WATER QUALITY MODELS IN RIVER MANAGEMENT

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Abstract

The concept of integrated watershed management is a holistic approach of understanding all the factors affecting the river system. The assimilative capacity, point sources and non-point sources pollution loads have to be measured or estimated and accounted for. The accounting tool for calculating the wasteload allocation, and better more, the total maximum daily loads (TMDLs) are water quality models. The use of water quality models in wasteload allocations is not a new concept, but their applications in the Malaysian watershed management are only recently. Most water quality models are used for wasteload allocation for the sustainability of the designated river water quality. To achieve the targeted water quality certain policy changes and the imperative cooperation of various government departments and agencies including but not restricted to local councils, Department of Environment (DOE), Department of Irrigation and Drainage (DID), Ministry of Housing and Local Government, Department of Forestry, Ministry of Agriculture and potable water companies. The policy changes needed would include the pollution load limits of point sources. There would be also the need to assess the non-point sources pollution of both urban and rural agricultural environment, and the necessity of pollution load assessment from the usually ignored sources such as hawkers, markets and untreated household sullage (greywater). There are many water quality models available for water quality managers – from the ones available in the public domain for free to the expensive ones where license has to be purchased annually. In all cases the water quality model users need to provide certain data such as water quality parameters, stream discharge, river hydrogeometry and pollution sources locations and loads. Water quality simulations from the calibrated model in the long run would help the managers to efficiently and effectively manage their respective rivers.

1. Introduction

Rivers and streams support many human usages including water supply for industries and domestic uses; recreational usages such as swimming and fishing; transportation mode and a means of waste disposal. The quality of river water is directly affected by the amount of waste discharged into the river and its assimilative capacity. The quality of river water also governs the extent to which the water can be used for other purposes such as for recreation or water supply. To better understand and manage the river, it is often helpful to use a water quality model.

Water quality modeling is the development of abstractions of phenomena of river systems. The main objective of river water quality modeling is to describe and to predict the observed effects of a change in the river system. The usual application of a water quality model is for forecasting changes in water quality parameters resulting from changes in the quality, discharge or location of the point or non-point input sources (Crabtree et al., 1986). Water quality models can be used to predict the characteristics of water quality conditions in aquatic systems in order to ensure the water quality objectives will be maintained under a wide variety of conditions. Models provide the ability to develop a credible and defensible water quality management program. They are continually being developed and improved to optimize the demands of environmental regulations and protection. There are a large number of available in the literature and the Internet, which can be used for water quality and wasteload allocation predictions.

Generally there are two types of water quality models; stochastic and deterministic models. Deterministic models attempt to simulate the natural processes of self-purification in a river system with each process modeled mathematically using derived parameters and rate constants. A deterministic model will predict a unique result from a specified set of input conditions without any consideration of the true relationship between the inputs and the predicted results. Meanwhile, stochastic or probabilistic models attempt to randomize error (Crabtree et al., 1986).

Both deterministic and stochastic models can be empirical or theoretical or both. An empirical model relates a water quality parameter to a specified output on the basis of past-observed empirical relationships while a theoretical model tries to represent mathematically the physical, chemical and biological processes affecting each water quality parameter. In the past, the most commonly used water quality models were theoretical deterministic type although the use of these models has been limited by the lack of understanding of some of the complex relationships

involved. Another constraint on the theoretical, deterministic models has been imposed by numerical methods. Models are generally limited to one dimensional, steady state conditions.

2. Development and Usage of Water Quality Models

Most of the early water quality modeling focused on the urban wasteload allocation problem. The earliest model for the Ohio River, Ohio, USA was developed by Streeter and Phelps (1925). This and subsequent modeling work provided a means to evaluate dissolved oxygen levels in streams and estuaries. Later research in surface water quality modeling indicated the dissolved oxygen sag model postulated was incapable of describing all the complexities of actual river systems. The nonavailability of computers during those years (1925 to early 1960s) limits the scope of the problems that could be addressed.

The presence of computers in the late 1960s led to major advances in both the models and the ways in which they could be applied. These advances involved numerical expressions of the analytical frameworks. Dissolved oxygen was still the main focus but modelers then could address more complicated kinetics and time-variable simulations.

In the 1970s, the focus on dissolved oxygen and wasteload allocations was shifted to a more general concern for the environment as society in general became more aware of the environment. The water quality issue during those years was eutrophication and modelers therefore broadened their horizon to include mechanistic representations of biological processes.

The major modeling advances in the late 1970s till now have been to recognize the role of solid matter in the transport and fate of toxicants. In particular, the associations of toxicants with the settling and resuspending particles represent a major mechanism controlling their transport and fate in natural waters.

Finally, the recent advancement of computer hardware and software rivals the initial advances made during the 1960s. Decision support systems (DSS) and graphical user interfaces facilitate the generation and visualization of the model output. Two and three-dimensional models with highly mechanistic kinetics can be simulated at a relatively reasonable cost (Chapra, 1997). Advances in the geographical information systems (GIS) such as ArcView and ArcGIS made the graphical interfaces and visualization of the modeling results easily interpreted, even by non-modelers.

3. Water Quality Usage in Malaysia

Although water quality models have been used by developed countries since early 1970s for water quality management, the usage in Malaysia is still patchy. Water quality models are sometimes required for certain environmental impact assessment (EIA) reports, especially if the development would create new point or non-point pollutant sources.

A river water quality model chosen by the Department of Environment (DOE) must be suitable for working in conjunction with the water quality monitoring system developed by the department. Other data from the DOE are necessary for the water quality model would be the pollution sources inventory within the river watershed as well as the discharge data, if available, from the Department of Irrigation and Drainage (DID). The calibrated and validated quality model for a particular watershed could be used to make predictions of the water quality resulting from any of the various combinations of flows and polluting discharges which might follow improved treatment of wastewater or the introduction of new discharges or abstractions.

Several legal amendments within the Environmental Quality Act, 1974 and procedural changes of the DOE operations would be needed to allow for the effective usage and application of water quality models in water and wastewater management. These changes include, but not limited to:

i) The need to amend the Environmental Quality (Sewage and Industrial Effluents) Regulations, 1979 for the requirement of unlisted critical parameters such as ammoniacal nitrogen to be included in the Third Schedule of the Regulation (Government of Malaysia, 1979);

ii) All industries are required to analyze its effluent for every quarterly (similar to requirements for the rubber and palm oil mills);

iii) The effluent discharge data (Q) also must be provided quarterly together with the effluent quality results;

iv) The effluent standards (A and B) would still be used but in parallel with pollutant load requirements instead of pollutant concentrations alone.

The above requirements would allow for the water quality model employed by the DOE to be accurately calibrated and at the same time the department could apply the "polluters pay principle" whereby industries would be charge on the basis of the amount of pollutant loads discharged into the river. The methodology, which was and is used by the United States Environmental Protection Agency (USEPA) allowed for

the gradual improvement of the river by reducing the total pollutant loads (total maximum daily load, TMDL) discharged it. A water quality model is therefore indispensable for the management of the river basin.

4. Case Studies in Malaysia Using QUAL2E/QUAL2K Water Quality Models

The QUAL2E model was developed by the United States Environmental Protection Agency (USEPA) for wasteload allocations, discharge-permit allocations, and other pollution evaluations. QUAL2E is applicable to well-mixed dendritic streams where the major transport mechanisms of advection and dispersion are only significant along the longitudinal axis of flow for a stream. Streamflow and input of waste loads are considered to be constant i.e. in steady state during the simulation period. The model can also be used to study the assimilative capacities of receiving streams and to identify non-point waste loads (Brown and Barnwell, Jr., 1987).

A river is represented in the QUAL2E model as a linked group of streams and tributary reaches that consist of headwaters (the beginning of a stream reach) and sequential strings of completely mixed reactors, which are referred to as computational elements. Within each reach, all the computational elements have the same average depth, stream slope, channel cross-section, and biological/chemical rate constants. The QUAL2E model calculates a flow and mass balance for each computational element.

The forcing function used for estimating transport is the stream discharge, which is assumed to be constant. Stream velocity, cross-sectional area, and depth are computed from streamflow. The QUAL2E model performs dissolved oxygen balance by including major source and sink terms in the mass balance equation. The nitrogen cycle is composed of four compartments: organic nitrogen, ammonia nitrogen, nitrite nitrogen, and nitrate nitrogen. The phosphorus cycle consists of dissolved phosphorus and organic phosphorus. Ultimate carbonaceous biochemical oxygen demand (cBOD) is modeled as a first order degradation process. The major source of dissolved oxygen is algal photosynthesis and atmospheric reaeration.

There are QUAL2E limitations that must be considered. These limitations become obvious during attempts to simulate conditions other than the steady state, constant effluent discharge for which it was developed. QUAL2E is also best suited for point sources discharges. The model is unsuitable for rivers that experience temporal variations or major discharges that fluctuate significantly over a diurnal period or even shorter time period (Shanahan et al., 1998).

4.1 Sg. Selangor

The study area is situated in the state of Selangor, north of Kuala Lumpur on latitude 03^0 40' N to 03^0 15' N, and longitude 101^0 14' to 101^0 47' (Figure 1) (DOE, 1994). Sungai Selangor flows from east to west, starting from the Titiwangsa Range, which forms the backbone of Peninsular Malaysia or West Malaysia. The Sungai Selangor watershed has a humid tropical climate as it is situated close to the equator. High temperature and humidity with relatively small seasonal variations characterize it. The watershed is subjected to two monsoon periods: the northeast monsoon from October to January and the southwest monsoon from May to September. The rainfall tends to peak during the monsoons with a larger peak during October to December. The inter-monsoon periods in February and July/August have the least rainfall. The average annual rainfall ranges from 2000 mm to 3500 mm (79 to 138 inches) (DOE, 1994).
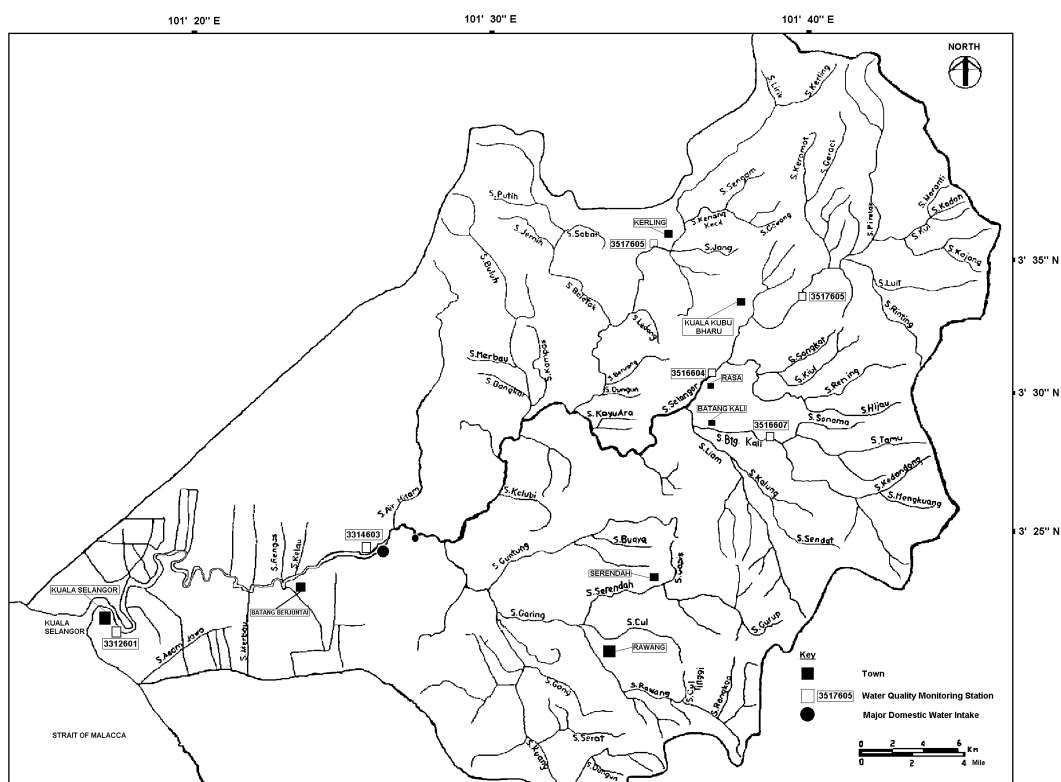

Figure 1. Sg. Selangor watershed, domestic water intakes and water quality monitoring station

Data used for the modeling process include discharge data from the Department of Irrigation and Drainage (DID) and water quality data from the Department of Environment (DOE). Before use the model must be calibrated and validated.

The calibration and validation process is critical to determine confidence in model simulations and the overall reliability of the calibrated model. Calibration is the process of adjusting or "tuning" the parameter values to obtain an optimal agreement between the simulated observed data. During model calibration, numerical values for each of the parameters, state variable initial condition, boundary conditions etc. must be supplied for the model.

Model validation is the process of assessing the degree of reliability of the calibrated model using one or more independent data sets data i.e. not the same data used for calibration. It is a process of testing whether the model meets the objectives stated. The calibrated model parameters are held constant (i.e. hydraulic conditions, climatic conditions etc.) and the independent initial and boundary conditions (stream water quality, headwater stream discharge) are entered into the model to simulate new conditions (Martin and McCutcheon, 1999).

Low-flow quantiles are used in water quality management applications such as waste-load allocations and discharge permits. Low-flow analysis allows water supply planning to calculate allowable water transfer and water withdrawals from a stream without causing detrimental effects to the ecosystem. Therefore, as water quality of a river is affected during low-flow periods, water quality models such as QUAL2E use the low-flow analysis for creating a worst condition scenario.

The commonly used low-flow index is the 7Q10, which is defined as the minimum 7-day flow that would be expected to occur every 10 years. This low-flow index is generally accepted as the standard design flow for water quality modeling (Chapra, 1997). The low-flow analysis for the Sg. Selangor at Rasa and Rantau Panjang gave the calculated low-flows at Rasa and at Rantau Panjang to be 3.93 m^3/s and 11.75 m^3/s respectively (Mohamed, 2000).

The calibrated and validated water quality model for Sg. Selangor could be used for the watershed and water quality planning and management. Hydrological changes such as the construction of the new dam would require the model to be re-calibrated and re-validated as the flow regimes would be altered.

4.2 Sg. Tebrau

Sg. Tebrau is located in the southern region of the state of Johor with a total area of 257.4 km^2. The downstream of the Tebrau catchment is highly developed while the middle and upstream portion is relatively less developed. The catchment has a rather unusual shape, starting with a narrow belt along the main river in the upstream to a wider river plain downstream (Figure 1). The topography in the downstream area is generally flat, but the middle and upstream of part of the catchment is characterized by undulating to hilly landscape.

A large portion of the catchment comprises mainly rubber and oil palm plantations. However, the rapid development in Johor Bahru, have resulted in several of the plantations such as Ladang Mount Austin and Ladang Tebrau being converted into residential areas. There are also several industrial areas located in the catchment. Aside from the large and medium size industries in the industrial areas, there are also many other smaller factories and workshops located in housing areas through out the catchment.

Based on a preliminary estimate, the total population within the catchment is about a quarter million. The region is undergoing rapid development and over the last decade, the population growth has increased at the rate of about 4.5 percent per year. Most of the population is concentrated in the lower portion of the catchment. Besides townships and housing estates, settlements also include traditional villages and squatters. The major settlements in the catchment are Johor Bahru and its suburbs in Mukim Plentong and Mukim Tebrau. There are also several smaller rural settlements such as Kg. Maju Jaya, Kg. Sinaran Baru, and Kg. Seelong located to the north.
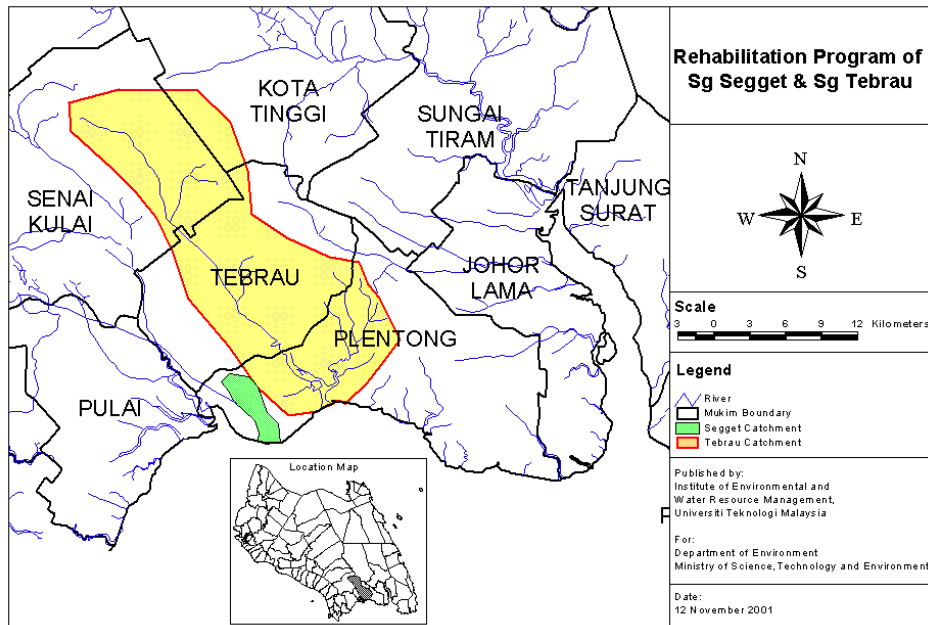
The Catchment of Sg Segget and Sg Tebrau

Figure 2: Location of Sg. Tebrau Watershed

The water quality results indicate that the river is highly polluted with organic pollution from partially and untreated sewage. Dissolved oxygen levels are very low in the mainstem Sg. Tebrau, as well as in the tributaries such as Sg. Bala, Sg. Pandan, Sg. Tampoi and Sg. Sebulung while BOD and COD concentrations are very high in the range of 30-50 mg/L of BOD. Ammoniacal nitrogen, which is an indicator of human waste pollution, also exists in high concentrations up to 10.3 mg/L at Sg. Plentong. Fecal and total coliforms are also at very high levels that surpass the upper limit of detection (200,000 MPN/100 mL) at the analytical laboratory.

Sg. Tebrau is basically split into a freshwater and a brackish zone is due to the physical division by the Public Utilities Board, Singapore (PUB) barrage. The freshwater zone is considered "clean" using the WQI classification and could be classified as Class II using the Interim National Water Quality Standards (INWQS), while the brackish water zone is considered "polluted" using the WQI classification and could be classified as Class V using the INWQS.

The data from the DOE stations were analyzed to give a better overall water quality condition of the river. In the interpretation of water quality data it is important to understand the spatial trend of parameters such as dissolved oxygen (DO), biochemical oxygen demand (BOD) and chemical oxygen demand (COD). These

spatial trends are especially important for water quality modeling, as it will roughly indicate the assimilative capacity of the river.

Figures 3 to 4 show the DO and BOD concentrations for Sg. Tebrau indicated a general trend of high DO/low BOD condition in the upper, freshwater stations (Station Nos. 1636612, 1537613, 153760) and low DO/high BOD condition for the brackish, estuarine station (Station No. 1537609).

The trends indicated that Sg. Tebrau pollution and pollution sources tend to concentrate in the saline estuarine zone, which is consistent with dense, urbanized nature of the area. The upper reaches of Sg. Tebrau consist of oil palm plantations, traditional villages, a few planned housing areas, orchards, secondary forests, a golf course and industries without or with minimal wastewater effluents. The high BOD concentrations at the brackish, estuarine zone are also consistent with the poorly treated sewage from the housing areas nearby, which rely mostly on rarely desludged septic tanks (Mohamed et al., 2003).
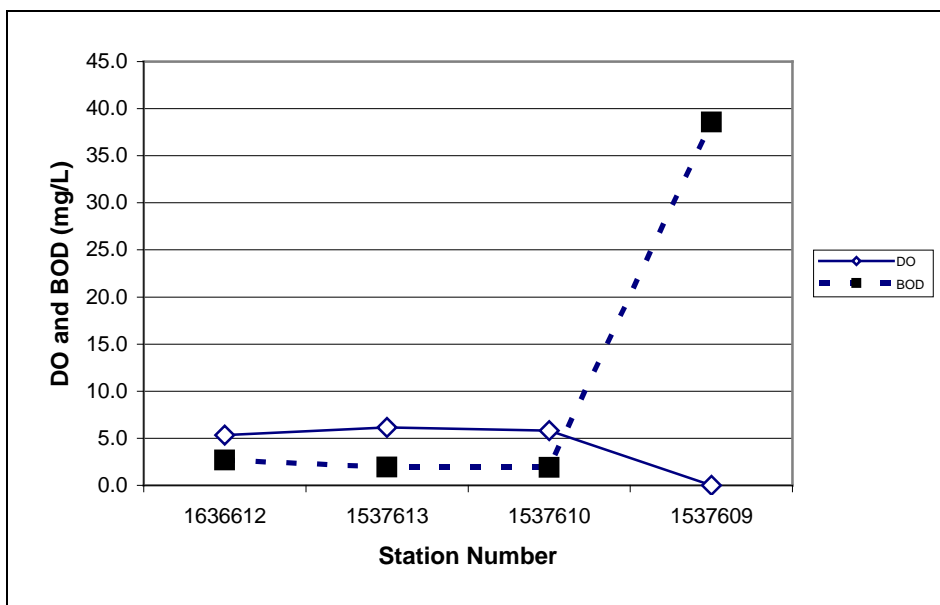

Fig. 3: Sg. Tebrau: Dissolved Oxygen and Biochemical Oxygen Demand Upstream to Downstream Trend for November 1997
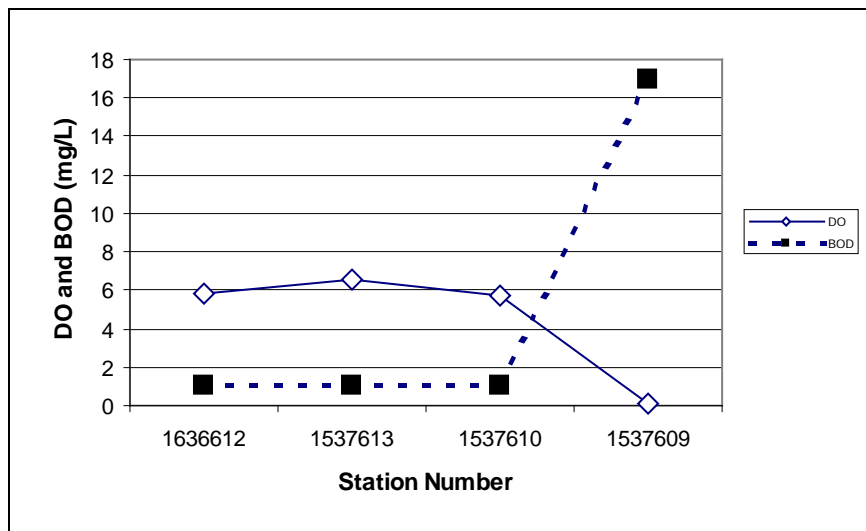
Fig. 4: Sg. Tebrau: Dissolved Oxygen and Biochemical Oxygen Demand
Upstream to Downstream Trend for July 2001

The calibrated and validated water quality model for Sg. Tebrau was used to predict
the reduction needed to achieve the water quality standard desired. The Department
of Environment Water Quality Index Class Standard (Department of Environment,
1999) is used for comparison (Table 1).

Table 1: The Department of Environment Water Quality Index Classification

Parameter	Unit	Class				
		I	II	III	IV	V
Ammoniacal Nitrogen	mg/L	< 0.1	0.1 – 0.3	0.3 – 0.9	0.9 – 2.7	> 2.7
Biochemical Oxygen Demand (BOD)	mg/L	< 1	1 - 3	3 – 6	6 – 12	> 12
Chemical Oxygen Demand (COD)	mg/L	< 10	10 - 25	25 - 50	50 - 100	> 100
Dissolved Oxygen (DO)	mg/L	< 7	5 - 7	3 - 5	1 - 3	< 1
pH		> 7	6.0 – 7.0	5.0 – 6.0	< 5.0	> 5.0
Total Suspended Solids (TSS)	mg/L	< 25	25 - 50	50 - 150	150 – 300	> 300
Water Quality Index (WQI)		**> 92.7**	**76.5 – 92.7**	**51.9 – 76.5**	**31.0 – 51.9**	**< 31.0**

The wasteload allocation for Sg. Tebrau using the QUAL2E model indicated that to achieve Class III, about 78.8 percent of the BOD pollution load has to be reduced (26,154.38 kg/day)(Table 2). A total reduction of 84.5 percent of the BOD load (28,033.58 kg/day) is needed to achieve Class II standard (Table 3) (Department of Environment, 2002).

Table 2: Minimum BOD Pollution Load Reduction to Achieve Class III for Sg. Tebrau

Type of Load	Load (kg/day)
Total pollution load used for modeling	33,186.34
Class III Load	7,031.97
Load Reduction needed	26,154.38
Percent Load Reduction	**78.8%**

Table 3: Minimum BOD Pollution Load Reduction to Achieve Class II for Sg Tebrau

Type of Load	Load (kg/day)
Total pollution load used for modeling	33,186.34
Class II Load	5152.77
Load Reduction needed	28,033.58
Percent Load Reduction	**84.5%**

5. Conclusion

Water quality models are indispensable tools in an integrated watershed management. As part of a decision support system (DSS) the modeling process would assist decision makers in carrying out day to day task as well as for policy changes. It is recommended that the government of Malaysia, especially relevant federal and state agencies such as the Department of Environment (DOE) and relevant agencies, needs to incorporate the use of water quality models at all department levels.

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