefficient, K_d, reflecting actual oxygen reduction in the system, is equal to the CBOD removal rate coefficient, K_r, Equation 2-20 may be transformed into the time domain by substituting the relationship Adx/Q is equal to dt, or

$$\begin{aligned} \frac{dC}{dt} \;=\; & K_a\,(C_s - C) - K_d\,L \\ & - \alpha_5\,\beta_1\,N_1 - \alpha_6\,\beta_2\,N_2 \\ & + (\alpha 3\,\mu - \alpha 4\,\rho)\,Ag - \frac{SOD}{H} \qquad \text{------(2-21)} \end{aligned}$$

Equation 2-21 is the differential equation that is numerically solved by QUAl2E to describe the rate of oxygen change in one-dimensional streams and rivers.

In some stream BOD/DO models, the dissolved oxygen deficit, D (= C_s-C), is used instead of dissolved oxygen to formulate the dissolved oxygen profile, and Equation 2-20 can be expressed as;

$$0 \;=\; -\frac{Q}{A}\frac{dD}{dx} - K_a\,D + K_d\,L + \alpha 5\,\beta_1\,N_1 + \alpha_6\,\beta_2\,N_2$$

$$+\,(\alpha 3\,\mu - \alpha 4\,\rho)\,Ag - \frac{SOD}{H} \qquad \text{------(2-22)}$$

Because of zero-order and first-order kinetics formulated in the model, the dissolved oxygen deficit terms due to different sources and sink may be added. For a simple case where nitrification, SOD, algal photosynthesis, and algal respiration are not significant and can be neglected, the solution to Equation 2-22 is;

$$D \;=\; \frac{K_d\,L_o}{K_a - K_r}\left(e^{-Kr\,\frac{X}{U}} - e^{-Ka\,\frac{X}{U}}\right) + Do\,e^{-Ka\,\frac{X}{U}} \qquad \text{------(2-23)}$$

Figure 2.14 shows the dissolved oxygen profile obtained by subtracting the dissolved oxygen deficit (Equation 2-23) from the saturated dissolved oxygen concentration. Also shown in Figure 2.14 is the $CBOD_U$ profile represented by Equation 2-4. At $x = 0$, the initial $CBOD_U$ concentration is 10 mg/l following complete mixing between the waste load and stream flow. After 10 days all of the $CBOD_U$ has been exerted. Since the CBOD test measures the amount of organic material present in terms of the amount of oxygen required for its stabilization by bacteria, the reduction of CBOD concentration is equivalent to the dissolved oxygen consumption. The bottom plot in Figure 2.14 shows two calculated dissolved oxygen profiles associated with the CBOD profile in the top plot. The lower profile represents the dissolved oxygen concentration in the river if case, the assumed initial dissolved concentration for the CBOD reduction (in top plot). The upper profile indicates the net effect of reaeration providing a source of oxygen.

The characteristic shape of the stream dissolved oxygen profile (called the DO sag curve) is the result of interplay of the biological oxidation and reaeration rates. Each is represented by first-order kinetics. In early stages, oxidation greatly exceeds reaeration because of high CBOD concentrations and river dissolved oxygen concentrations close to saturation (i.e., small deficit). Oxygen is used faster than it is resupplied, and stream dissolved oxygen concentrations decrease. As the waste moves downstream, the consumption of oxygen decrease with the stabilization of waste and the supply of oxygen from the atmosphere increases because of greater deficits. The driving force to replenish oxygen by atmospheric reaeration is directly proportional to the oxygen deficit, (i.e., low oxygen concentration).

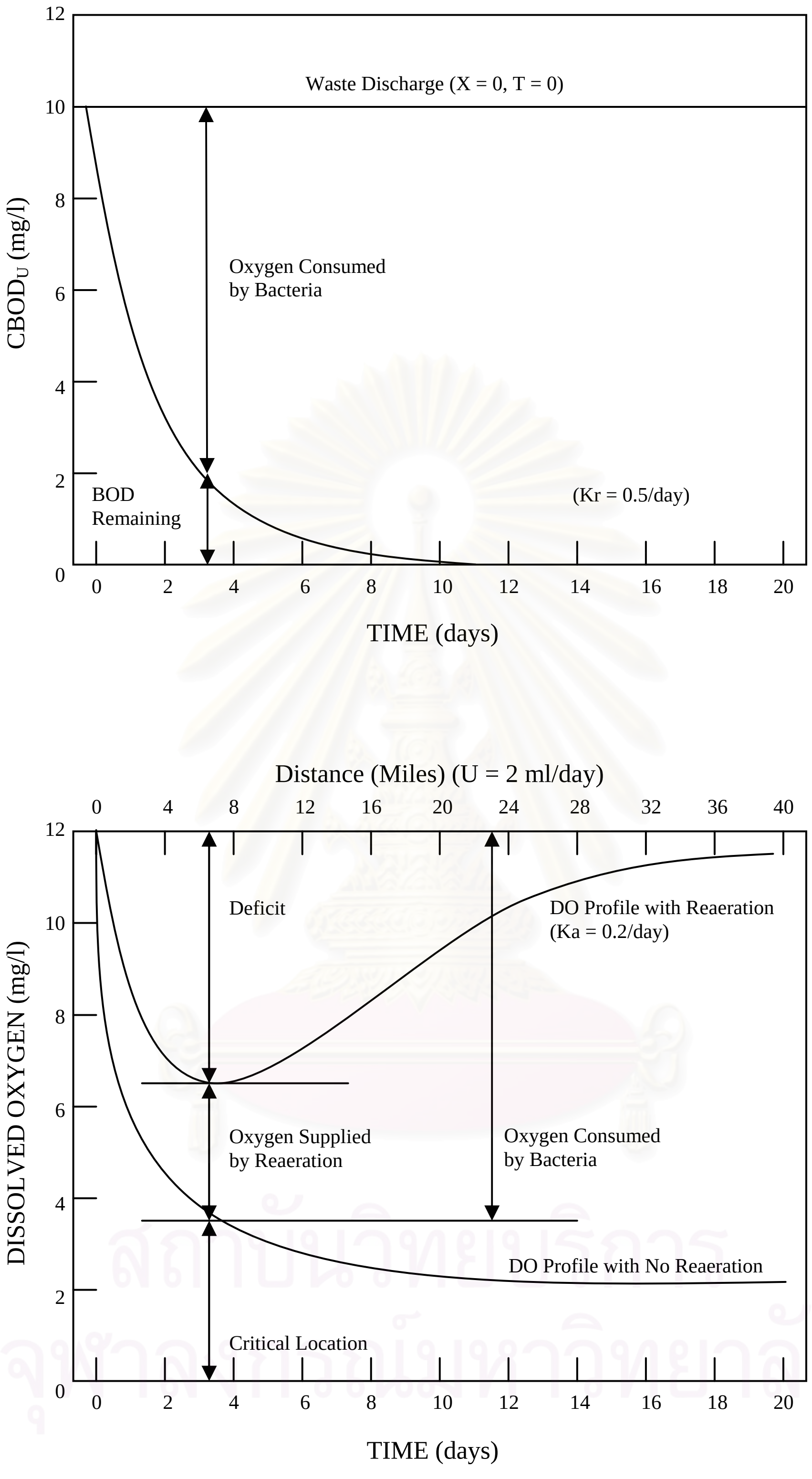


Figure 2.14: Components of DO profile (sag curve) downstream of waste discharge

Source: *U.S. EPA, 1997*

At some point downstream from the waste discharge, the decreasing utilization and the increasing supply are equal. This is the critical location, where the lowest concentration of dissolved oxygen occurs. Further downstream, the rate of supply exceeds the utilization rate, resulting in a full recovery of the dissolved oxygen concentration. The above discussion is a simple illustration of the BOD/DO modeling analysis concept when it is assumed that organic decomposition and reaeration are the dominant processes affecting the organic balance. In reality, many other factors such as nitrification and SOD can significantly change the shape of profile. Many streams receive non-point sources upstream or other point sources that depress the upstream dissolved oxygen in certain streams. It is difficult to find constant hydraulic geometry for more than a few miles. In this case, the stream is divided into a number of reaches with uniform geometry.

2.3.3 Separate Mass Balance Equations by Constituent

Dissolved oxygen dynamics depend on the interactions of several constituents and processes. The constituents that directly influence oxygen include BOD, ammonia nitrite, and nitrate. Nitrogen and phosphorus determine growth of phytoplankton, periphyton, and aquatic plants and subsequently affect dissolved oxygen via photosynthesis and respiration. For each constituent that is in the dissolved oxygen mass balance, a separate mass balance equation is used to account for the reactions of that parameter. Using the notation developed thus far, these constituents may be modeled by the mass balance equations summarized in Table 2.3. The mass balance equations in Table 2.3 can be found in many stream water quality models that have been used in TMDL studies. Thomann and Mueller (1987) present a simplified version of the eutrophication equation for river and stream eutrophication analysis.

One should note that the major difference between the BOD/DO modeling and nutrient/eutrophication modeling is in terms of model formulations. That is, the equations governing phytoplankton growth are nonlinear functions of nutrients and light availability, whereas the BOD/DO equations are all linear. In fact, the phytoplankton/nutrient problems are the most difficult models to work with because of the complexity of the algal biology, the nonlinear interactions between nutrients and aquatic plants, and the interactions of the sediment-water column interface. As a result, the superposition of results from BOD/DO equations is appropriate to isolate the effects of the various linear reaction terms, whereas the same is not true of the eutrophication results.

Table 2.3: Separate mass balance equations used for each constituent in BOD, DO, and nutrient analyses

Carbonaceous BOD (CBOD)	$\frac{dL}{dt} = -(K_d + K_s)\,L = -K_r L$
Ammonia Nitrogen	$\frac{dN_1}{dt} = \beta_3 N_4 - \beta_1 N_1 + \frac{\sigma_3}{H} - F\,\alpha_1\,\mu\,Ag$
Nitrite Nitrogen	$\frac{dN_2}{dt} = \beta_1 N_1 - \beta_2 N_2$
Nitrate Nitrogen	$\frac{dN_3}{dt} = \beta_2 N_2 - (1 - F)\,\alpha_1\,\mu\,Ag$
Organic Nitrogen	$\frac{dN_4}{dt} = \alpha_1\,\rho\,Ag - \beta_3 N_4 - \sigma_4 N_4$
Algae	$\frac{dAg}{dt} = (\mu - \rho)\,Ag$
Organic Phosphorus	$\frac{dP_1}{dt} = \alpha_2\,\rho\,Ag - \beta_4 P_1 - \alpha_5 P_1$
Dissolved Phosphorus	$\frac{dP_2}{Dt} = \beta_4 P_1 + \frac{\sigma_2}{H} - \alpha_2\,\mu\,Ag$

Variables and coefficients not previously identified in Figure 2.13

N_3 = nitrate nitrogen concentration (m/L^3)

N_4 = organic nitrogen concentration (m/L^3)

P_1 = organic phosphorus concentration (m/L^3)

P_2 = dissolved phosphorus concentration (m/L^3)

α_1 = fraction of algal biomass that is nitrogen (M/M)

α_2 = phosphorus content of algae (M/M)

K_s = effective loss rate due to settling (T^{-1})

F = fraction of algal nitrogen uptake from ammonia pool

β_3 = organic nitrogen hydrolysis rate coefficient (T^{-1})

β_4 = organic phosphorus decay rate (T^{-1})

σ_2 = benthos source rate for dissolved phosphorus (M/L^2T)

σ_3 = benthos source rate for ammonia nitrogen (M/L^2T)

σ_4 = rate coefficient for organic nitrogen settling (T^{-1})

σ_5 = rate coefficient for organic phosphorus settling (T^{-1})

2.4 Waste Load Allocation and Total Maximum Daily Load (TMDL)

2.4.1 Waste Load Allocation Principles

The central problem of water quality management is the assignment of allowable discharges to a water body. Figure 2.15 is a representation of the overall waste load allocation (WLA) problem for dissolved oxygen. There are several components to the problem, including the determination of desirable water use standards, the relationship between load, water quality, and selection of projected conditions. It is generally not sufficient to simply make a scientific engineering analysis of the effect of waste load inputs on water quality. The analysis framework must also include economic impacts which, in turn, must also recognize the sociopolitical constraints that are operative in the overall problem context. (Thomann and Mueller, 1987)

2.4.2 Steps in the WLA Process

The principal steps in the WLA process are summarized in Figure 2.16 as; (Thomann and Mueller, 1987)

1) A designation of a desirable water use or uses, for example, recreation, water supply, agriculture.

2) An evaluation of water quality criteria that will permit such uses.

3) The synthesis of the desirable water use and water quality criteria to a water quality standard promulgated by a local, state, interstate or federal agency.

4) An analysis of the cause-effect relationship between present and projected waste load inputs and water quality response through use of

    4.1) Site-specific field data or data from related areas and calibrated and verified the mathematical model.

    4.2) Simplified modeling analysis based on the literature, other studies, and engineering judgment.

5) A sensitivity analysis and a projection analysis for achieving water quality standards under various levels of waste load input.

6) Determination of the “factor of safety” to be employed through, for example, a set-aside of reserve waste load capacity.

7) For the residual load, an evaluation of

    7.1) The individual costs to the dischargers.

    7.2) The regional cost to achieve the load and the concomitant benefits of the improved water quality.

8) Given all of the above, a complete review of the feasibility of the designated water use and water quality standard.

9) If both are satisfactory, a promulgation of the waste load allocated to each discharger.

Within the above framework, it is assumed that a calibrated and verified water quality model is available. There are several points at which careful judgments are required to provide a defensible WLA. For example, the determination of design conditions including flow and parameters must be evaluated for a WLA. The specification or projection of flow and parameter conditions under a given design event is a most critical step and is a blend of engineering judgment and sensitivity analysis.

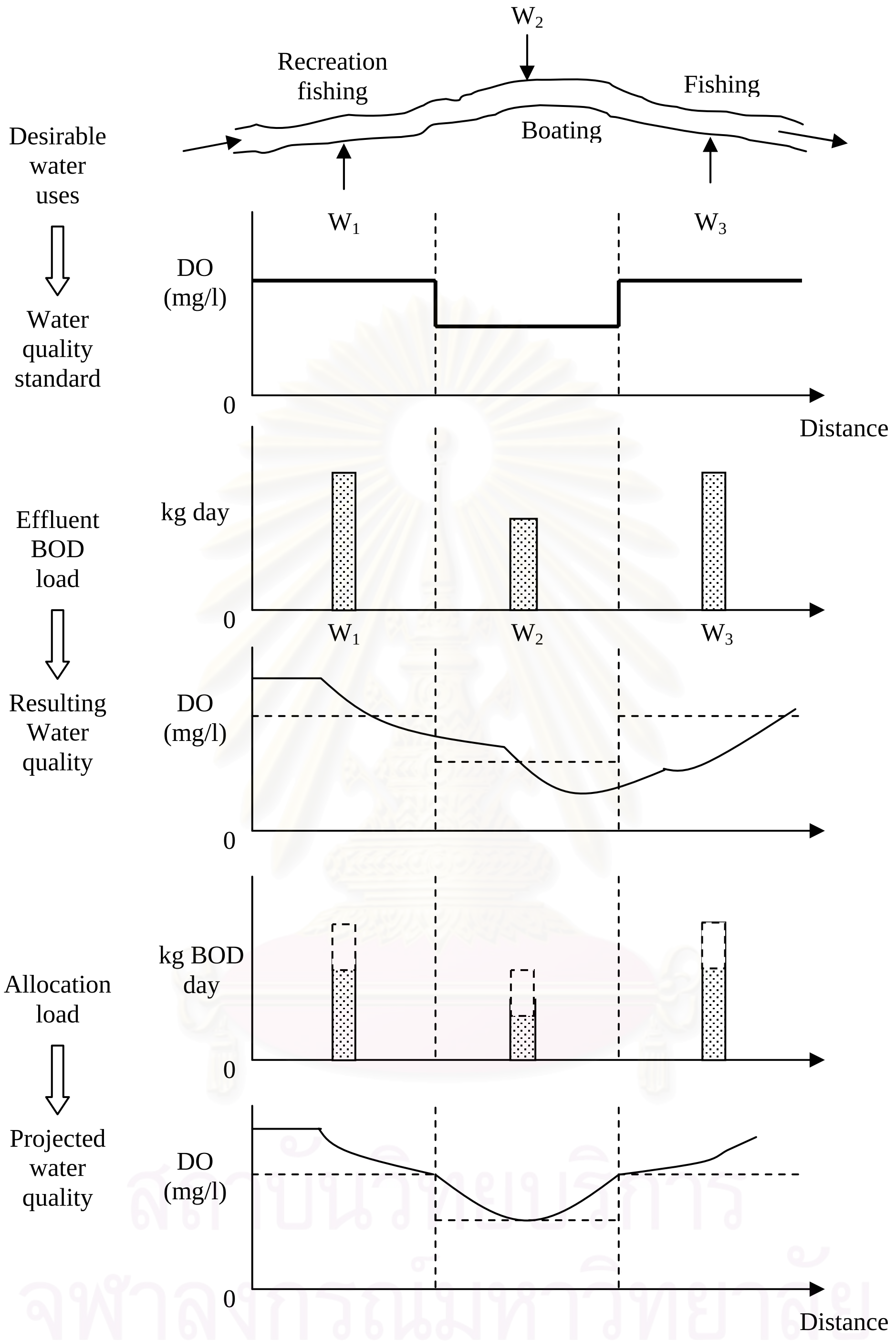


Figure 2.15: Representation of waste load allocation problem for dissolved oxygen

Source: *Thomann and Mueller, 1987*

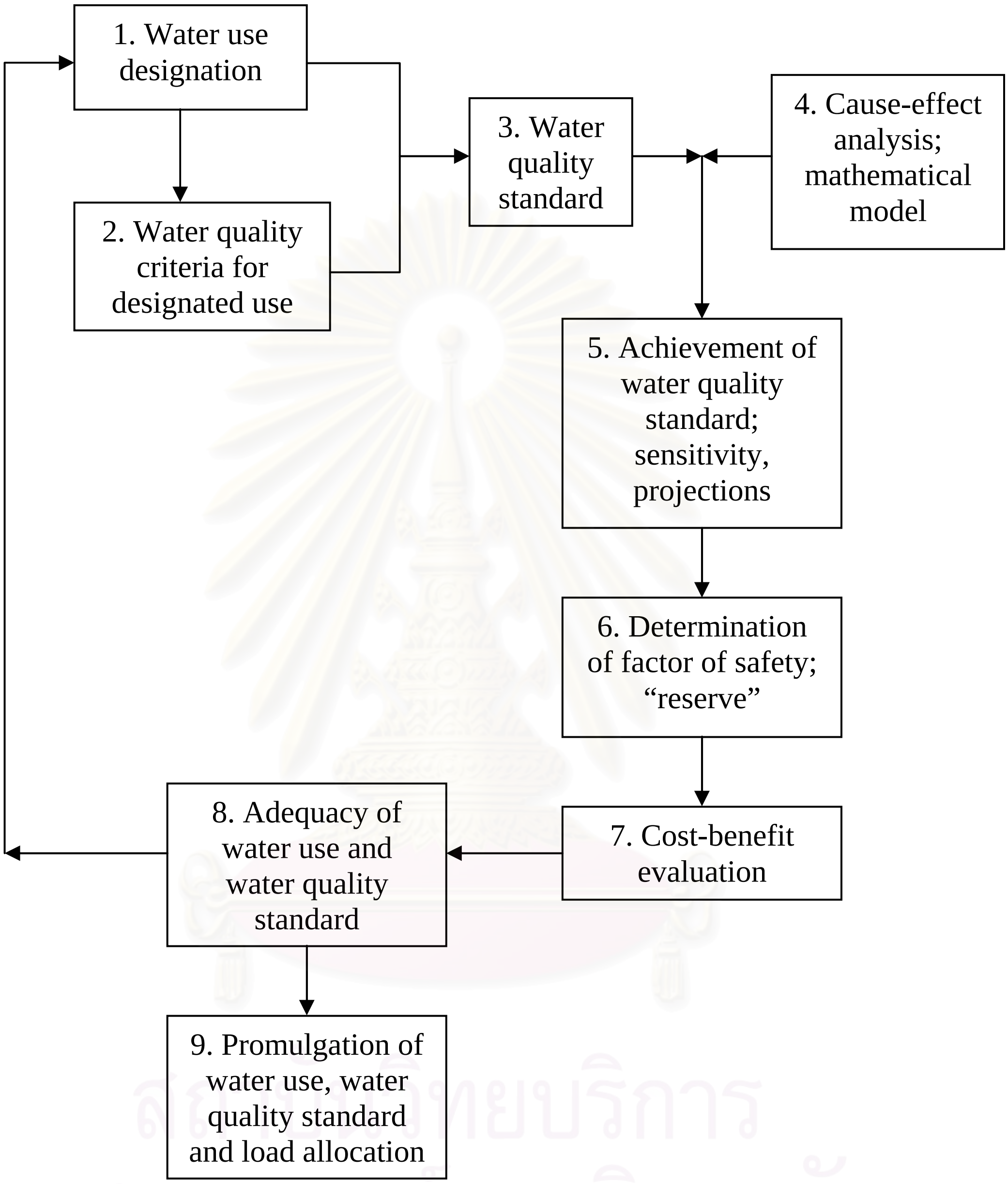


Figure 2.16: Principal steps in waste load allocation process

Source: *Thomann and Mueller, 1987*

2.4.3 Total Maximum Daily Load (TMDL)

A TMDL or Total Maximum Daily Load is a calculation of the maximum amount of a pollutant that a water body can receive and still meet water quality standards, and an allocation of that amount to the pollutant's sources. A TMDL is the portion of the total loading capacity (LC) or TMDL that is allocated to one of its existing or future *point sources* of pollution. A load allocation (LA) is the portion of the TMDL that is allocated to one of its existing or future *non-point sources* of pollution and natural background. The sum of the individual WLAs for point sources and LAs for non-point sources (including natural background sources and tributaries) plus the margin of safety (MOS) is equivalent to the TMDL. This can be expressed as Equation 2-24.

$$\mathbf{TMDL = LC = WLA + LA + MOS} \qquad \text{------(2-24)}$$

TMDL studies utilizing, field monitoring data and predictive models provide quantitative information to assist managers in making effective decisions to protect water quality. Models and water quality equations are used to establish cause and effect relationships correlating incremental changes in stream water quality to changes in pollutant loading. The MOS can be included implicitly in the TMDL model calculations to account for the uncertainly about the relationship between the allocated waste loads and the predicted quality of the receiving water body. A reserve capacity for future development can be included in the TMDL at this stage.

Knowledge of the quantitative cause and effect relationship between receiving water quality and pollutant loads is the key to making reliable determinations of the total loading capacity. This relationship is quite sensitive to natural environmental conditions. These conditions include physical characteristics such as stream flow, velocity, depth, slope, time of travel, and temperature and chemical/biological characteristics such as in-place sediment oxygen demand, algal photosynthesis and respiration, and nitrification. The determination of the rates at which various water quality reactions take place in the receiving water body introduces additional complications in establishing cause and effect relationships and protecting water quality impacts. In some instances, the water quality response can be as sensitive to the reaction rates as it is to the total amount of pollutant loadings. This is particularly important in BOD/ DO reactions where the resulting dissolved oxygen concentration is determined by competing reactions of oxygen consumption from BOD, nitrification, and sediment oxygen demand (SOD) and oxygen replenishment from reaeration and photosynthesis.

Models not only are used to determine the relationships between pollutant loads and the resulting water quality response, but also are necessary to predict future water quality conditions and conditions that may not have been monitored for in the past. There are also useful to evaluate the array of variables (temperature, stream flow, load, reaction rates, etc.) that simultaneously influence water quality response, especially where the system is relatively complex as a result of multiple sources, varying stream geometry, flow changes due to tributaries and storm events, and other factors.

We will discuss concentration and load in greater detail. In the meantime, keep in mind that TMDL bridge many often-disparate concepts. In the absence of very specific guidance documents from US EPA, the key components of watershed plan, TMDL development and water quality monitoring in general hinge upon generating valid data and communicating these data and associated results among all the stakeholders in the watershed.

2.4.4 Concentrations and Loads

In watershed planning to enhance water quality, it is important to understand the interrelationships between concentration and load. The quality of the water itself – the way it directly affects organisms, including humans – depends on the concentration of pollutants, which is measured in mass/volume units, such as mg/L. Though TMDL are written in terms of load (e.g. 56 pounds of phosphorus/day), assessing non-point sources and monitoring in-stream water quality are typically handled by measuring concentration (e.g. 0.07 mg/L total P).

The connecting factor is flow, which is not directly regulated in the TMDL process in most cases. As noted earlier, the relationship *Load = Concentration x Flow* defines the links among the three variables.

Compared with simply collecting a water sample and analyzing concentrations, determining flow rates in open channel systems is time-consuming. By monitoring flow at 10 to 20 evenly spaced points across the stream, total flow can be determined. This may be done on every visit to a site, or may be measured by in situ flow monitors.

After direct flow measurements have been taken over a wide range of flow conditions, a relationship between depth at one point in the stream and the flow for the whole stream can be developed. This relationship is called the "rating curve," and is generally useful over the range of flows with which it was developed, as long as the channel shape doesn't change. Once a valid rating curve is available for a reach of stream, only one depth measurement needs to be taken to calculate flow.

Controlling loads can be accomplished in two ways: lowering concentrations or lowering flow rates. For point sources, either approach is useful, because the flow is typically a small fraction of the total input into the system. Excluding this small point source flow, basically all the rest of the flow is from non-point sources. In contrast, eliminating non-point source load by eliminating flow will dry up the stream or lake. So the best option is to maintain or even increase flow, but focus on lowering concentrations in that water.

Maximum Allowable Loads

Maximum allowable loads are determined based on the concentrations or amounts of pollutants that will not degrade the quality of the water body, adversely affecting its beneficial uses.

Waste Load Allocations - Point Sources

Each major point source in a TMDL-affected watershed is allocated a quantity of additional pollutant that it may add to the water body – a waste load allocation, or WLA. In most instances these systems are already regulated by National Pollution Discharge Elimination System (NPDES) permits, which require monitoring effluent flow rates and concentrations. Monitoring the stream above and below a point source outfall is important for determining the actual impact of the source on both the regulated parameter and other stream water quality parameters.

Load Allocations – Non-point Sources

A total load allocation (LA) is established to cover all non-point sources in a watershed covered by a TMDL. This total LA is divided into individual allocations. The basis for this allocation rests on a wide range of factors, including estimates of sources, expected ability to meet the TMDL limits, willingness of stakeholders to implement BMP, and overall economics.

Background Loading

Every natural water body contains most of the parameters managed with TMDL. Nutrients, in particular, are always present, although in some aquatic systems their concentrations are very low. Thus, setting the TMDL for a given body of water generally assumes that there is a difference between the natural background and the TMDL for a given beneficial use. This difference is caused by human-related inputs, which can be then assigned LAs and WLAs.

Margin of Safety

The margin of safety (MOS) is “insurance” based upon the uncertainty of the response of the system to the parameter in question. As noted above, this depends on how well the water body is understood. If best available science suggests that a given concentration of a nutrient will be low enough to limit algal growth to acceptable levels, the MOS may dictate that the TMDL be set even lower – for example, at 70 percents of that concentration – because of the uncertainty of that number.

CHAPTER III

METHODOLOGY

3.1 Modeling Framework

The computational framework chosen for the modeling of water quality of Pak Phanang River was WASP 6.0 (EUTRO 6.0) – Water Quality Analysis Simulation Program. This program provides a generalized framework for modeling contaminant fate and transport in surface waters and is based on the finite-segment approach. It is a very versatile program, capable of studying time-variable or steady-state, one, two or three dimensional, linear or non-linear kinetic water quality problems (Wool et al., 2001). So far, WASP has been employed in many modeling applications that include river, lake, estuarine and ocean environments, and the model has been used to investigate dissolved oxygen, eutrophication, and toxic substance problems.

WASP is supported and distributed by the U.S. EPA’s Center for Exposure Assessment Modeling (CEAM) in Athens, Georgia. The eutrophication submodel ‘EUTRO 6.0’ is the component of WASP 6.0 that is recommended as an EPA standard model for dynamic water quality analysis. EUTRO is applicable for modeling eutrophication, incorporating eight water quality constituents (state variables) in the water column and sediment bed (Figure 3.1). They constitute four interacting systems: e.g. phytoplankton kinetics, phosphorus cycle, nitrogen cycle, and dissolved oxygen.

3.1.1 The Basic Water Quality Model

The equations solved by WASP 6.0 are based on the key principle of the conservation of mass. This principle requires that the mass of each water quality constituent being investigated must be accounted for in one way or another. To perform these mass balance computations, the input data defining seven important characteristics must supply;

- Simulation and output control
- Model segmentation
- Advective and dispersive transport
- Boundary concentrations
- Point and diffuse source waste loads
- Kinetic parameters, constants, and time functions
- Initial concentrations

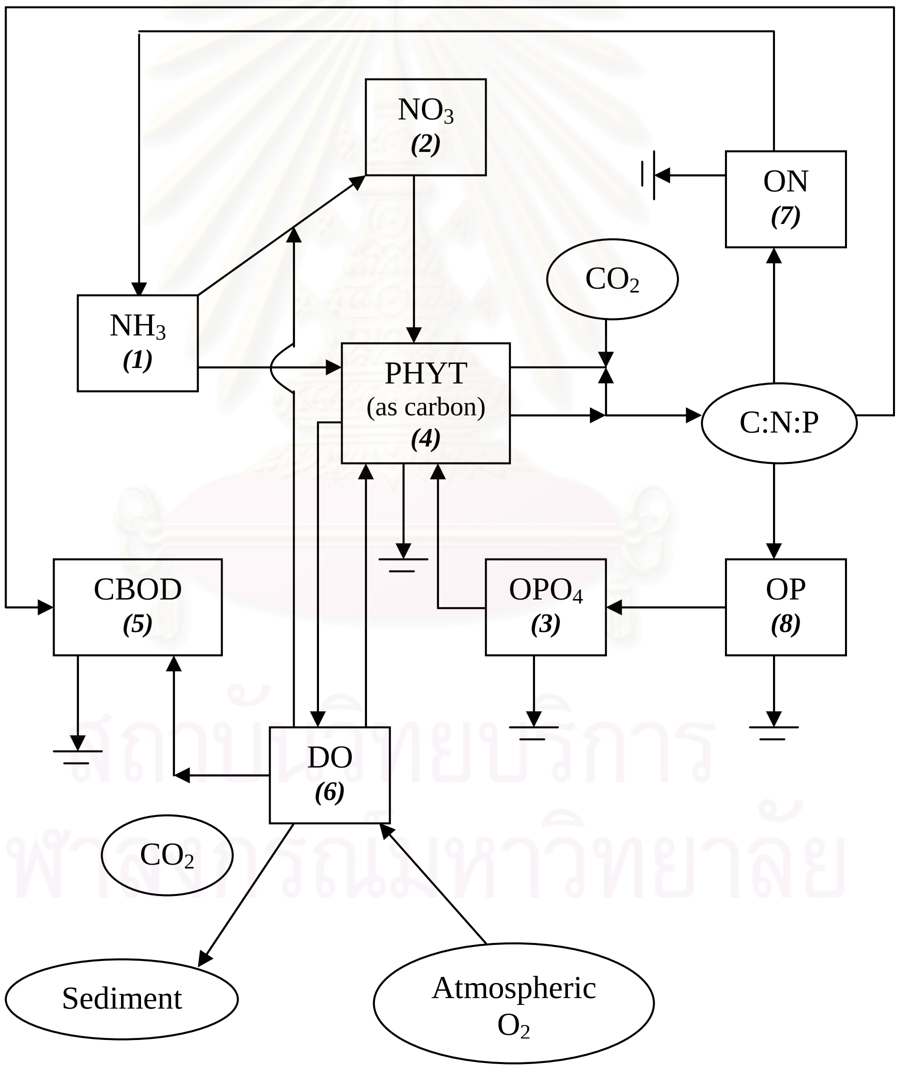


Figure 3.1: State variables simulated in WASP model

Source: *Wool et al., 2001*

Implementation of Mass Balance Equation

A mass balance equation for dissolved constituents in a body of water must account for all the material entering and leaving through direct and diffuse loading; advective and dispersive transport; and physical, chemical and biological transformation as described in the section 2.3.1 entitled *Mass Balance Principle* (chapter 2).

By expanding the infinitesimally small control volumes into larger adjoining “segments,” and by specifying proper transport, loading, and transformation parameters, WASP implements a finite-difference from Equation 2-18. However, for brevity and clarity the derivation of the finite-different form of the mass balance equation will be for a one-dimensional reach. Assuming vertical and lateral homogeneity, it can obtain to Equation 3-1.

$$\frac{\partial (AC)}{\partial t} = \frac{\partial}{\partial x}\left(-U_x AC + E_x A \frac{\partial C}{\partial x}\right) + A\,(S_L + S_B) + A\,S_K \qquad \text{-------(3-1)}$$

where

A = cross-sectional area (m^2)

C = concentration of the water quality constituent (mg/L or g/m^3)

t = time (days)

U_x = longitudinal advective velocity (m/day)

E_x = longitudinal diffusion coefficient (m^2/day)

S_L = direct and diffuse loading rate (g/m^3-day)

S_B = boundary loading rate (including upstream, downstream, benthic, and atmospheric) (g/m^3-day)

S_K = total kinetic transformation rate; positive is source, negative is sink (g/m^3-day)

This equation represents the three major classes of water quality processes – transport (term 1), loading (term 2), and transformation (term 3).

Model Network

The model network is a set of expanded control volumes, or “segments,” that together represents the physical configuration of the water body. As Figure 3.2

illustrate, the network may subdivide the water body laterally and vertically as well as longitudinally. Benthic segments can be included along with water column segments.

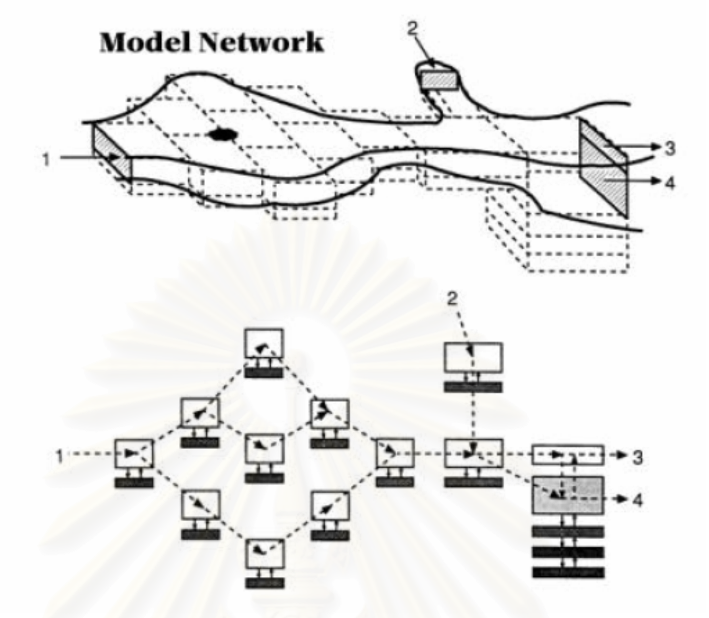


Figure 3.2: Model segmentation schematic

Source: *Wool et al., 2001*

Segments in WASP may be one of four types – indicate the epilimnion (surface water), indicate hypolimnion layers (subsurface), indicate an upper benthic layer, and indicate lower benthic layers. The segment type plays an important role in bed sedimentation and in certain transformation processes.

Model Transport Scheme

Transport includes advection and dispersion of water quality constituents. Advection and dispersion in WASP are each divided into six distinct types, of "fields".

- The first transport field: involves advective flow and dispersive mixing in the water column.
- The second transport field: specifies the movement of pore water in the sediment bed.

- The third, fourth and fifth transport fields: specify the transport of particulate pollutants by the settling, resuspension, and sedimentation of solids.

- The sixth transport field: represents evaporation or precipitation from or to surface water segments.

3.1.2 Chemical Tracer Transport

A chemical tracer is a non-reactive chemical that is passively transported throughout the water body. Examples include salinity or chlorides. Setting up and calibrating a tracer is the first step in simulating more complex water quality variables.

Hydraulic Geometry

The method described below is follows the implementation in QUAL2E (Brown and Barnwell, 1987 cited in Wool et al., 2001). In WASP 6.0, the segment velocities and depths are only used for calculations of reaeration and volatilization rates; they are not used in the transport scheme.

Discharge coefficients giving depth and velocity from stream flow are based on empirical observations of the stream flow relationship with velocity and depth (Leopold and Maddox, 1953 cited in Wool et al., 2001) It is important to note that these coefficients are only important when calculating reaeration or volatilization. The equations relate velocity, channel width, and depth to stream flow through power functions:

$$U = a\,Q^{b} \qquad \text{-------(3-2)}$$

$$D = c\,Q^{d} \qquad \text{-------(3-3)}$$

$$B = e\,Q^{f} \qquad \text{-------(3-4)}$$

where

D = average depth (m)

B = average width (m)

a, b, c, d, e, and f = empirical coefficients or exponents

Given that area is a function of average width (B) and average depth (D),

$$A = D B \qquad \text{-------(3-5)}$$

It is clear from continuity that:

$$Q = U * A = U * D * B = (a Q^{b}) * (c Q^{d}) * (e Q^{f}) \qquad \text{-------(3-6)}$$

and, therefore, the following relationships hold:

$$a c e = 1 \qquad \text{-------(3-7)}$$

$$b + d + f = 1 \qquad \text{-------(3-8)}$$

WASP 6.0 only requires specification of the relationships for velocity, Equation 3-2, and depth, Equation 3-3; the coefficients for Equation 3-4 are implicitly specified by Equation 3-7 and Equation 3-8.

This option can be put into perspective by nothing that, for a given specific channel cross-section, the coefficients (a, c, e) and exponents (b, d, f) can be derived from Manning’s equation.

Water Column Dispersion

Dispersive water column exchanges significantly influence the transport of dissolved and particulate pollutants in such water bodies as lakes, reservoirs, and estuaries. Even in rivers, longitudinal dispersion can be the most important process diluting peak concentrations that may result from unsteady loads or spills. In WASP 6.0, the dispersive exchange between segments j and i at time t is given by:

$$\frac{\partial M_{ik}}{\partial t} = \frac{E_{ij}(t) * A_{ij}}{L_{cij}} (C_{jk} - C_{ik}) \qquad \text{-------(3-9)}$$

where

M_{ik} = mass of chemical k in segment i (g)

C_{ik}, C_{jk} = concentration of chemical k in segment i and j (mg/L or g/m^3)

E_{ij} (t) = dispersion coefficient time function for exchange ij (m^2/day)

A_{ij} = interfacial area shared by segments i and j (m^2)

L_{cij} = characteristic mixing length between segments i and j (m)

Boundary Processes

A boundary segment is characterized by water exchanges from outside the network, including tributary inflows, downstream outflows and open water dispersive exchanges. Boundary concentrations C_{Bik} (mg/L) must be specified for each simulated variable “k” at each boundary segment “i”. These concentrations may vary in time.

At upstream boundary segments, WASP 6.0 applies the following mass loading rates:

$$V_i\, S_{Bik} = Q_{0i}\,(t) * C_{Bik} \qquad \text{------(3-10)}$$

where

S_{Bik} = boundary loading rate response of chemical k in segment i (g/m^3-day)

V_i = volume of boundary segment i (m^3)

Q_{0i} (t) = upstream inflow into boundary segment i (m^3/day)

At downstream boundary segments, WASP 6.0 applies the following mass loading rates:

$$V_i\, S_{Bik} = Q_{i0}\,(t) * C_{ik} \qquad \text{------(3-11)}$$

where

Q_{i0} (t) = downstream outflow from boundary segment I (m^3/day)

C_{ik} = internal concentration of chemical k in segment i (mg/L)

At exchange boundary segments, WASP 6.0 applies the following mass loading rates:

$$V_i\, S_{Bi} = \frac{E_{i0}\,(t) * A_{i0}}{L_{ci0}}\,(C_{Bk} - C_{ik}) \qquad \text{------(3-12)}$$

Loading Processes

Two types of loadings are provided for – point source loads and runoff loads (non-point source loads). Both kinds of loads, in kg/day, are added to designated segments at the following rates:

$$V_i\, S_{Lik} = 1000 * L_{ik}\,(t) \qquad \text{------(3-13)}$$

where

S_{Lik} = loading rate response of chemical k in segment i (g/m^3-day)

L_{ik} (t) = loading rate of chemical k into segment i (kg/day)

3.1.3 Dissolved Oxygen

Dissolved oxygen (DO) is one of the most important variables in water quality analysis. DO is a sensitive indicator of the health of the aquatic system because it is affected by many other water quality parameters. There is have been modeled for over 70 years. The basic steady-state equations were developed and used by Streeter and Phelps (1925).

Dissolved oxygen and associated variables are simulated using EUTRO 6.0 program. EUTRO can be operated at various level of complexity to simulate some or all of the variables and interactions as shown in Figure 3.1. Four levels of complexity are (1) Streeter-Phelps, (2) modified Streeter-Phelps, (3) full linear DO balance, and (4) nonlinear DO balance. There are should refer to the kinetic equations summarized in Equations 3-14 and 3-15, and the reaction parameters and coefficients in Table 3.1.

Carbonaceous Biochemical Oxygen Demand

$$\frac{\partial C_5}{\partial t} = \underbrace{a_{OC}\, K_{1D}\, C_4}_{\textit{Death}} - \underbrace{k_D\, \Theta_D^{(T-20)} \left(\frac{C_6}{K_{BOD} + C_6}\right) C_5}_{\textit{Oxidation}} - \underbrace{\frac{v_{s3}\,(1 - f_{D5})}{D}\, C_5}_{\textit{Settling}}$$

$$- \underbrace{\frac{5}{4}\,\frac{32}{14}\, k_{2D}\, \Theta_{2D}^{(T-20)} \left(\frac{K_{NO3}}{K_{NO3} + C_6}\right) C_2}_{\textit{Denitrification}} \qquad \text{------(3-14)}$$

Dissolved Oxygen

$$\frac{\partial C_6}{\partial t} = \underbrace{k_2\,(C_5 - C_6)}_{\textit{Reaeration}} - \underbrace{k_D\, \Theta_D^{(T-20)} \left(\frac{C_6}{K_{BOD} + C_6}\right) C_5}_{\textit{Oxidation}}$$

$$- \underbrace{64\, k_{12}\, \Theta_{12}^{(T-20)} \left(\frac{C_6}{K_{NIT} + C_6}\right) C_1}_{\textit{Nitrification}} - \underbrace{\frac{SOD}{D}\, \Theta_s^{(T-20)}}_{\textit{Sediment demand}}$$

$$+ G_{P1} \underbrace{\left(\frac{32}{12} + \frac{48}{14}\,\frac{14}{12}\,(1 - P_{NH3}) \right) C_4}_{\textit{Phytoplankton growth}} - \underbrace{\frac{32}{12}\, k_{1R}\, \Theta_{1R}^{(T-20)}\, C_4}_{\textit{Respiration}} \qquad \text{------(3-15)}$$

Table 3.1: CBOD and DO reaction terms

Description	**Notation**	**Value from Potomac Estuary model**	**Units**
Ammonia Nitrogen	C_1	-	mg N/L
Nitrate Nitrogen	C_2	-	mg N/L
Phytoplankton Carbon	C_4	-	mg C/L
Carbonaceous BOD	C_5	-	mg O_2/L
Dissolved Oxygen	C_6	-	mg O_2/L
Oxygen to carbon ratio	a_{OC}	32/12	mg O_2/mg C
Phytoplankton nitrogen-carbon ratio	a_{NC}	0.25	mg N/mg C
Deoxygenation rate @ 20°C, Temperature coefficient	K_D Θ_D	0.21-0.16 1.047	day^{-1} -
Half saturation constant for oxygen limitation	K_{BOD}	0.5	mg O_2/L
Nitrification rate @ 20°C, Temperature coefficient	k_{12} Θ_{12}	0.09-0.13 1.08	day^{-1} -
Half saturation constant for oxygen limitation	K_{NIT}	0.5	mg N/L
Denitrification rate @ 20°C, Temperature coefficient	k_{2D} Θ_{2D}	- 1.08	day^{-1} -
Half saturation constant for oxygen limitation	K_{NO3}	0.1	mg N/L
Phytoplankton growth rate	G_{P1}	0.1-0.5	day^{-1}
Phytoplankton respiration rate @ 20°C, Temperature coefficient	k_{1R}	0.125 1.045	day^{-1} -
Sediment Oxygen Demand, Temperature coefficient	SOD Θ_s	0.2-4.0 1.08	g/m^2-day -
Reaeration rate @ 20°C, Temperature coefficient	k_2 Θ_a	Equation 3-16 to 3-22 1.028	day^{-1} -
DO saturation	C_s	Equation 3-22	mg O_2/L
Fraction dissolved CBOD	f_{D5}	0.5	none
Organic matter settling velocity	v_{s3}	-	m/day

Five EUTRO state variables can participate directly in the DO balance: phytoplankton carbon, ammonia, nitrate, carbonaceous biochemical oxygen demand, and dissolved oxygen. The methodology for the analysis of dissolved oxygen dynamics in natural waters, particularly in streams, rivers, and estuaries is reasonably well-developed (O'Connor and Thomann, 1972 cited in Wool et al., 2001)

Reaeration

EUTRO calculates flow-included reaeration based on the Covar method (Covar, 1976 cited in Wool et al., 2001). This method calculates reaeration as a function of velocity and depth by one of three formulas – Owens, Churchill, or O'Connor – Dobbins, respectively;

$$k_{qj}\ (20^0C) = 5.349\ v_j^{0.67}\ D_j^{-1.85} \qquad \text{------(3-16)}$$

$$k_{qj}\ (20^0C) = 5.049\ v_j^{0.97}\ D_j^{-1.67} \qquad \text{------(3-17)}$$

or $$k_{qj}\ (20^0C) = 3.93\ v_j^{0.50}\ D_j^{-1.50} \qquad \text{------(3-18)}$$

where

k_{qj} = flow-induced reaeration rate coefficient at 20^0C (day^{-1})

v_j = average water velocity in segment j (m/sec)

D_j = average segment depth (m)

The Owen formula (Equation 3-16) is automatically selected for segments width depth less than 2 feet. For segments deeper than 2 feet, the O'Connor-Dobbins (Equation 3-17) or Churchill formula (Equation 3-18) is selected based on a consideration of depth and velocity. Deeper, slowly moving rivers require O'Connor-Dobbins; moderately shallow, faster moving streams require Churchill.

Segment temperatures are used to adjust the flow-induced k_{qj} (20^0C) by the standard formula:

$$k_{qj}\ (T) = k_{qj}\ (20^0C)\ \Theta_a^{\ T-20} \qquad \text{------(3-19)}$$

where

T = water temperature (^{0}C)

k_{qj} (T) = reaeration rate coefficient at ambient segment temperature (day^{-1})

Θ_a = temperature coefficient

Wind-induced reaeration is determined by O'Connor (1983) cited in Wool et al. (2001). This method calculates reaeration as a function of wind speed, air and water temperature, and depth using one of three formulas:

$$k_{wj} = \frac{86400}{100\,D_j}\left(\frac{D_{OW}}{v_W}\right)^{2/3}\left(\frac{\rho_a}{\rho_W}\right)^{1/2}\frac{\kappa^{1/3}}{\Gamma}\sqrt{C_d}\,(100 * W) \qquad \text{---(3-20)}$$

$$k_{wj} = \frac{86400}{100\,D_j}\left[(\text{TERM1} * 100W)^{-1} + (\text{TERM2}\,\sqrt{100W})^{-1}\right]^{-1} \qquad \text{---(3-21)}$$

where

$$\text{TERM1} = \left(\frac{D_{OW}}{v_W}\right)^{2/3}\left(\frac{\rho_a}{\rho_W}\right)^{1/2}\frac{\kappa^{1/3}}{\Gamma_u}\sqrt{C_d} \qquad \text{---(3-21a)}$$

$$\text{TERM2} = \left(\frac{D_{OW}}{\kappa_{Z0}}\,\frac{\rho_a}{\rho_W}\,\frac{v_a}{V_W}\sqrt{C_d}\right)^{1/2} \qquad \text{---(3-21b)}$$

or

$$k_{wj} = \frac{86400}{100\,D_j}\left(\frac{D_{OW}}{\kappa_{Ze}}\,\frac{\rho_a}{\rho_W}\,\frac{v_a}{V_W}\sqrt{C_d}\right)^{1/2}\sqrt{100W} \qquad \text{---(3-22)}$$

where

k_{wj} = wind-induced reaeration rate coefficient, day^{-1}

W = time-varying wind speed at 10 cm above surface, m/sec

T_a = air temperature, °C

ρ_a = density of air, a function of T_a, g/cm^3

ρ_W = density of water, 1.0 g/cm^3

v_a = viscosity of air, a function of T_a, cm^2/s

v_W = viscosity of water, a function of T, cm^2/s

D_{OW} = diffusivity of oxygen in water, a function of T, cm^2/s

κ = von Karman's coefficient, 0.4

v_t = transitional shear velocity, set to 9, 10, and 10 for small, medium, and large scales, cm/s

v_c = critical shear velocity, set to 22, 11, and 11 for small, medium, and large scales, cm/s

z_e = equivalent roughness, set to 0.25, 0.35, and 0.35 for small, medium, and large scales, cm

z_0 = effective roughness, a function of z_e, Γ, C_d, v_t, v_a, and W, cm

λ = inverse of Reynold's number, set to 10, 3, and 3 for small, medium, and large scales

Γ = nondimensional coefficient, set to 10, 6.5, and 5 for small, medium, and large scales

Γ_u = nondimensional coefficient, a function of Γ, v_c, C_d, and W

C_d = drag coefficient, a function of z_e, Γ, v_a, κ, v_t, and W

Equation 3-20 is used for wind speeds of up to 6 m/sec, where interfacial conditions are smooth and momentum transfer is dominated by viscous forces. Equation 3-22 is used for wind speeds over 20 m/sec, where interfacial conditions are rough and momentum transfer is dominated by turbulent eddies. Equation 3-21 is used for wind speeds between 6 and 20 m/sec, and represents a transition zone in which the diffusional sublayer decays and the roughness height increases.

There is referred to O'Connor (1983) cited in Wool et al. (2001) for details on the calculation of air density, air and water viscosity, the drag coefficient, the effective roughness, and Γu. Small scale represents laboratory conditions. Large scale represents open ocean conditions. Medium scale represents most lakes and reservoirs.

Dissolved oxygen saturation, C_s, is determined as a function of temperature, in degrees K, and salinity S, in mg/L (APHA, 1985 cited in Wool et al., 2001):

$$\begin{aligned}\ln C_s \;=\; & -139.34 + (1.5757 * 10^5)\, T_K^{-1} - (6.6423 * 10^7)\, T_K^{-2} \\ & + (1.2438 * 10^{10})\, T_K^{-3} - (8.6219 * 10^{11})\, T_K^{-4} \\ & - 0.5535\, S\, (0.031929 - 19.428\, T_K^{-1} + 3867.3\, T_K^{-2}) \qquad \text{---(3-23)}\end{aligned}$$

3.1.4 Eutrophication

Eutrophication has been modeled for approximately 30 years. The equations implemented in EUTRO were derived from the Potomac Eutrophication Model (PEM) (Thomann and Fitzpatrick, 1982 cited in Wool et al., 2001), and are fairly standard.

The nutrient enrichment, eutrophication, and DO depletion processes are simulated using the EUTRO 6.0 program. Figure 3.1 presents the EUTRO simulates the transport and transformation reaction of up to eight state variables. They can be considered as four interacting systems: phytoplankton kinetics, the phosphorus cycle, the nitrogen cycle, and the dissolved oxygen balance. The general WASP 6.0 mass balance equation is solved for each state variable.

EUTRO can be operated at various levels of complexity to simulate some or all of these variables and interactions. Three levels of complexicity for simulating eutrophication are (1) simple eutrophication kinetics, (2) intermediate eutrophication kinetics, and (3) intermediate eutrophication kinetics with benthos. There are should refer to the summarized equations of phosphorus in Equation 3-24 to 3-26 and nitrogen in Equation 3-27 to 3-31, and the reaction parameters and coefficients in Table 3.2

Phytoplankton Phosphorus

$$\frac{\partial(C_4\, a_{pc})}{\partial t} = \underbrace{G_{P1}\, a_{pc}\, C_4}_{Growth} - \underbrace{D_{P1}\, a_{pc}\, C_4}_{Death} - \underbrace{\frac{V_{S4}}{D}\, a_{pc}\, C_4}_{Settling} \qquad \text{---(3-24)}$$

Organic Phosphorus

$$\frac{\partial C_8}{\partial t} = \underbrace{D_{P1}\, a_{pc}\, f_{op}\, C_4}_{Death} - \underbrace{k_{83}\, \Theta_{83}^{(T-20)} \left(\frac{C_4}{K_{mPc} + C_4}\right) C_8}_{Mineralization} - \underbrace{\frac{V_{S3}\,(1 - f_{D5})}{D}\, C_8}_{Settling} \qquad \text{---(3-25)}$$

Inorganic Phosphorus

$$\frac{\partial C_3}{\partial t} = \underbrace{D_{P1}\, a_{pc}\, (1 - f_{op})\, C_4}_{Death} + \underbrace{k_{83}\, \Theta_{83}^{(T-20)} \left(\frac{C_4}{K_{mPc} + C_4}\right) C_8}_{Mineralization} - \underbrace{G^{P1}\, a_{pc}\, C_4}_{Growth} \qquad \text{---(3-26)}$$

Table 3.2: Phosphorus reaction terms

Description	**Notation**	**Value from Potomac Estuary model**	**Units**
Inorganic Phosphorus	C_3	-	mg P/L
Phytoplankton Carbon	C_4	-	mg C/L
Organic Phosphorus	C_8	-	mg P/L
Phytoplankton biomass as carbon	P_c	-	mg C/L
Specific phytoplankton growth rate	G_{p1j}	Equation 2-10	day^{-1}
Phytoplankton loss rate	D_{p1j}	Equation 2-14	day^{-1}
Phosphorus to carbon ratio	a_{pc}	0.025	mg P/mg C
Dissolved organic phosphorus mineralization @ 20°C	k_{83}	0.22	day^{-1}
Temperature coefficient	Θ_{83}	1.08	none
Half saturation constant for phytoplankton limitation of phosphorus recycle	K_{mPc}	1.0	mg C/L
Fraction of dead and respired phytoplankton recycled to the organic phosphorus pool	f_{op}	0.5	none
Fraction of dead and respired phytoplankton recycled to the phosphate phosphorus pool	$(1-f_{op})$	0.5	none
Fraction dissolved inorganic phosphorus in the water column	f_{D3}	0.85, 0.70	none
Fraction dissolved organic phosphorus	f_{D8}	-	none
Organic matter settling velocity	V_{S3}	-	m/day
Inorganic sediment settling velocity	V_{S4}	-	m/day

Phytoplankton Nitrogen

$$\frac{\partial (C_4\, a_{nc})}{\partial t} = \underbrace{G_{P1}\, a_{nc}\, C_4}_{\textit{Growth}} - \underbrace{D_{P1}\, a_{nc}\, C_4}_{\textit{Death}} - \underbrace{\frac{V_{S4}}{D}\, a_{nc}\, C_4}_{\textit{Settling}} \qquad \text{---(3-27)}$$

Organic Nitrogen

$$\frac{\partial C_7}{\partial t} = \underbrace{D_{P1}\, a_{nc}\, C_4}_{\textit{Death}} - \underbrace{k_{71}\, \Theta_{71}^{(T-20)} \left(\frac{C_4}{K_{mPc} + C_4}\right) C_7}_{\textit{Mineralization}} - \underbrace{\frac{V_{S3}\,(1 - f_{D7})}{D}\, C_7}_{\textit{Settling}} \qquad \text{---(3-28)}$$

Ammonia Nitrogen

$$\begin{aligned}\frac{\partial C_1}{\partial t} = {} & \underbrace{D_{P1}\, a_{nc}\, (1 - f_{on})\, C_4}_{\textit{Death}} + \underbrace{k_{71}\, \Theta_{71}^{(T-20)} \left(\frac{C_4}{K_{mPc} + C_4}\right) C_7}_{\textit{Mineralization}} \\ & - \underbrace{G_{P1}\, a_{nc}\, P_{NH3}\, C_4}_{\textit{Growth}} + \underbrace{k_{12}\, \Theta_{12}^{(T-20)} \left(\frac{C_6}{K_{NIT} + C_6}\right) C_1}_{\textit{Nitrification}} \qquad \text{---(3-29)}\end{aligned}$$

Nitrate Nitrogen

$$\begin{aligned}\frac{\partial C_2}{\partial t} = {} & \underbrace{k_{12}\, \Theta_{12}^{(T-20)} \left(\frac{C_6}{K_{NIT} + C_6}\right) C_1}_{\textit{Nitrification}} - \underbrace{G_{P1}\, a_{nc}\, (1 - P_{NH3})\, C_4}_{\textit{Growth}} \\ & - \underbrace{k_{2D}\, \Theta_{2D}^{(T-20)} \left(\frac{K_{NO3}}{K_{NO3} + C_6}\right) C_2}_{\textit{Denitrification}} \qquad \text{---(3-30)}\end{aligned}$$

where

$$P_{NH3} = \underbrace{C_1 \left(\frac{C_2}{(K_{mN} + C_1)\,(K_{mN} + C_2)}\right) + C_1 \left(\frac{K_{mN}}{(C_1 + C_2)\,(K_{mN} + C_2)}\right)}_{\textit{Ammonia Preference Factor}} \qquad \text{---(3-31)}$$

Table 3.3: Nitrogen reaction terms

Description	**Notation**	**Value from Potomac Estuary model**	**Units**
Ammonia Nitrogen	C_1	-	mg N/L
Nitrate Nitrogen	C_2	-	mg N/L
Phytoplankton Carbon	C_4	-	mg C/L
Dissolved Oxygen	C_6	-	mg O_2/L
Organic Nitrogen	C_7	-	mg N/L
Nitrogen to carbon ratio	a_{nc}	0.25	mg N/gm C
Organic nitrogen mineralization rate @ 20°C	k_{71}	0.075	day^{-1}
Temperature coefficient	Θ_{71}	1.08	-
Nitrification rate	k_{12}	0.09-0.13	day^{-1}
Temperature coefficient	Θ_{12}	1.08	-
Half saturation constant for oxygen limitation of nitrification	K_{NIT}	2.0	mg 0_2/L
Denitrification rate @ 20°C	k_{2D}	0.09	day^{-1}
Temperature coefficient	Θ_{2D}	1.045	-
Michaelis constant for denitrification	K_{NO3}	0.1	mg O_2/L
Fraction of dead and respired phytoplankton recycled to the organic nitrogen pool	f_{on}	0.5	-
Fraction of dead and respired phytoplankton recycled to the ammonia nitrogen pool	$(1 - f_{on})$	0.5	-
Preference for ammonia uptake term	P_{NH3}	-	-
Fraction dissolved organic nitrogen	f_{D7}	1.0	-
Organic matter settling velocity	v_{s3}	-	m/day

3.2 Model Setting

3.2.1 Model Segmentation

Pak Phanang River is extends from Mai Siap Weir (upstream) to Uthokvibhjaprasid Gate (downstream) for about 100 kilometers along the mainstream. Following a review of hydraulic computational data from MIKE 11 model for the Pak Phanang River from Pollution Control Department, the system was divided into 99 segments as shown in Figure 3.3. Table 3.4 lists the segment volumes and depth of the 99 segments. Table 3.5 lists the characteristic lengths and interfacial areas between segment pairs.

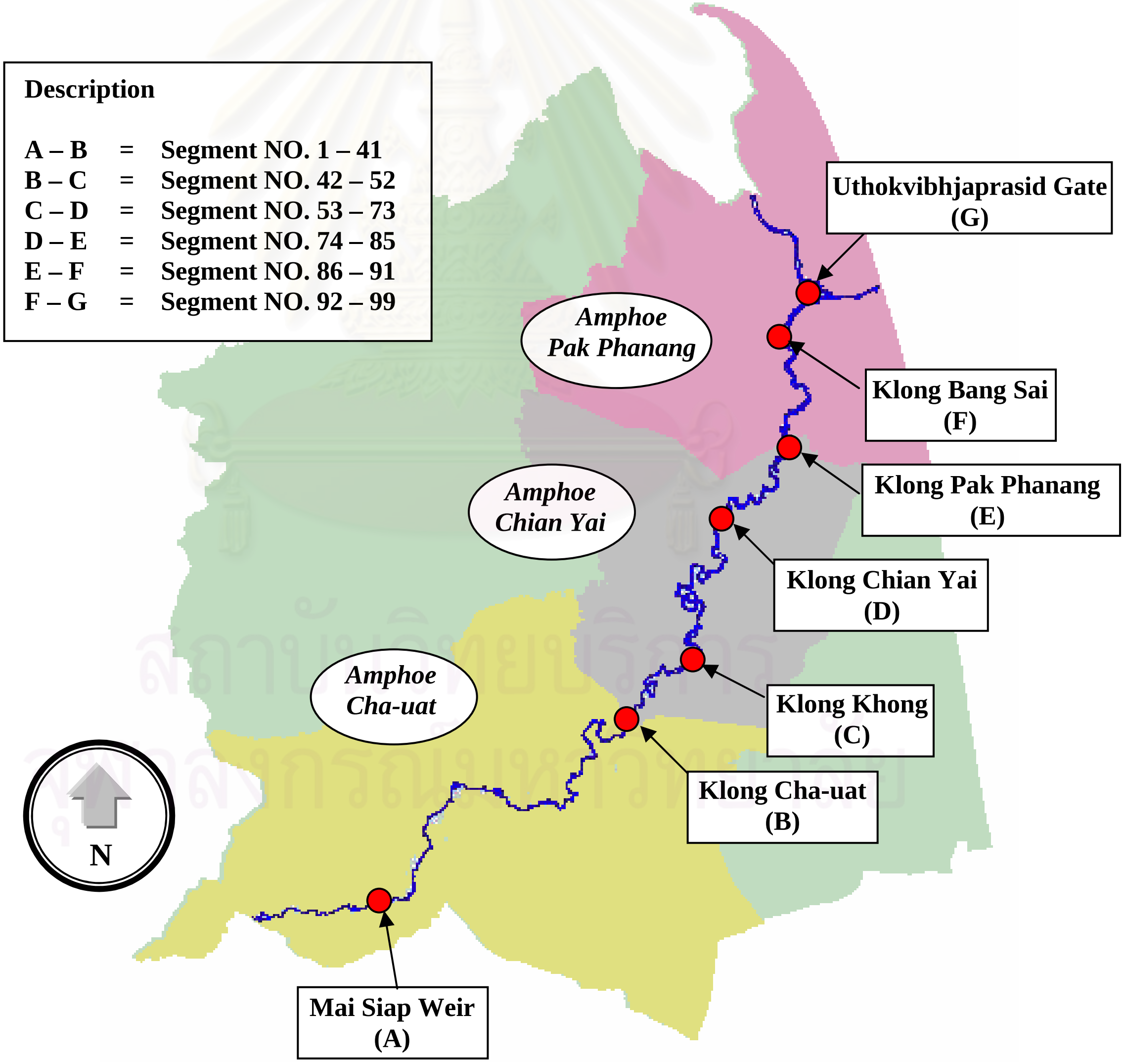


Figure 3.3: Model segmentation

Table 3.4: Water quality model segment volumes and depths

Water Quality Segments	Volume (m^3)	Depth (m)	Water Quality Segments	Volume (m^3)	Depth (m)
1	314,772.50	2.583	26	272,107.50	5.024
2	306,600.00	6.888	27	304,470.00	5.584
3	309,315.00	7.447	28	298,660.00	5.436
4	221,752.50	5.308	29	306,155.00	6.014
5	178,622.50	5.381	30	414,006.00	5.037
6	147,285.00	5.633	31	315,361.20	5.143
7	98,725.00	3.684	32	304,924.80	5.066
8	56,740.00	3.855	33	348,087.50	4.760
9	31,052.45	2.687	34	399,327.50	6.454
10	25,892.25	2.229	35	429,970.00	7.522
11	17,230.00	1.881	36	480,860.00	6.646
12	13,657.50	1.391	37	717,345.00	5.637
13	22,072.50	1.414	38	676,008.00	7.628
14	30,515.00	2.728	39	655,242.50	5.577
15	32,875.00	2.688	40	652,845.00	6.729
16	41,627.50	2.170	41	720,690.00	8.443
17	120,355.00	1.910	42	731,160.00	9.810
18	128,200.00	4.636	43	740,985.00	8.444
19	200,832.50	2.307	44	724,655.00	8.836
20	284,580.00	5.893	45	819,195.00	8.790
21	389,400.00	5.253	46	955,170.00	10.515
22	486,125.00	7.410	47	894,415.00	9.364
23	448,130.00	6.573	48	900,875.00	7.668
24	413,830.00	6.758	49	928,880.00	8.961
25	298,377.50	6.524	50	877,220.00	9.164

Table 3.4: Water quality model segment volumes and depths (continue)

Water Quality Segments	Volume (m^3)	Depth (m)
51	1,142,370.00	9.080
52	1,316,505.00	10.546
53	1,198,255.00	9.028
54	1,255,255.00	9.288
55	1,281,605.00	10.088
56	1,243,920.00	11.019
57	1,205,920.00	10.052
58	1,240,185.00	10.906
59	1,326,230.00	11.895
60	1,250,315.00	11.432
61	1,201,090.00	9.032
62	1,194,190.00	11.079
63	1,125,045.00	7.979
64	1,283,395.00	8.736
65	1,332,555.00	10.125
66	1,214,835.00	9.173
67	1,290,595.00	5.637
68	1,208,675.00	8.052
69	1,251,245.00	8.069
70	1,422,025.00	7.337
71	1,396,250.00	7.196
72	1,370,730.00	6.201
73	1,487,785.50	6.201
74	1,042,595.20	8.157
75	1,371,430.00	9.569
76	1,366,200.00	9.411
77	999,727.50	6.719
78	1,209,728.63	8.614
79	1,103,081.63	7.426
80	1,177,345.00	6.273
81	1,163,495.00	5.702
82	1,024,825.00	7.472
83	858,972.75	4.798
84	357,351.75	9.033
85	1,253,080.00	5.353
86	1,228,310.00	6.248
87	1,242,315.00	6.288
88	1,174,240.00	6.201
89	1,149,860.00	6.906
90	1,338,545.00	7.044
91	1,426,005.00	10.584
92	1,228,685.00	5.855
93	1,271,700.00	3.975
94	1,306,640.00	9.919
95	1,140,485.00	6.444
96	1,032,140.00	5.600
97	1,029,615.00	5.324
98	1,112,625.00	5.954
99	1,539,570.00	5.514

Table 3.5: Water quality segment pair characteristic lengths and interfacial areas

Water Quality Segment Pairs		Interfacial Areas (m^2)	Characteristic Length (m)
0	1	386.945	1000
1	2	242.600	1000
2	3	370.600	1000
3	4	248.030	1000
4	5	195.475	1000
5	6	161.770	1000
6	7	132.800	1000
7	8	64.650	1000
8	9	48.830	860
9	10	23.385	1140
10	11	22.040	1000
11	12	12.420	1000
12	13	14.895	1000
13	14	29.250	1000
14	15	31.780	1000
15	16	33.970	1000
16	17	49.285	1000
17	18	191.425	1000
18	19	64.975	1000
19	20	336.690	1000
20	21	232.470	1000
21	22	546.330	1000
22	23	425.920	1000
23	24	470.340	1000
24	25	357.320	1000
25	26	239.435	1000
26	27	304.780	1000
27	28	304.160	1000
28	29	293.160	1000
29	30	319.150	1200
30	31	370.860	880
31	32	345.870	920
32	33	317.010	1000
33	34	379.165	1000
34	35	419.490	1000
35	36	440.450	1000
36	37	521.270	1000
37	38	913.420	900
38	39	588.820	1100
39	40	602.530	1000
40	41	703.160	1000
41	42	738.220	1000
42	43	724.100	1000
43	44	757.870	1000
44	45	691.440	1000
45	46	946.950	1000
46	47	963.390	1000
47	48	825.440	1000
48	49	976.310	1000
49	50	881.450	1000

Remark: *Segment 0 = boundary*

Table 3.5: Water quality segment pair characteristic lengths and interfacial areas (continue)

Water Quality Segment Pairs		Interfacial Areas (m^2)	Characteristic Length (m)	Water Quality Segment Pairs		Interfacial Areas (m^2)	Characteristic Length (m)
50	51	872.990	1000	75	76	1,557.640	1000
51	52	1,411.750	1000	76	77	1,174.760	850
52	53	1,221.260	1000	77	78	1,177.540	1095
53	54	1,175.250	1000	78	79	1,032.010	1055
54	55	1,335.260	1000	79	80	1,059.140	1000
55	56	1,227.950	1000	80	81	1,295.550	1000
56	57	1,259.890	1000	81	82	1,031.440	1000
57	58	1,151.950	1000	82	83	1,018.210	730
58	59	1,328.420	1000	83	84	1,335.140	270
59	60	1,324.040	1000	84	85	1,311.910	1000
60	61	1,176.590	1000	85	86	1,194.250	1000
61	62	1,225.590	1000	86	87	1,262.370	1000
62	63	1,162.790	1000	87	88	1,222.260	1000
63	64	1,087.300	1000	88	89	1,126.220	1000
64	65	1,479.490	1000	89	90	1,173.500	1000
65	66	1,185.620	1000	90	91	1,503.590	1000
66	67	1,244.050	1000	91	92	1,348.420	1000
67	68	1,337.140	1000	92	93	1,108.950	1000
68	69	1,080.210	1000	93	94	1,434.450	1000
69	70	1,422.280	1000	94	95	1,178.830	1000
70	71	1,421.770	1000	95	96	1,102.140	1000
71	72	1,370.730	1000	96	97	962.140	1000
72	73	1,370.730	1140	97	98	1,097.090	1000
73	74	1,239.420	860	98	99	1,128.160	1500
74	75	1,185.220	1000	99	0	924.60	1500

Remark: *Segment 0 = boundary*

3.2.2 Water Quality Data

The Pollution Control Department conducted five times of water quality surveys at Pak Phanang River in 2003. The surveys comprised 14 sampling locations as shown in Figure 3.4 and were conducted in January, March, April, July, and December. The physical parameters – dissolved oxygen (DO), salinity, conductivity, and water temperature – were measured in situ at each water quality monitoring station. Grab samples were also collected for laboratory analysis. The samples were collected at a middle of depth from the surface. Table 3.6 lists the water quality survey data and Figure 3.5 to 3.8 present Pak Phanang water quality profiles.

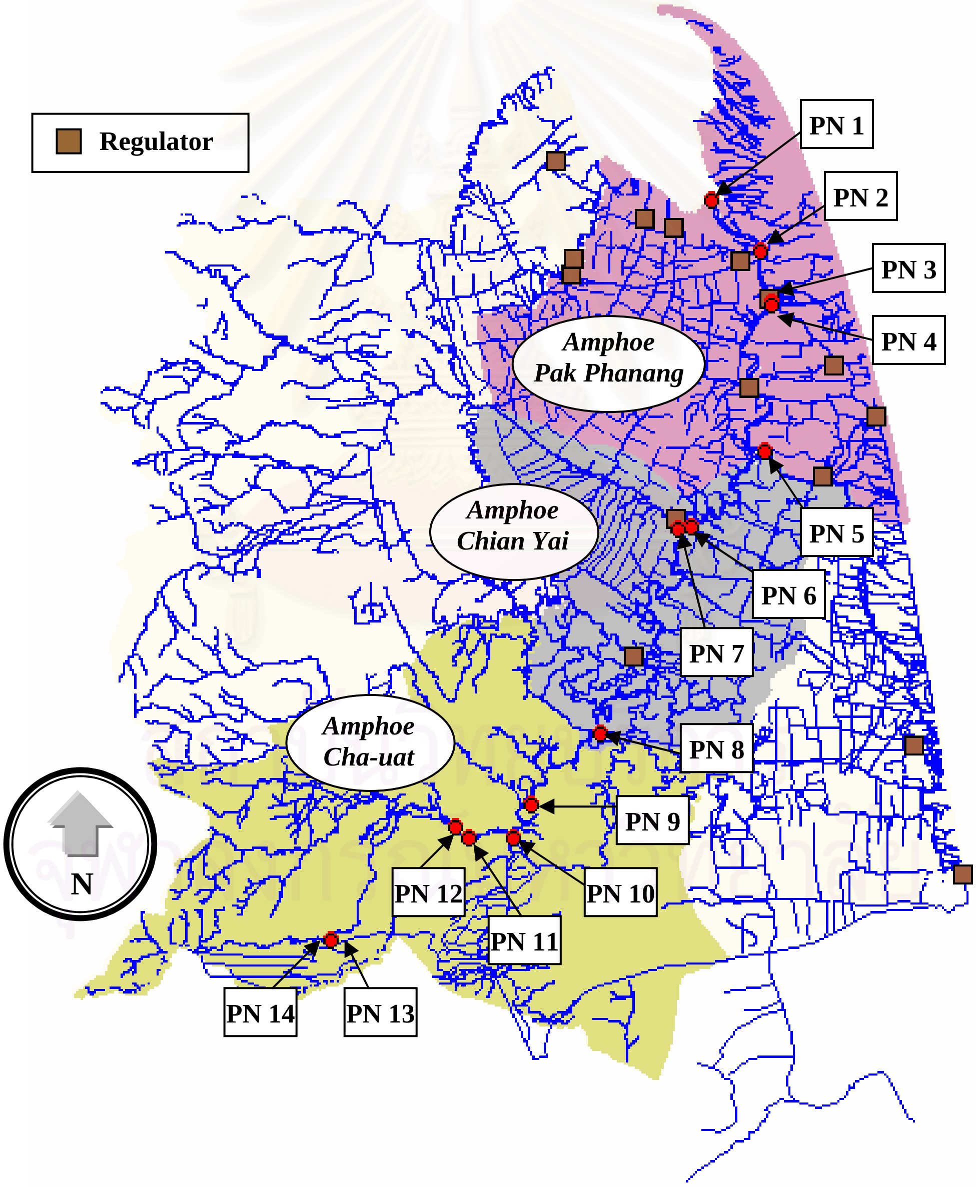


Figure 3.4: Pak Phanang River water quality monitoring stations

Table 3.6: Pak Phanang River field observed water quality data

Sample Station	Description	Date	Water Temperature (^{0}C)	Depth (m)	Salinity (ppt)	DO (mg/L)	BOD (mg/L)	NO_3–N (mg/L)	NO_2–N (mg/L)	NH_3–N (mg/L)	TP (mg/L)	PO_4 (mg/L)
PN 14	Upper Mai Siap Weir	01/13/2003	28.3	1	0.1	3.7	1	0.28	< 0.01	0.23	-	< 0.03
Segment 1		03/05/2003	31.8	2	0.1	4.5	1.5	0.01	0.01	0.1	0.03	< 0.01
		04/24/2003	29.4	> 10	0.1	6.6	0.7	0.2	0.03	0.3	0.03	-
		07/29/2003	28.7	1.5	0.1	6.7	1.2	0.23	0.01	0.01	0.01	-
		12/18/2003	29.8	2.5	0	6.4	1.5	0.01	0.01	0.08	0.03	-
		Average	**29.6**	**3.4**	**0.08**	**5.58**	**1.18**	**0.146**	**0.014**	**0.144**	**0.025 ****	**0.01 ****
PN 13	Lower Mai Siap Weir	01/13/2003	27.9	0.5	0.1	8.5	0.8	0.25	< 0.01	0.09	-	0.06
		03/05/2003	32	1	0.1	6.1	< 0.6	0.01	0.01	0.1	0.02	< 0.01
		04/24/2003	-	-	-	-	1.8	0.21	0.02	0.21	0.03	-
		07/29/2003	28.7	-	0.1	7.2	1.7	0.21	0.01	0.01	0.01	-
		12/18/2003	29.9	1	0	8	1.3	0.05	0.05	0.05	0.02	-
		Average	**29.63**	**0.83**	**0.075**	**7.45**	**1.24**	**0.146**	**0.02**	**0.092**	**0.02 ****	**0.01 ****

Remark: *** Average for March, April, July and December not include January*

Table 3.6: Pak Phanang River field observed water quality data (continue)

Sample Station	**Description**	**Date**	**Water Temperature (^{0}C)**	**Depth (m)**	**Salinity (ppt)**	**DO (mg/L)**	**BOD (mg/L)**	**NO_3–N (mg/L)**	**NO_2–N (mg/L)**	**NH_3–N (mg/L)**	**TP (mg/L)**	**PO_4 (mg/L)**
PN 12 *Segment 14*	Upper Cha-uat District	01/13/2003	26.3	5	0	5.5	1.6	0.17	< 0.01	0.1	-	< 0.03
		03/05/2003	30.2	6	0.1	5.2	3.6	0.01	0.01	0.11	0.07	< 0.01
		04/24/2003	32.4	> 10	0.1	8.8	4.9	0.01	0.01	0.2	0.1	-
		07/29/2003	31	-	0.1	7.2	2.6	0.21	0.01	0.01	0.01	-
		12/18/2003	27.8	6	0	5.2	1.6	0.01	0.01	0.07	0.03	-
		Average	**29.54**	**6.75**	**0.06**	**6.38**	**2.86**	**0.082**	**0.01**	**0.098**	**0.053 ****	**0.01 ****
PN 11 *Segment 15*	Lower Cha-uat District	01/13/2003	28.3	5	0	6	1.6	0.24	< 0.01	0.12	-	0.05
		03/05/2003	31.2	5	0.1	1.6	3.5	0.01	0.01	0.11	0.07	< 0.01
		04/24/2003	31.1	> 10	0.1	8	2.2	0.01	0.01	0.18	0.05	-
		07/29/2003	28	2.5	0.1	6.3	1.9	0.52	0.01	0.01	0.01	-
		12/17/2003	28.3	5	0	4.8	2.1	0.02	0.02	0.04	0.03	-
		Average	**29.38**	**5.5**	**0.06**	**5.34**	**2.26**	**0.16**	**0.012**	**0.092**	**0.04 ****	**0.01 ****

Remark: *** Average for March, April, July and December not include January*

Table 3.6: Pak Phanang River field observed water quality data (continue)

Sample Station	Description	Date	Water Temperature (^0C)	Depth (m)	Salinity (ppt)	DO (mg/L)	BOD (mg/L)	NO_3–N (mg/L)	NO_2–N (mg/L)	NH_3–N (mg/L)	TP (mg/L)	PO_4 (mg/L)
PN 10 *Segment 22*	Upper Kuan Kreng Swamp Forest	01/16/2003	26.8	5.5	0	4	0.7	< 0.01	< 0.01	0.1	-	0.03
		03/05/2003	30.2	4	0.1	1.7	1.5	0.01	0.01	0.25	0.05	0.01
		04/24/2003	30.7	4.5	0.1	6.4	2.4	0.01	< 0.01	0.16	0.03	-
		07/29/2003	29	5.5	0.3	3.1	1.6	0.11	0.01	0.01	0.01	-
		12/17/2003	27	8	0	4.4	1.7	0.01	0.01	0.09	0.03	-
		Average	**28.74**	**5.5**	**0.1**	**3.92**	**1.58**	**0.03**	**0.01**	**0.122**	**0.03 ****	**0.01 ****
PN 9 *Segment 23*	Kuan Kreng Swamp Forest	01/16/2003	26.4	6	0	3.8	0.6	< 0.01	0.07	0.1	-	0.03
		03/05/2003	28.9	4.5	0.1	4.1	2.9	0.01	0.01	0.2	0.02	< 0.01
		04/24/2003	31	> 10	0.1	5.7	3	0.01	0.01	0.2	0.04	-
		07/29/2003	29	5	0.2	1	2	0.02	0.01	0.01	0.01	-
		-	-	-	-	-	-	-	-	-	-	-
		Average	**28.83**	**6.38**	**0.1**	**3.65**	**2.13**	**0.013**	**0.025**	**0.128**	**0.023 ****	**0.01 ****

Remark: *** Average for March, April, July and December not include January*

Table 3.6: Pak Phanang River field observed water quality data (continue)

Sample Station	**Description**	**Date**	**Water Temperature (^{0}C)**	**Depth (m)**	**Salinity (ppt)**	**DO (mg/L)**	**BOD (mg/L)**	**NO_3–N (mg/L)**	**NO_2–N (mg/L)**	**NH_3–N (mg/L)**	**TP (mg/L)**	**PO_4 (mg/L)**
PN 8 *Segment 40*	Lower Kuan Kreng Swamp Forest	01/16/2003	27.4	9	0.1	1.7	0.3	< 0.01	< 0.01	0.1	-	< 0.03
		03/04/2003	28.4	5	0.2	1	1.7	< 0.01	< 0.01	0.14	0.02	< 0.01
		04/27/2003	32.3	> 10	0.2	5	0.9	0.16	0.01	1.21	0.02	< 0.01
		07/29/2003	30	4	0.1	3.5	3	0.05	0.01	0.01	0.01	-
		12/17/2003	28.4	3	0	2.8	1.7	0.01	0.01	0.05	0.03	-
		Average	**29.3**	**6.2**	**0.12**	**2.8**	**1.52**	**0.048**	**0.01**	**0.302**	**0.02 ****	**0.01 ****
PN 7 *Segment 68*	Upper Chian yai District	01/16/2003	27.7	13	0.1	3.4	0.3	< 0.01	< 0.01	0.09	-	< 0.03
		03/04/2003	30.8	12	0.2	1	0.6	< 0.01	< 0.01	0.25	0.03	< 0.01
		04/27/2003	30.1	> 10	0.2	5.9	1.2	0.01	0.01	1.8	0.03	< 0.01
		07/29/2003	29.5	-	0.8	0.5	2.4	0.03	0.01	0.01	0.01	-
		12/17/2003	28.4	14	0	2	1.9	0.01	0.01	0.06	0.04	-
		Average	**29.3**	**12.25**	**0.26**	**2.56**	**1.28**	**0.014**	**0.01**	**0.442**	**0.028 ****	**0.01 ****

Remark: *** Average for March, April, July and December not include January*

Table 3.6: Pak Phanang River field observed water quality data (continue)

Sample Station	**Description**	**Date**	**Water Temperature (^{0}C)**	**Depth (m)**	**Salinity (ppt)**	**DO (mg/L)**	**BOD (mg/L)**	**NO_3–N (mg/L)**	**NO_2–N (mg/L)**	**NH_3–N (mg/L)**	**TP (mg/L)**	**PO_4 (mg/L)**
PN 6 *Segment 69*	Lower Chian Yai District	01/16/2003	27.7	10.5	0.1	2.5	0.4	< 0.01	< 0.01	0.08	-	< 0.03
		03/04/2003	31.5	10	0.2	1	0.9	< 0.01	< 0.01	0.27	0.02	0.01
		04/27/2003	30.1	> 10	0.2	1.1	1.3	0.01	0.01	0.38	0.02	< 0.01
		07/29/2003	30.7	13	0.8	6.8	2.9	0.07	0.01	0.01	0.01	-
		12/17/2003	28.5	10	0	2	2	0.01	0.01	0.05	0.05	-
		Average	**29.7**	**10.7**	**0.26**	**2.68**	**1.5**	**0.022**	**0.01**	**0.158**	**0.025 ****	**0.01 ****
PN 5 *Segment 85*	Pak Prake Temple	01/14/2003	28.7	10	0.1	3	0.9	< 0.01	< 0.01	0.07	-	0.11
		03/03/2003	30	10.5	0.3	1.5	< 0.6	0.01	0.01	0.22	0.02	-
		04/29/2003	32.3	> 10	0.5	3.6	2.3	0.01	0.01	0.2	0.04	< 0.01
		07/27/2003	28.7	9	1.1	2.9	1.8	0.01	0.01	0.01	0.01	-
		12/15/2003	27	2	0	2.4	< 0.6	0.02	0.01	0.31	0.03	-
		Average	**29.34**	**8.3**	**0.4**	**2.68**	**1.24**	**0.012**	**0.01**	**0.162**	**0.025 ****	**0.01 ****

Remark: *** Average for March, April, July and December not include January*

Table 3.6: Pak Phanang River field observed water quality data (continue)

Sample Station	Description	Date	Water Temperature (^{0}C)	Depth (m)	Salinity (ppt)	DO (mg/L)	BOD (mg/L)	NO_3–N (mg/L)	NO_2–N (mg/L)	NH_3–N (mg/L)	TP (mg/L)	PO_4 (mg/L)
PN 4	Upper Uthokvibha – japrasid Gate	01/14/2003	27.7	7	0.1	3	1	0.01	< 0.01	0.09	-	0.12
Segment 99		03/02/2003	32	5	0.5	6.1	1.1	0.01	0.01	0.13	0.04	< 0.01
		04/30/2003	30.1	> 10	0.7	1.5	1.4	0.01	0.01	0.2	0.04	0.01
		07/27/2003	30.9	7	1	8.7	2.4	0.01	0.01	0.01	0.01	-
		12/15/2003	27.7	7.5	0.1	2	< 0.6	0.04	0.02	0.33	0.04	-
		Average	**29.68**	**7.3**	**0.48**	**4.26**	**1.3**	**0.016**	**0.012**	**0.152**	**0.033 ****	**0.01 ****
PN 3	Lower Uthokvibha – japrasid Gate	01/14/2003	28.9	7	0.1	3.2	1.1	0.04	< 0.01	0.09	-	0.15
		03/02/2003	31.4	8	19.3	0.9	0.6	0.02	0.02	0.42	0.08	0.04
		04/30/2003	30.3	> 10	27.5	0	0.8	0.02	0.02	0.2	0.14	0.1
		07/27/2003	30.2	7	28.3	2.7	3	0.04	0.01	1.1	0.09	-
		12/15/2003	29.3	7.5	0	4	< 0.6	0.05	0.02	0.35	0.04	-
		Average	**30.02**	**7.9**	**15.04**	**2.16**	**1.22**	**0.034**	**0.016**	**0.432**	**0.088 ****	**0.07 ****

Remark: *** Average for March, April, July and December not include January*

Table 3.6: Pak Phanang River field observed water quality data (continue)

Sample Station	Description	Date	Water Temperature (^{0}C)	Depth (m)	Salinity (ppt)	DO (mg/L)	BOD (mg/L)	NO_3–N (mg/L)	NO_2–N (mg/L)	NH_3–N (mg/L)	TP (mg/L)	PO_4 (mg/L)
PN 2	Ferry Port	01/14/2003	28.2	6	0.1	3	1.1	0.04	< 0.01	0.08	-	0.09
		03/02/2003	31.2	5	25.6	3.3	0.8	0.01	0.03	0.35	0.08	0.03
		04/30/2003	30	1	27.7	2.5	1.5	0.03	0.03	0.48	0.06	0.03
		07/27/2003	30.8	6	27.4	2.4	2.7	0.04	0.01	0.01	0.08	-
		12/15/2003	28.4	7	0.1	2	< 0.6	0.06	0.02	0.34	0.04	-
		Average	**29.72**	**5**	**16.18**	**2.64**	**1.34**	**0.036**	**0.02**	**0.252**	**0.065 ****	**0.03 ****
PN 1	Mouth of River	01/14/2003	29	2.5	2	3.4	0.8	0.02	< 0.01	0.12	-	< 0.03
		03/02/2003	31.5	2	-	3.8	1.7	< 0.01	0.03	0.22	0.02	0.02
		04/30/2003	31.2	3	27.7	5.8	2.2	0.02	0.02	0.34	0.02	0.01
		07/27/2003	32	1	27	7.7	8.8	0.04	0.01	0.01	0.04	-
		12/15/2003	27.7	2	0.1	3.6	< 0.6	0.08	0.03	0.36	0.11	-
		Average	**30.28**	**2.1**	**14.2**	**4.86**	**2.82**	**0.034**	**0.02**	**0.21**	**0.048 ****	**0.015 ****

Remark: *** Average for March, April, July and December not include January*

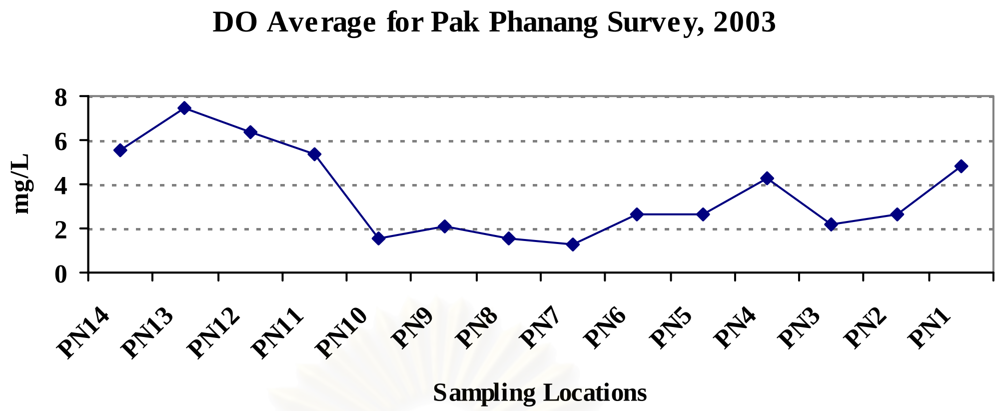


Figure 3.5: Longitudinal profile of dissolved oxygen data

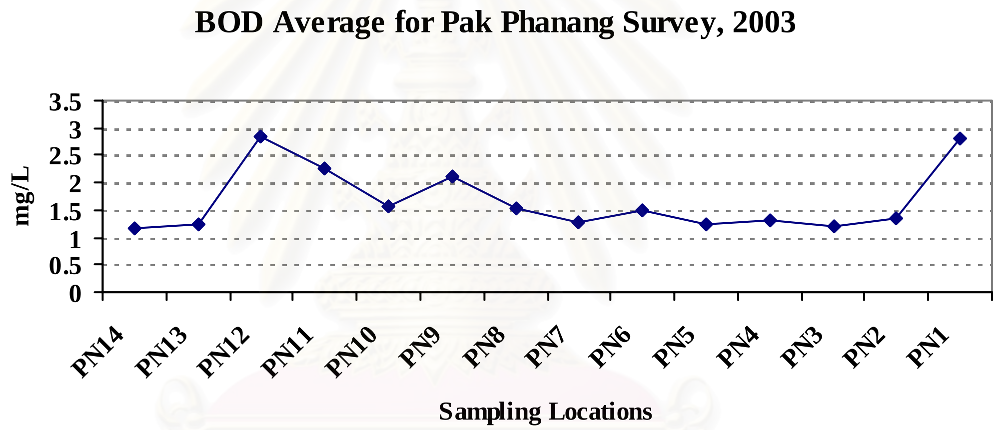


Figure 3.6: Longitudinal profile of biochemical oxygen demand data

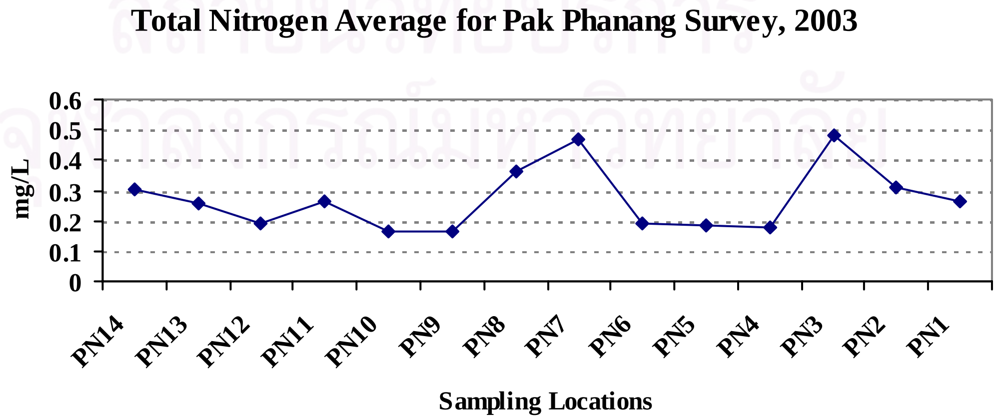


Figure 3.7: Longitudinal profile of total nitrogen data

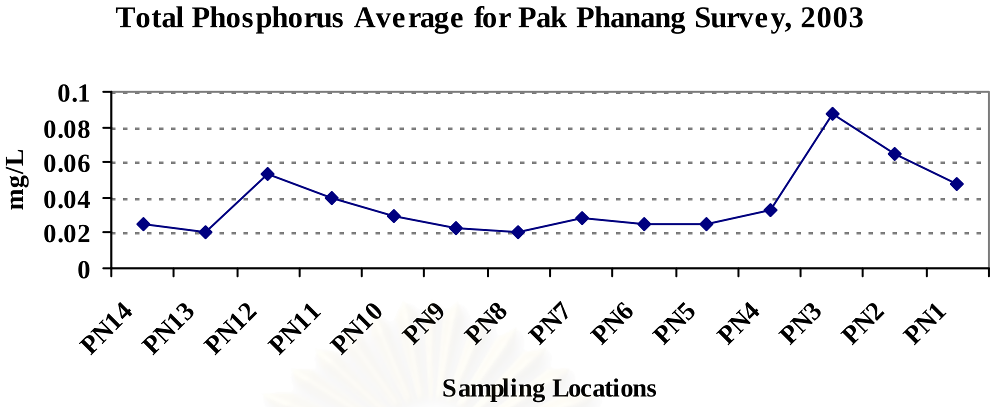


Figure 3.8: Longitudinal profile of total phosphorus data

3.3.3 Determining Point and Non-point Source Loading

The Pak Phanang River basin has an area of approximately 2 million rai or 3000 square kilometers. The land uses in the basin consists of agriculture (1,229,124 rai or 62%), aquaculture (106,295 rai or 5%), forest (384,850 rai or 19%), water (12,197 rai or 1%), urban (67,341 rai or 3%) and other (190,125 rai or 10%), based on 2001 survey data of Land Development Department. Figure 3.9 shows the relative amounts of the different land uses. Figure 3.10 shows the geographic distribution of the different land uses.

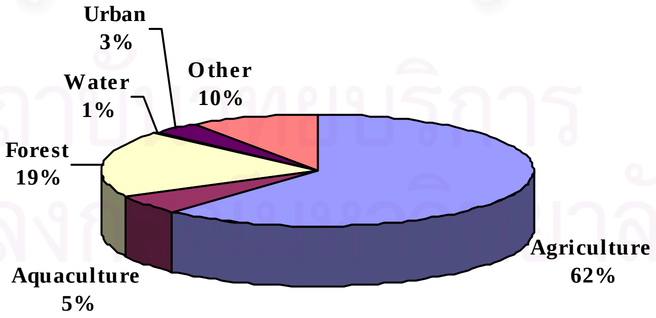


Figure 3.9: Estimated land use in Pak Phanang River basin

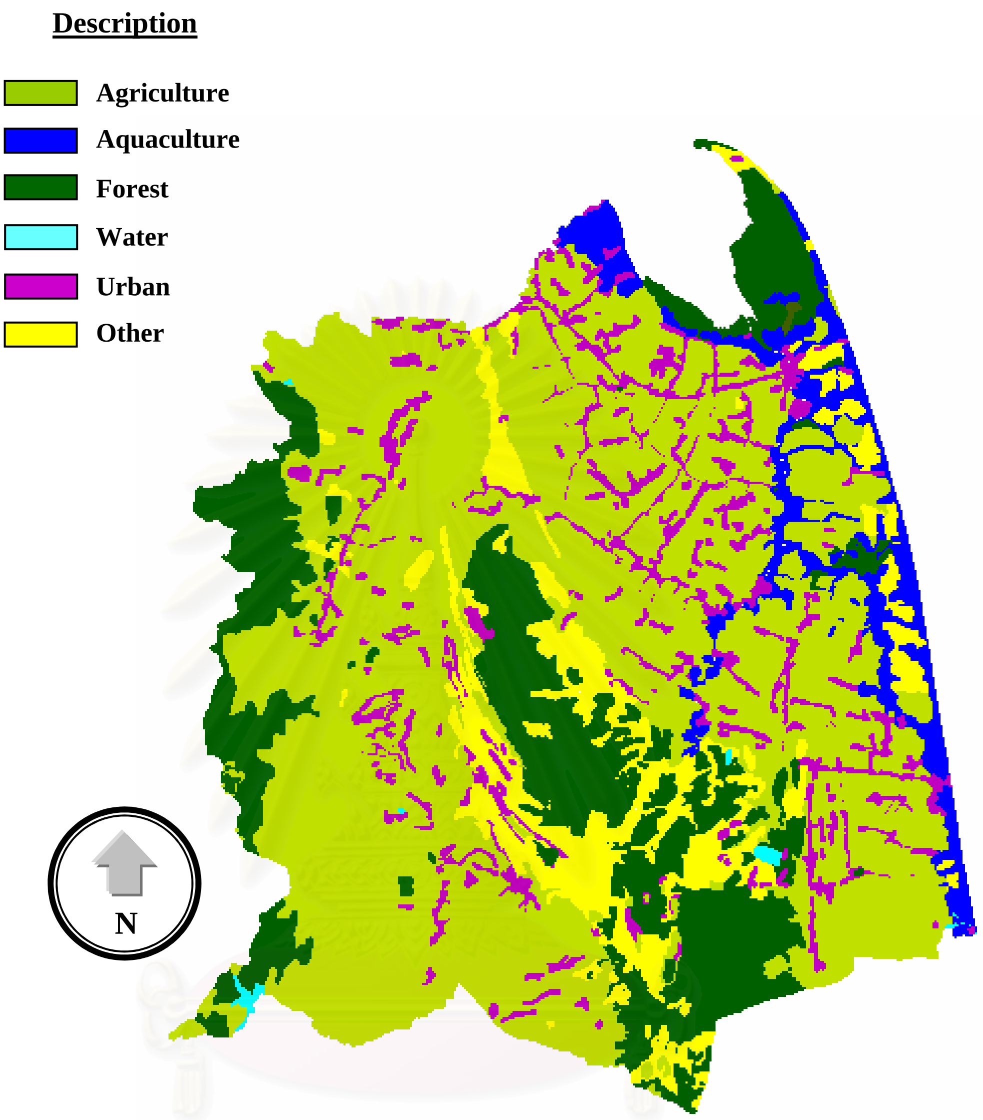


Figure 3.10: Land use in Pak Phanang River basin

The estimation of point and non-point sources in this study was determined from land use loading coefficients as used in the study of Pollution Control Department (2002). The land use information was based on 2001 land use planning data of Land Development Department.

Figure 3.11 shows the overall scheme of pollutant loading from various sources which considered in this study.

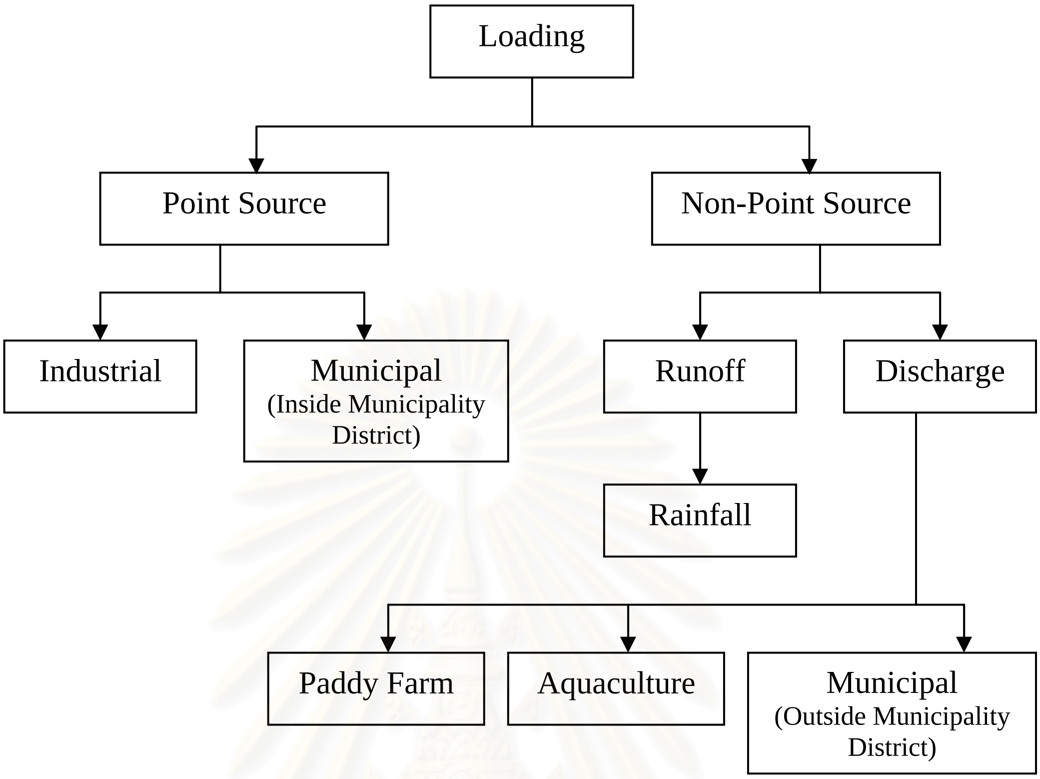


Figure 3.11: Pollutant loading from various sources

Point Source Loadings

Two industrial point sources were considered in this study. They are manufactures of pound fish. Both factories used aerated lagoon for wastewater treatment.

Table 3.7: Summary of industrial point sources loading

Factory Name	Location (Amphoe)	Existing Load (m^3/day)	Discharge Load (m^3/day)	Effluent BOD (mg/L)	Effluent BOD Loading (kg/day)
Pak Phanang pond fish	Pak Phanang	5	1	13	0.01
Sangchareon pond fish	Pak Phanang	5	1	13	0.01

Source: *Survey by Pollution Control Department, 2002*

The municipal point sources loading in this study came from three districts; Cha-uat, Chian Yai, and Pak Phanang. The loading estimation used loading coefficients for municipal wastewater from the study of Pollution Control Department (2002) as follow.

$$\mathrm{BOD}_5 = 80\ \mathrm{mg/L}$$

$$\mathrm{TKN} = 30\ \mathrm{mg/L}$$

Loading from municipal point sources for each district could be calculated from the Equation 3-32 and 3-33. Summary of municipal point source loading was listed in Table 3.8.

$$\underset{(m^3/day)}{\textbf{Wastewater Discharge}} = \textbf{Number of Population} \times \underset{(L/person/day)}{\textbf{Wastewater Generation Rate}} \times 10^{-3} \quad \text{---(3-32)}$$

$$\underset{(kg/day)}{\textbf{Loading}} = \underset{(m^3/day)}{\textbf{Wastewater Discharge}} \times \underset{(mg/L)}{\textbf{Loading Coefficient}} \times 10^{-3} \quad \text{---(3-33)}$$

Table 3.8: Summary of municipal point sources loading

Source	Inside Municipality District Population[(1)]	Wastewater Generation Rate[(2)] (L/person/day)	Wastewater Discharge (m^3/day)	Loading (kg/day)	
				BOD	TKN
Cha-uat	4,086	181	739.57	59.17	22.19
Chian Yai	2,041	181	369.42	29.55	11.08
Pak Phraek ** (Pak Phanang)	3,967	254	1007.62	80.61	30.23

Sources: *(1) Office of Administrator–Nakorn Si Thammarat Province, 2002*

(2) Office of Environmental Policy and Planning, 1995

Remark: *** Pak Phanang municipality is located outside segment consideration*

Non-Point Source Loading

The total runoff loading was calculated from Equation 3-34 as followed.

$$\underset{(kg/day)}{\textbf{Total runoff loading}} = \underset{(m^3/sec)}{\textbf{Rainfall runoff}} \times \underset{(mg/L)}{\textbf{Mean runoff concentration}} \quad \text{-----(3-34)}$$

The rainfall runoff information for Pak Phanang River sub-basin was based on the study of Office of Environmental Policy and Planning (2003). Mean runoff concentration lists in Table 3.9 were suggested by Pollution Control Department (2002). Figure 3.12 shows schematic of Pak Phanang River sub-basin. Summary of total runoff loading was listed in Table 3.10.

Table 3.9: Mean runoff concentration

Land Use Type	Mean Runoff Concentration (mg/L)		
	BOD	**TN**	**TP**
Urban	10.60	2.22	0.47
Rural	4.40	1.77	0.18
Paddy	3.83	2.68	0.42
Cultivate	3.83	2.05	0.14
Forest/Wetland	6.00	0.83	0.06
Other	13.00	5.20	0.59

Source: *Pollution Control Department, 2002*

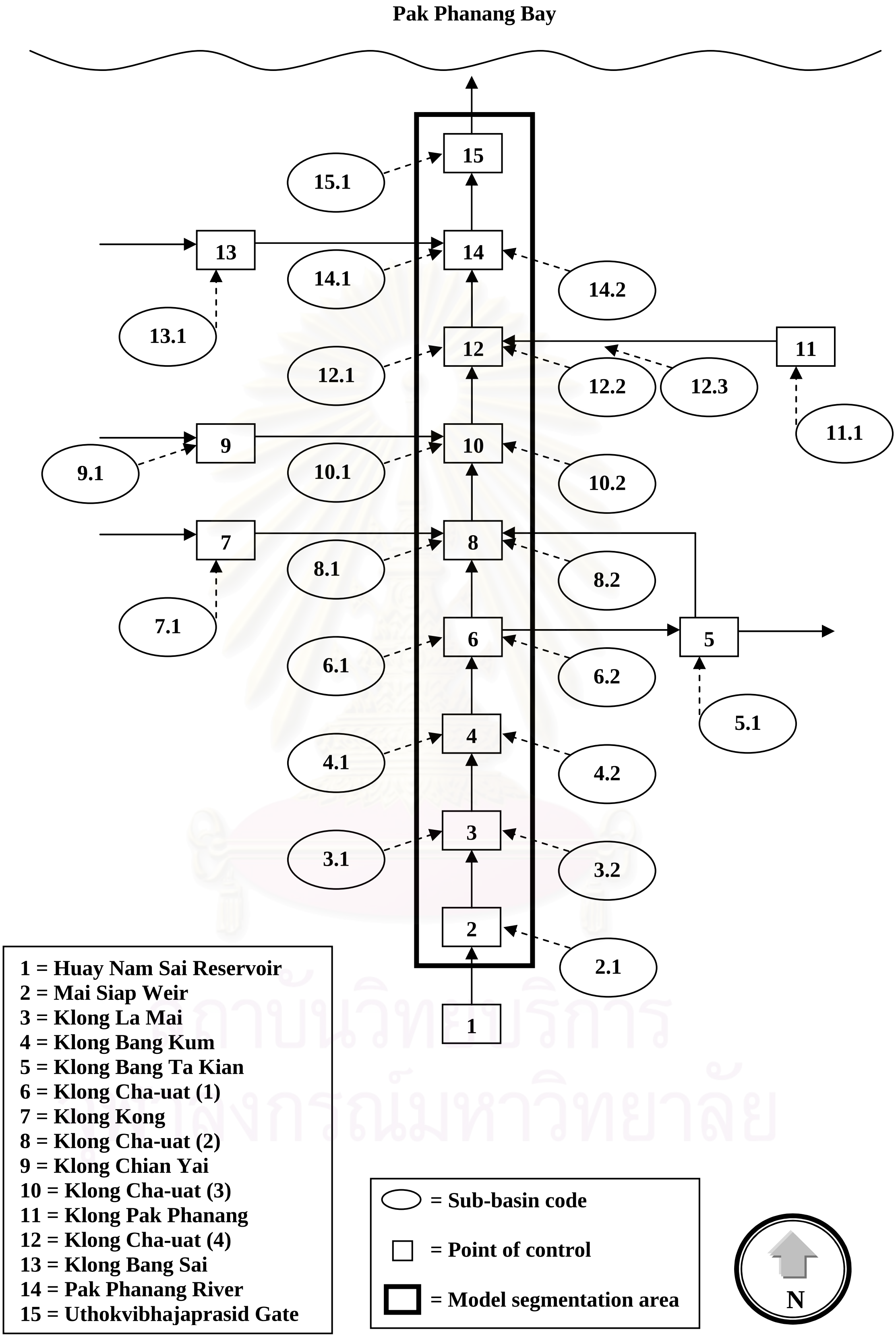


Figure 3.12: Schematic of Pak Phanang River sub-basin

Table 3.10: Summary of total runoff loading

Sub Basin	Description	Area (km^2)	Rainfall Runoff (m^3/sec)	Loading (kg/day)		
				BOD	TN	TP
2.1	Klong Mai Siap	36.7	0.92	3.52	1.89	0.13
3.1	Klong La Mai	59.0	1.39	5.32	2.85	0.19
3.2	Klong Cha-uat (1)	148.0	3.68	14.09	7.54	0.52
4.1	Klong Bang Kum	258.6	5.78	22.14	11.85	0.81
4.2	Klong Cha-uat (2)	145.6	3.4	13.02	6.97	0.48
5.1	Klong Bang Ta Kian	36.6	0.88	3.87	1.56	0.16
6.1	Klong Cha-uat (3)	54.2	1.31	5.76	2.32	0.24
6.2	Klong Cha-uat (4)	18.6	0.45	1.98	0.80	0.08
7.1	Klong Khong	227.0	5.52	21.14	9.77	0.99
8.1	Klong Cha-uat (5)	13.5	0.34	1.30	0.60	0.06
8.2	Klong Cha-uat (6)	65.1	1.66	6.36	2.94	0.30
9.1	Klong Chian Yai	138.0	3.63	38.48	8.06	1.71
10.1	Klong Cha-uat (7)	41.8	1.12	11.87	2.49	0.53
10.2	Klong Cha-uat (8)	40.3	1.08	11.45	2.40	0.51
11.1	Klong Pak Phanang	70.4	1.81	19.19	4.02	0.85
12.1	Klong Cha-uat (9)	21.0	0.58	2.22	1.55	0.24
12.2	Klong Cha-uat (10)	26.8	0.73	2.80	1.96	0.31
12.3	Klong Ban Klang	63.7	1.69	7.44	2.99	0.30
13.1	Klong Bang Sai	120.0	3.21	12.29	8.60	1.35
14.1	Klong Cha-uat (11)	13.9	0.37	1.42	0.76	0.05
14.2	Klong Cha-uat (12)	35.7	0.95	3.64	1.95	0.13
15.1	Pak Phanang River	26.4	0.74	2.83	1.52	0.10

Aquaculture is the critical source of water pollutant in Pak Phanang River basin. Shrimp farms were found along the riverside and coastal area. Shrimp farms in Chian Yai and Pak Phanang districts release wastewater into Pak Phanang River. Table 3.11 lists the waste water generation rates and loading coefficients suggested by Pollution Control Department (2002). The values for South–East region were used in this study. In addition, Pollution Control Department (2002) also suggested that wastewater discharge is 25 percents of wastewater generated from shrimp farm. Loading from shrimp farms for each district could be calculated from the Equation 3-35 and 3-36. Table 3.12 lists the calculated loading from shrimp farming.

$$\underset{(m^3/day)}{\textbf{Wastewater Discharge}} = \underset{(rai)}{\textbf{Shrimp Farm Area}} \times \underset{(m^3/rai/day)}{\textbf{Wastewater Generation Rate}} \times \textbf{0.25} \qquad \text{---(3-35)}$$

$$\underset{(kg/day)}{\textbf{Loading}} = \underset{(rai)}{\textbf{Shrimp Farm Area}} \times \underset{(kg/rai/day)}{\textbf{Unit Loading}} \times \textbf{0.25} \qquad \text{---(3-36)}$$

Table 3.11: Wastewater generation rate from shrimp farm in various regions of Thailand

Region	**Wastewater Generation Rate (m^3/rai/day)**	**Unit Loading (kg/rai/day)**			
		BOD	**NH_3–N**	**TP**	**TKN**
Center	9.90	0.101	0.020	0.004	0.068
East	12.00	0.108	0.020	0.004	0.075
South–East	28.00	0.234	0.075	0.007	0.198
South–Andaman	21.00	0.139	0.020	0.004	0.057

Source: *Pollution Control Department, 2002*

Table 3.12: Summary of shrimp farm loading

Source	**Area(1) (rai)**	**Wastewater Discharge (m^3/day)**	**Loading (kg/day)**			
			BOD	**NH_3–N**	**TP**	**TKN**
Chian Yai	3,873	27,111	226.57	72.62	6.78	191.71
Pak Phanang	17,742	124,194	1,037.91	332.66	31.05	878.23

Source: *(1) Office of Fisheries–Nakorn Si Thammarat Province, 2002*

The total effect of CBOD and NBOD has been modeled on occasion as total BOD (= CBOD + NBOD) but this is not recommended for waste load allocations because of the difficulty in forecasting total BOD (Ambrose et al., 1990). WASP also requires BOD to be input as CBOD. Thus, all the BOD estimates were converted to CBOD by using a conversion factor of 1.5, i.e. CBOD = 1.5 BOD (Maryland Department of Environment, 2003).

3.3.4 Initial Conditions

The initial conditions used in the model were set as close to the observed values as possible. However, since the model was run for a long period of time (100 days) it was found that initial conditions did not impact the final results.

3.3.5 Kinetic Coefficients

Water column kinetic coefficients are universal constants used in this study. They are formulated to characterize the kinetic interactions among the water quality constituents. The initial values were taken from past modeling studies from Potomac River (Clark and Roesh, 1978; Thomann and Fitzpatrick, 1982; Cerco, 1985), Mattawoman Creek (Panday and Haire, 1985; Domotor et al., 1987), and the Patuxent River (Lung, 1993) as described in the modeling framework (section 3.1). The kinetic coefficients used for this study are listed in Table 3.13.

Table 3.13: EUTRO 6.0 kinetic coefficients

Constant	Value	Reference
Nitrification rate Temperature coefficient	0.15 day $^{-1}$@ 20^{0}C 1.08	Swan Creek, Town Creek
Denitrification rate Temperature coefficient	0.08 day $^{-1}$@ 20^{0}C 1.08	Manokin River, Swan Creek
Saturated growth rate of phytoplankton Temperature coefficient	2.0 day $^{-1}$@ 20^{0}C 1.08	Manokin River, Swan Creek
Endogenous respiration rate Temperature coefficient	0.1 day^{-1}@ 20^{0}C 1.045	Swan Creek, Town Creek
Nonpredatory phytoplankton death rate	0.01 day $^{-1}$	Manokin River, Swan Creek, Town Creek

Table 3.13: EUTRO 6.0 kinetic coefficients (continue)

Constant	Value	Reference
Phytoplankton Stoichometry Oxygen-to-carbon ratio Carbon-to-chlorophyll ratio Nitrogen-to-carbon ratio Phosphorus-to-carbon ratio	 2.67 mg O_2/mg C 30 0.25 mg N/mg C 0.025 mg PO_4-P/mg C	Transquaking River, Manokin River, Newport Bay, Northern Coastal Bay, Swan Creek, Town Creek
Half-saturation constants for phytoplankton growth Nitrogen Phosphorus	 0.025 mg N/L 0.001 mg P/P	Manokin River, Swan Creek, Town Creek
Fraction of dead phytoplankton recycled to organic Nitrogen Phosphorus	 1 0.5	Transquaking River, Swan Creek, Town Creek
Light Formulation Switch	1 (= Di Toro)	Transquaking River, Manokin River, Newport Bay, Northern Coastal Bay, Swan Creek, Town Creek
Saturation light intensity for phytoplankton	300 Ly/day	Swan Creek, Town Creek
BOD deoxygenation rate Temperature coefficient	0.2 day^{-1}@ 20^0C 1.05	Calibrated Manokin River, Swan Creek, Town Creek
Reaeration rate constant	0.5 day^{-1}@ 20^0C	Swan Creek, Town Creek
Mineralization rate of dissolved organic nitrogen Temperature coefficient	0.02 day^{-1} 1.08	Manokin River, Swan Creek, Town Creek
Mineralization rate of dissolved organic phosphorus Temperature coefficient	0.15 day^{-1} 1.08	Manokin River, Swan Creek, Town Creek
Dispersion Coefficient	0.06	Calibrated
Light extinction coefficient (Ke)	3.9 m^{-1}	Ke = 1.95/Ds where Ds = Secchi depth (m)

CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 Model Calibration

4.1.1 Dispersion Coefficient

The dispersion coefficient (E_x) for dissolved oxygen was calibrated for WASP 6.0 model using the average in-stream water quality data from Pollution Control Department 2003. The model was applied to several different dispersion coefficients under similar flow and loading conditions. For the model execution, water quality parameters at all boundaries were set to zero. The dispersion coefficient was reduced slightly until it does not affect to DO concentration on the previous segment of input loading. Final value of the dispersion coefficient is 0.06 m^2/s.

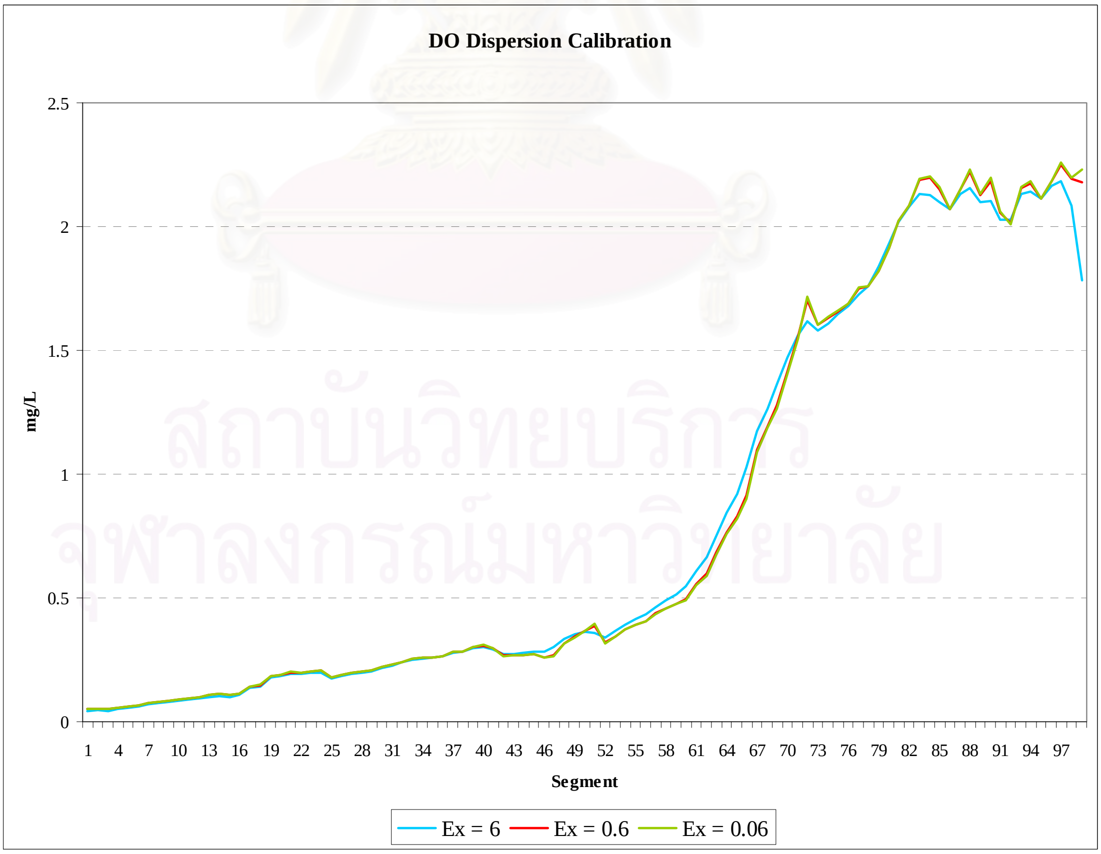


Figure 4.1: Results of the calibration for dispersion coefficient

4.1.2 Model Run Conditions

The model used average annual flow and waste loads of the stream. The upstream flow data was taken from Royal Irrigation Department (2003). The total non-point source load was calculated by summing all of the individual land use areas and multiplying by the corresponding land use coefficients based on the study of Pollution Control Department (2002). The land use information was based on 2001 land use planning data of Land Development Department. The annual flow runoff for Pak Phanang sub-basin was taken from the study of Office of Environmental Policy and Planning (2003). The considered districts which have shrimp farm activity are Chian Yai and Pak Phanang. The point source loads were determined using municipal wastewater loading coefficients based on the study of Pollution Control Department (2002). The three districts which direct municipal pollution loading to the river are Cha-uat, Chian Yai, and Pak Phraek (Pak Phanang). The industrial pollution loading was taken from the survey by Pollution Control Department 2002.

Under the above condition (condition 1), modeling results in DO level along Pak Phanang River was above the observed data. However, from field observation, it was found that DO levels always dropped after the follow passed the swamp forest. So load from swamp forest was hypothetical introducing to model execution (condition 2). As a result, the DO was more in line with the measured trend.

Furthermore, under condition 2, values of BOD deoxygenation rate constants (k_D) were investigated. Initially k_D = 0.1 day^{-1} was used as suggested in literatures. The increasing of BOD deoxygenation rate constants for 0.2 and 0.3 day^{-1} provided both DO and BOD modeling results close to the observed trend. Finally, the 0.2 day^{-1} value of the BOD deoxygenation rate constants was used for model execution. All of model results as discussed above were illustrated in Figure 4.2, 4.3, and 4.4.

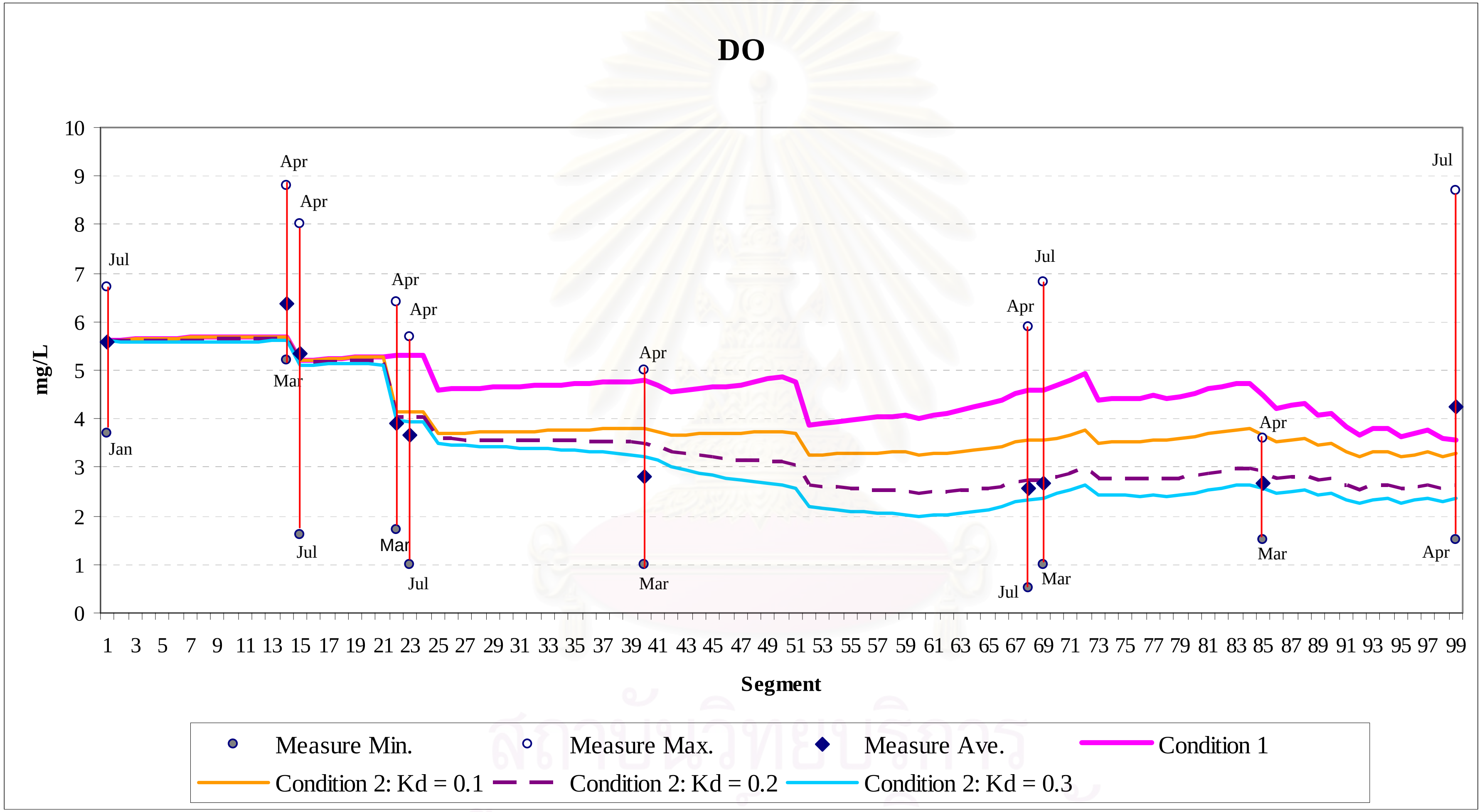


Figure 4.2: DO model results in average annual flow and waste loads during various conditions

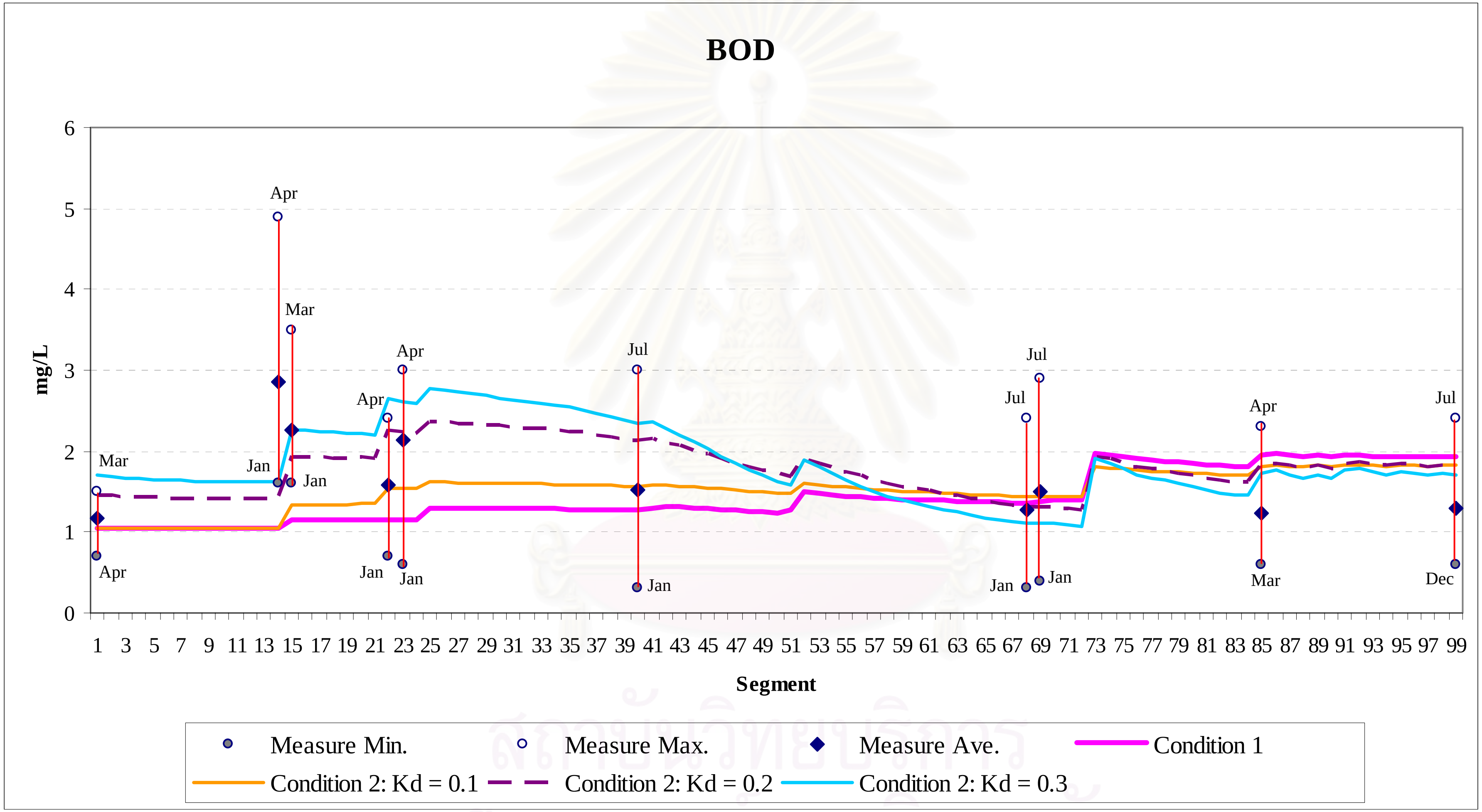


Figure 4.3: BOD model results in average annual flow and waste loads during various conditions

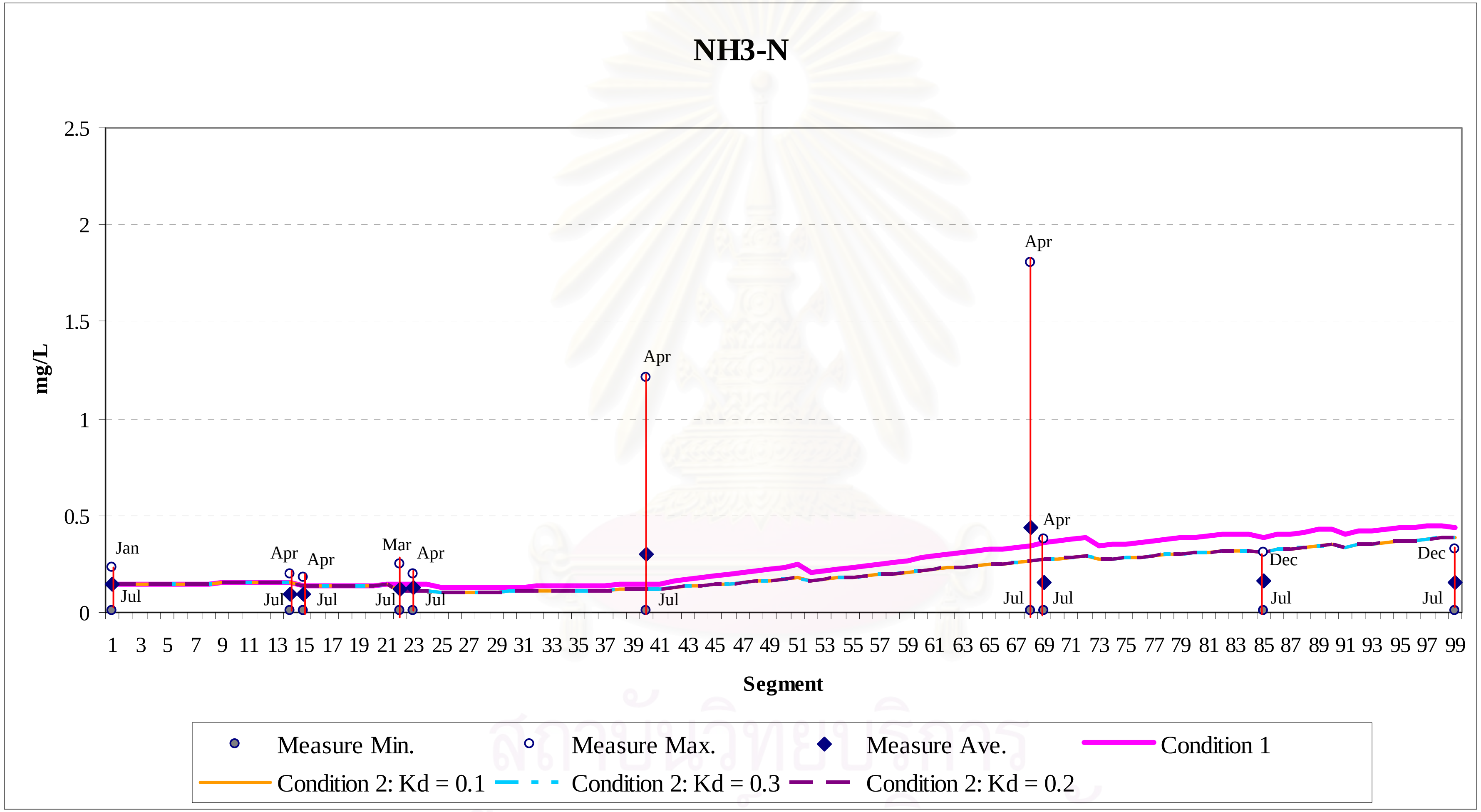


Figure 4.4: Ammonia-nitrogen (NH_3-N) model results in average annual flow and waste loads during various conditions

4.2 System Responses

The WASP 6.0 (EUTRO) model of Pak Phanang River was applied to predict the impacts of average annual organic waste load on DO under various treatment and stream flow conditions. The various scenarios were established to achieve the water quality goal of maintaining a DO concentration of 4 mg/L. It is important to note that the SOD was not considered in this study. Swamp forest loading was assumed with respect to the observed DO trend in the river.

4.2.1 Scenario Settings

The first scenario represents baseline conditions of the stream during average annual flow and waste loads of the year 2003.

The second, third, and forth scenarios represent cases where loads are reducing from the existing loads for 30, 60, and 80 percents during average annual flow of the year 2003.

The fifth scenario represents the case where loads are increased to the capacity of upstream river, during average annual flow and waste loads of the year 2003.

4.2.2 Scenario Results

All of the DO, BOD, and ammonia-nitrogen (NH_3-N) results in various scenarios were presented in Figure 4.5, 4.6, and 4.7 respectively.

The first scenario represents the expected condition for average annual flow, when water quality is impaired by low DO concentrations. It shows that almost DO and BOD along Pak Phanang River are not in line with class 3 water quality standard (over 4.0 mg/L and under 2.0 mg/L respectively). Nonetheless, all of ammonia-nitrogen (NH_3-N) was under the standard level through out the river.

The second scenario represents the treatment condition for 30 percents of existing loads. The BOD passed the water quality standard while DO still falls below the standard of 4.0 mg/L.

The third scenario represents the treatment condition for 60 percents of existing loads. It can be seen that DO level passed the desired goal of 4.0 mg/L almost part of the river.

The forth scenario represents the treatment condition for 80 percents of existing loads. The model shows that DO concentrations are above 4.0 mg/L through out the Pak Phanang River.

The fifth scenario represents the capacity of upstream river condition. The model shows that DO concentrations will be lower than 4.0 mg/L when the existing loads are multiplying by 7.

4.3 Loading Capacity of Pak Phanang River

This section presents the Loading Capacity (LC) of organic waste on Pak Phanang River. The organic wastes from point and non-point sources are composing with BOD, total nitrogen (TN) and total phosphorus (TP). From loading estimated in chapter 3 section 3.3.3, total existing loads can be considered as 2,978 kg/day.

The following LCs were developed on the basis of results from the WASP 6.0 simulation model. It should be noted that swamp forest loads were hypothetically considered in this study. Under the current loads, it was found that water quality for the most part of Pak Phanang River did not meet the standard of river class 3. Thus, the outcomes of LC analyses are presented in terms of annual average flow under several treatment conditions. It was desired to achieve a water quality goal of DO concentrations not below 4.0 mg/L.

Following the illustration in Figures 4.5 and 4.6, however, the 60 percents treatment of waste loads can achieve DO standard level for most part of the river (scenario 3). Besides, the achieved of BOD standard level was done by reduce waste loads for 30 percents treatment (scenario 2).

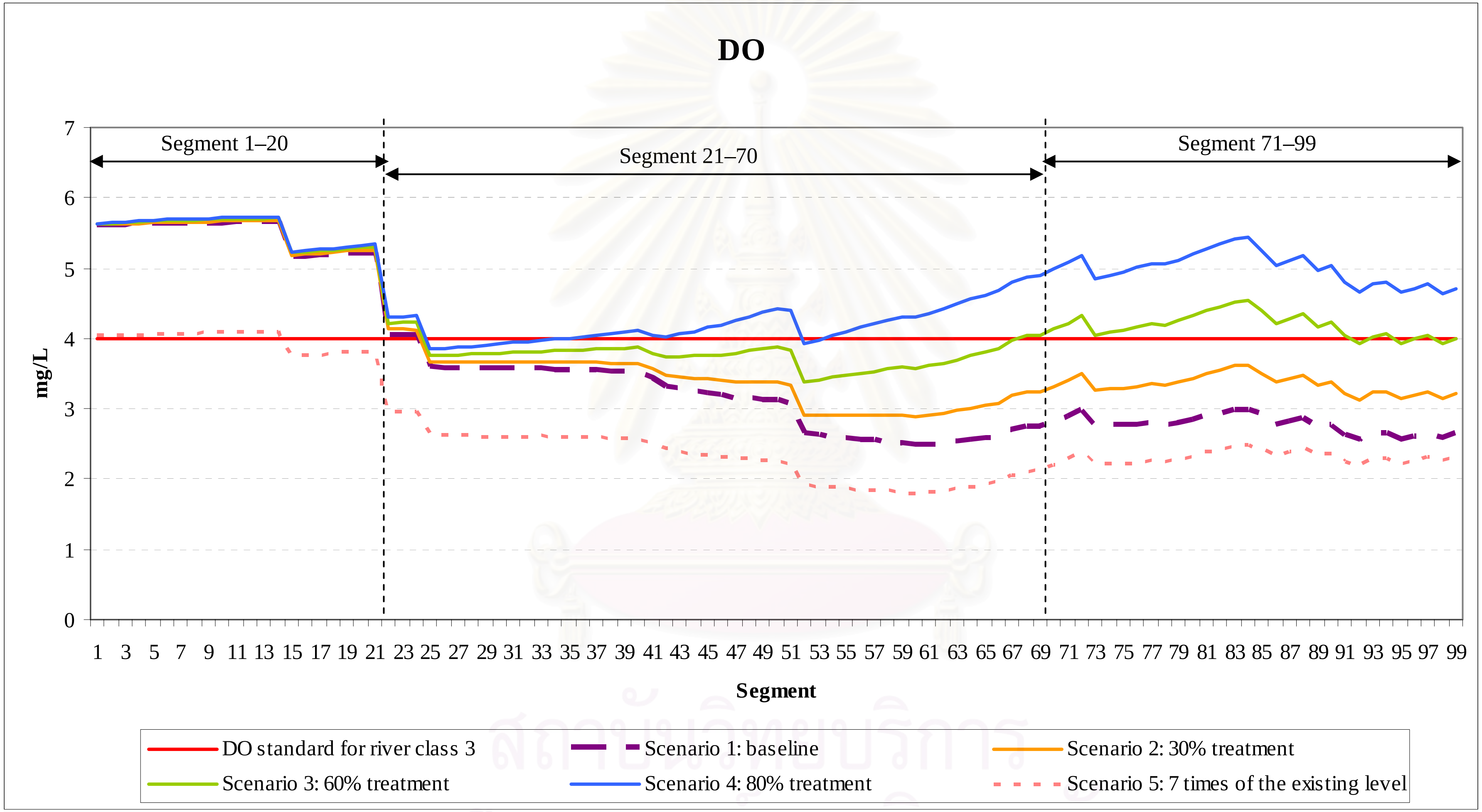


Figure 4.5: Model results for DO under various scenarios

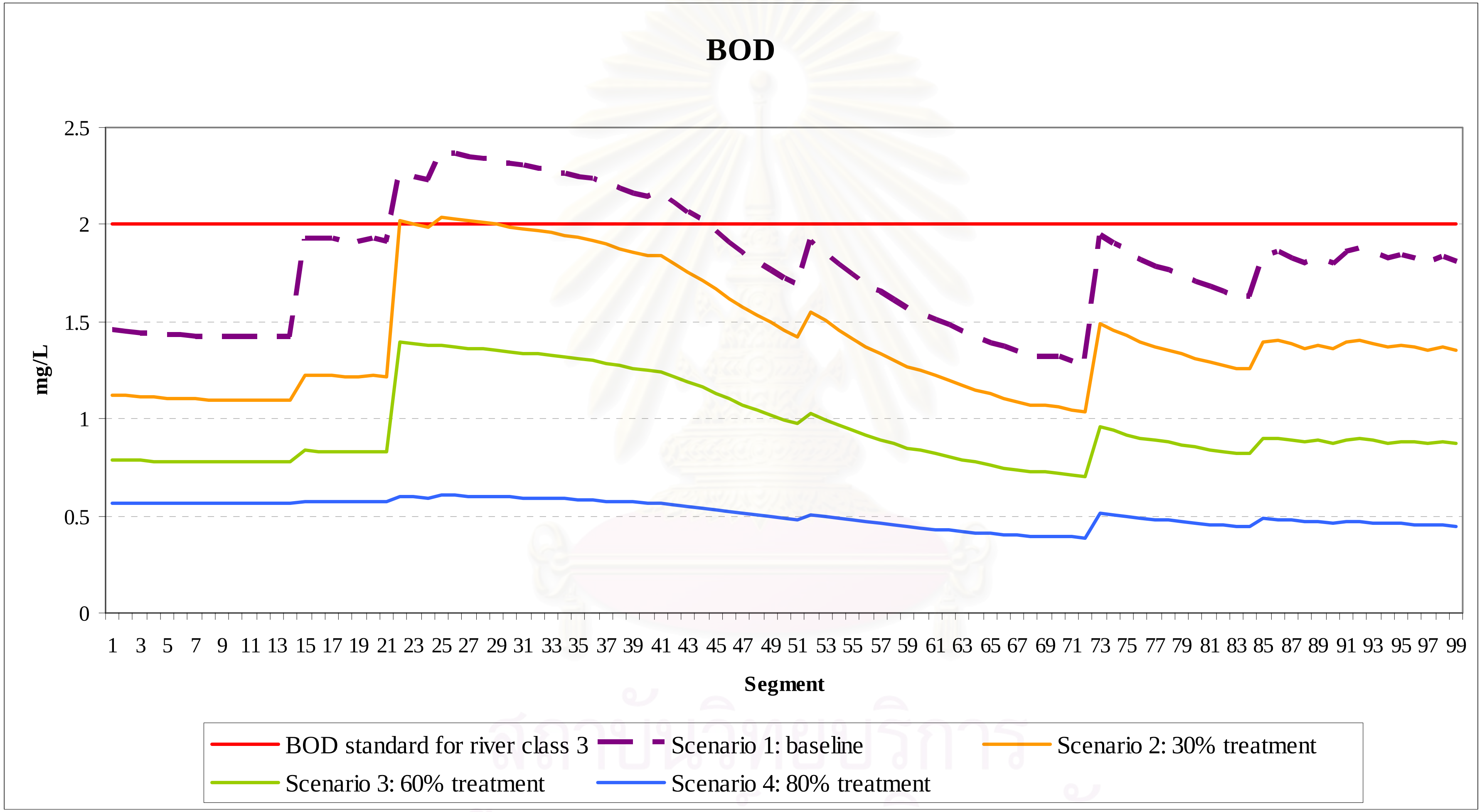


Figure 4.6: Model results for BOD under various scenarios

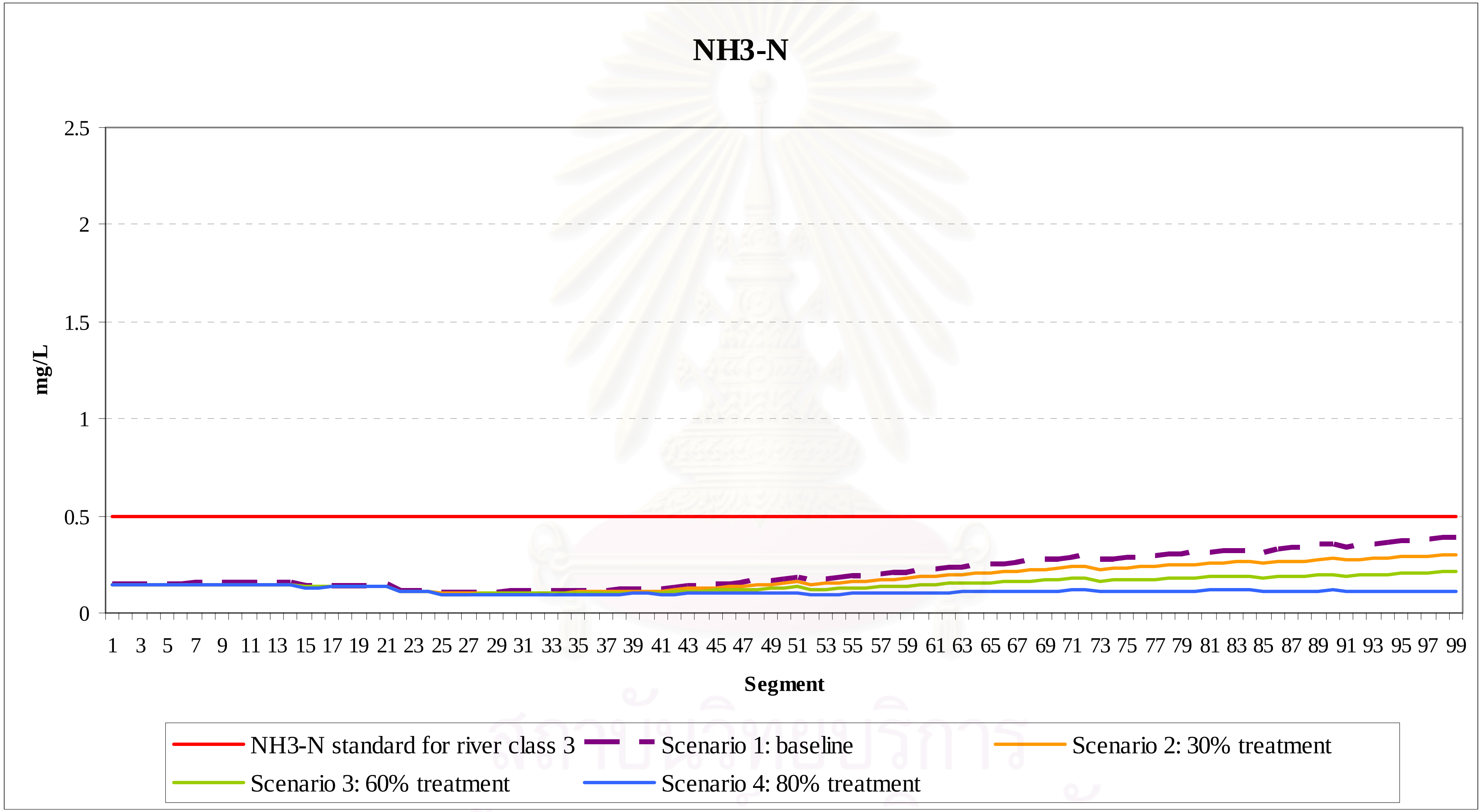


Figure 4.7: Model results for ammonia-nitrogen (NH_3-N) under various scenarios

From model results, it is possible to separate the river into 3 parts to use different scenario for achieving a DO concentrations above 4.0 mg/L. This study proposes the suitable treatment condition for each river part as followed.

For segment 1 – 20, from Mai Siap weir to Kuan Kreng swamp forest
no treatment is required and it can receive additional loads 7 times of the existing level (scenario 5):

Existing Load + Receiving Load = LC
147 kg/day + 1,028 kg/day = 1,175 kg/day

For segment 21 – 70, from Kuan Kreng swamp forest to Klong Chian Yai
80 percents treatment is required (scenario 4):

Existing Load – Reduction Load = LC
647 kg/day – 517 kg/day = 130 kg/day

For segment 71 – 99, from Klong Chian Yai to Uthokvibhajaprasid Gate
60 percents treatment is required (scenario 3):

Existing Load – Reduction Load = LC
2,185 kg/day – 1,311 kg/day = 874 kg/day

Hence, the total loading capacity of Pak Phanang River can be expressed as;

1,175 kg/day + 130 kg/day + 874 kg/day = 2,179 kg/day

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The WASP 6.0 (EUTRO) was used to forecast the water quality of Pak Phanang River under various conditions to maintain a DO concentration of 4 mg/L. The value of loading capacity of Pak Phanang River have been determined from average annual waste loads from point and non-point sources in the year 2002 to 2003. The study found that:

1) The loading capacity of the river from Mai Siap weir to Kuan Kreng swamp forest is 1,175 kg/day. It suggests that the upper part of the river can receive additional current organic waste loads.

2) The loading capacity of the river from Kuan Kreng swamp forest to Klong Chian Yai is 130 kg/day; therefore, it should reduce current organic waste loads in this section for 517 kg/day.

3) The loading capacity of the river from Klong Chian Yai to Uthokvibhajaprasid Gate is 874 kg/day; therefore, it should reduce current organic waste loads in this section for 1,311 kg/day.

4) The total loading capacity of Pak Phanang River is 2,179 kg/day while the existing load is 2,978 kg/day. That is possible, why the current water quality of the river was below the standard.

5.2 Recommendations

This study used WASP 6.0 (EUTRO) to forecast the water quality of Pak Phanang River under various conditions to maintain a DO concentration of 4 mg/L. Although the available data for model calibration was not sufficient, the parameter assumptions for model verification have been accomplished. In order to improve the simulation of model, some parameters should be added such as;

1) The value of sediment oxygen demand (SOD) along Pak Phanang River should be investigated because it is a significant factor to uptake the dissolved oxygen.

2) The wastewater characteristics from Kuan Kreng swamp forest should be determined because it is a significant factor to impair the dissolved oxygen concentrations.

3) The seasonal flow of pollution loads both point and non-point sources should be considered more because it is important to establish the waste load allocation on water quality management.

4) The flow effect of the regulators along the river should be regarded in addition because it is important to operate water level, water quantity, and salt water intrusion problem.

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APPENDICES

APPENDIX A

SURFACE WATER QUALITY STANDARDS

Table A-1: Classification and objectives

Classification	**Objectives/Condition and Beneficial Usage**
Class 1	Extra clean fresh surface water resources used for: 1. conservation not necessary pass through water treatment process require only ordinary process for pathogenic destruction 2. ecosystem conservation where basic organisms can breed naturally
Class 2	Very clean fresh surface water resources used for: 1. consumption which requires ordinary water treatment process before use 2. aquatic organism of conservation 3. fisheries 4. recreation
Class 3	Medium clean fresh surface water resources used for: 1. consumption, but passing through an ordinary treatment process before using 2. agriculture
Class 4	Fairly clean fresh surface water resources used for: 1. consumption, but requires special water treatment process before using 2. industry
Class 5	The sources which are not classification in class 1-4 and used for navigation

Table A-2: Pak Phanang River Water Quality Standard

Control Areas	Water Quality Standards (Same as Standards of Water Classification)
from river mouth to Maisieb Dam in Cha-ued, Nakhonsrithammarat Province	Class 3

Source: *Notification of Pollution Control Department, published in the Royal Government Gazette, Vol. 116, Part 72, dated September 9, B.E.2542 (1999).*

Table A-3: Surface water quality standard

Parameter	Units	Statistics	Standard Value for Class					Methods for Examination
			Class 1	Class 2	Class 3	Class 4	Class 5	
1. Color, odor, taste	-	-	n	n	n	n	-	-
2. Temperature	C^0	-	n'	n'	n'	n'	-	Thermometer
3. pH	-	-	n	5-9	5-9	5-9	-	Electrometric pH Meter
4. Dissolved Oxygen	mg/l	P20	n	6	4	2	-	Azide Modification
5. BOD (5 days, 20^0C)	mg/l	P80	n	1.5	2.0	4.0	-	Azide Modification at 20^0C, 5 days
6. Coliform bacteria								Multiple Fermentation Technique
- Total coliform	MPN/ 100 ml	P80	n	5,000	20,000	-	-	
- fecal coliform	MPN/ 100 ml	P80	n	1,000	4,000	-	-	
7. NO_3-N	mg/l	Max. allowance	n		5.0		-	Cadmium Reduction
8. NH_3-N	mg/l	-	n		0.5		-	Distillation Nesslerization
9. Phenols	mg/l	-	n		0.005		-	Distillation,4-Amino antipyrene
10. Copper (Cu)	mg/l	-	n		0.1		-	Atomic Absorption-Direct Aspiration
11. Nickle (Ni)	mg/l	-	n		0.1		-	Atomic Absorption-Direct Aspiration
12. Manganese (Mn)	mg/l	-	n		1.0		-	Atomic Absorption-Direct Aspiration
13. Zinc (Zn)	mg/l	-	n		1.0		-	Atomic Absorption-Direct Aspiration
14. Cadmium (Cd)	mg/l	-	n		0.005 * 0.05 **		-	Atomic Absorption-Direct Aspiration

Table A-3: Surface water quality standard (continue)

Parameter	Units	Statistics	Standard Value for Class Class 1	Class 2	Class 3	Class 4	Class 5	Methods for Examination
15. Chromium Hexavalent	mg/l	-	n		0.05		-	Atomic Absorption-Direct Aspiration
16. Lead (Pb)	mg/l	-	n		0.05		-	Atomic Absorption-Direct Aspiration
17. Total Mercury	mg/l	-	n		0.002		-	Atomic Absorption-Cold Vapour Technique
18. Asenic (As)	mg/l	-	n		0.01		-	Atomic Absorption-Gaseous Hydride
19. Cyanide (CN)	mg/l	-	n		0.005		-	Pyridine-Barbituric Acid
20. Radioactivity								Low Background Proportional Counter
- Alpha	Becqurel/l	-	n		0.1		-	
- Beta	Becqurel/l	-	n		1.0		-	
21. Total Organochlorine Pesticides	mg/l	-	n		0.05		-	Gas-Chromatography
22. DDT	µg/l	-	n		1.0		-	Gas-Chromatography
23. Alpha-BHC	µg/l	-	n		0.02		-	Gas-Chromatography
24. Dieldrin	µg/l	-	n		0.1		-	Gas-Chromatography
25. Aldrin	µg/l	-	n		0.1		-	Gas-Chromatography
26. Heptachlor & Heptachlorepoxide	µg/l	-	n		0.2		-	Gas-Chromatography
27. Endrin	µg/l	-	n		none		-	Gas-Chromatography

***Source:** Notification of the National Environmental Board, No. 8, B.E. 2537 (1994), issued under the Enhancement and Conservation of National Environmental Quality Act B.E.2535 (1992), published in the Royal Government Gazette, Vol. 111, Part 16, dated February 24, B.E.2537 (1994).*

Remark: *P* = *Percentile value*

n = *naturally*

n' = *naturally but changing not more than* 3^0C

* = *when water hardness not more than 100 mg/l as* $CaCO_3$

** = *when water hardness more than 100 mg/l as* $CaCO_3$

Based on Standard Methods for the Examination of Water and Wastewater recommended by APHA: American Public Health Association, AWWA: American Water Works Association and WPCF: Water Pollution Control Federation

APPENDIX B

SURFACE WATER FLOW

Table B-1: Surface water flow at Mai Siap weir (upstream flow)

Month	Average Flow (m^3/sec)
January	0.97
February	0.29
March	0.61
April	1.83
May	1.4
June	1.31
July	2.64
August	2.73
September	1.79
October	3.38
November	4.21
December	2.32
Annual	**1.96**

APPENDIX C

WATER QUALITY MONITORING STATIONS

Table C-1: Illustrated of water quality monitoring stations

Stations	Figures
PN 14 *Upper* *Mai Siap Weir*	
PN 13 *Lower* *Mai Siap Weir*	
PN 12 *Upper* *Cha-uad District*	

Table C-1: Illustrated of water quality monitoring stations (continue)

Stations	Figures
PN 11 *Lower* *Cha-uad District*	
PN 10 *Upper Kuan Kreng* *Swamp Forest*	
PN 9 *Kuan Kreng Swamp* *Forest*	
PN 8 *LowerKuan Kreng* *Swamp Forest*	

Table C-1: Illustrated of water quality monitoring stations (continue)

Stations	**Figures**
PN 7 *Upper* *Chian Yai District*	
PN 6 *Lower* *Chian Yai District*	
PN 5 *Pak Prake Temple*	
PN 4 *Upper* *Uthokvibhajaprasid* *Gate*	

Table C-1: Illustrated of water quality monitoring stations (continue)

Stations	Figures
PN 3 *Lower Uthokvibhajaprasid Gate*	
PN 2 *Ferry Port*	
PN 1 *Mouth of River*	

APPENDIX D

MODELS USED IN TMDL DEVELOPMENT

There are many models used in TMDL development. It can highlight a few specific models of interest that have been used to develop TMDL. (Frey and Hansen, 2002)

- ***WASP6***

Water Quality Analysis Simulation Program (WASP6) is a receiving water model that is used to assess the fate and transport of both conventional and toxic pollutants. It predicts concentrations of water quality parameters over time.

Used for: River, streams, lakes, reservoirs, estuaries, and coastal waters. The prediction of the fate and transport of organic chemicals (PCB, PAH, TCE, Dioxin), Metals (simple speciation).

Strengths: It has a track record of use for regulatory purposes. Model processes incorporate temperature, salinity, bacteria, DO-BOD, the nitrogen and phosphorus cycles, phytoplankton, and more.

Weaknesses: Does not handle mixing zones or near field affects, and sinkable or floatable materials.

For more information: For general information and a download of the new WASP update, visit: www.epa.gov/region4/water/tmdl/tools/wasp.htm. Trainings are available from EPA by contacting Tim Wool at wool.tim@epa.gov.

- ***AGNPS***

The Agricultural Non-point Source Pollution (AGNPS) model is a watershed-scale loading model. It is designed to evaluate non-point source pollution contributions from agriculture by comparing the pollution impacts of different conservation practices.

To be used for: Pollutants: sediment, nutrients, pesticides, and chemical oxygen demand.11 Situations: erosion, nutrient runoff, and chemical transport.

Strengths: Includes source accounting so pollutants can be tracked as they move through the watershed. Can model single, multiple, or diffuse sources as well as continuous or intermittent discharges. It can be linked to GIS software so it can present data in visual form.

Weaknesses: Is designed for agricultural watersheds only. Does not simulate subsurface soil processes so it only models above-ground processes like erosion on farmland, and doesn't track the water once it goes underground. It does not account for nutrient transformation and in-stream processes and does not address urban runoff issues.

For more information: Visit www.wcc.nrcs.usda.gov/water/quality/wst.html for more information on the AGNPS model, including a downloadable version and training materials.

- ***BASINS***

Better Assessment Science Integrating Point and Non-point Sources (BASINS) is an integrated model that includes both receiving water and watershed-scale loading models. It is a collection of existing models, packaged together with a graphical GIS-based user interface.

Best used for: Modeling nutrients, sediment, bacteria and toxics.

Strengths: Addresses both point and non-point source loadings. Includes the Non-point Source Model, which is a Windows interface of HSPF (described below), TOXI-ROUTE, and QUAL2E. Linked to GIS software so it can present data in visual form.

Weaknesses: TOXI-ROUTE uses simple dilution calculations and so may not be appropriate for complicated situations. However, QUAL2E can be substituted in these cases.

For more information: This model is free from U.S. EPA. Find the model, data, and support information at www.epa.gov/ost/basins/

- ***HSPF***

The Hydrological Simulation Program – FORTRAN (HSPF) model is a watershed-scale integrated model that allows you to calculate surface runoff and subsurface discharge of pollutants. It also models receiving water quality. HSPF is a dynamic model and has been applied extensively.

Best used for: Well mixed streams, rivers, lakes and reservoirs. Pollutants: nitrogen, phosphorus, pesticides, organics, and BOD-DO interactions.12

Strengths: Allows modeling of both pollutant load and water quality (concentration) in complex situations. Can model single, multiple, or diffuse sources as well as continuous or intermittent discharges. It is allow for evaluation of best management practices and design criteria.

Weaknesses: Should only be used for well-mixed rivers and reservoirs. Requires a lot of data in order to run, calibrate, and verify the model. Extensive water quality data is needed in order to calibrate and verify the model. Highly trained modelers are required.

For more information: Visit www.epa.gov/OWOW/watershed/tools/model.html#12 or water.usgs.gov/software/hspf.html

- ***QUAL2E***

The Enhanced Stream Water Quality Model (QUAL2E) is a receiving water model that can simulate multiple parameters in a branching stream system

Used for: Streams, rivers, lakes, reservoirs, and estuaries. Pollutants: dissolved oxygen, BOD, temperature, chlorophyll a, ammonia, nitrite, nitrate, organic N, organic and dissolved phosphorus, coliforms, and more.

Strengths: Has been in use for over two decades for waste load allocation studies and other management activities.

Weaknesses: This is a complicated model that can be cumbersome due to the need for extensive field data and many adjustments. The steady state version of QUAL2E assumes DO values do not vary over the day/night cycle so does not reflect in-stream reality. The dynamic version of the model is designed to account for diurnal DO swings, but is very complicated to set up and verify.

For more information: Download at www.epa.gov/OST/QUAL2E_WINDOWS/

- ***WARMF***

Watershed Analysis Risk Management Framework (WARMF) is an integrated model that predicts changes in water quality due to point and non-point source control, land use changes, and best management practices.

Used for: DO, bacteria, pesticides, algae, total P, total N, TOC, TSS, acid mine drainage pollutants.

Strengths: Data entry and results are based on a GIS-based graphical user interface. Include a module designed specifically for TMDL development, and a consensus module for facilitating stakeholder processes.

Weaknesses: A relatively new model, it has only been used for a few TMDL.

For more information: www.systechengineerng.com/warmf.htm

BIOGRAPHY

Kittiya Limpiponapaiboon was born on January 1, 1981 in Bangkok. She received a Bachelor degree of Science in Environmental Science, from Kasetsart University in 2002. In same year she entered a Master degree program at the Inter-department of Environmental Science, Graduate School of Chulalongkorn University.