A Water Quality Study of the Selangor River, Malaysia

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ABSTRACT

Malaysia's rapid economic and demographic development has put pressures on its water supplies and consequently on the quality of its river water. The Selangor River, close to the nation's capital, is now a major source of water and there are fears that its water quality will deteriorate. The Malaysian Government in its Vision for Water 2025 states that rivers should achieve Class II as measured by Malaysia's Water Quality Index (WQI) (Class I is cleanest). The objectives of this thesis are to investigate the effects of flow through the 10 major tidal control gates (TCGs) which regulate run-off from the oil-palm plantations into the river, and to predict the water quality for the river in 2015, 2020 and 2030. In order to achieve these objectives it was necessary to set-up, calibrate and validate a commercial one-dimensional numerical model, InfoWorks, which includes both the hydrodynamics and water quality of the river-estuary network. It was concluded that there was insufficient hydrodynamic (stage and current) and water quality data to fully calibrate and validate the InfoWorks model but it performed well when compared with measured salinity transects. The model was found to be relatively insensitive to the choice of diffusion parameters but needed a high value for the oxygen transfer velocity, 0.3 m h^{-1}, to get reasonable values for the dissolved oxygen (DO) along the river. The effect of run-off through the TCGs was less than expected and attributed to the high oxygen transfer velocity and needs to be addressed before the model can properly represent run-off through the TCGs. The model shows the WQI of the lower reaches of the river to be Class III in both wet and dry seasons except close to the estuary where it is Class II due to tidal flushing. The dissertation identifies several deficiencies in the model; the lack of an operational ramp function at the estuary boundary, the use of a single value of the oxygen transfer velocity throughout, and the exclusion of water extraction. Land-use changes above Rantau Panjang, the upper boundary of the InfoWorks model, and water quality data were used to estimate the water quality and its uncertainties at Rantau Panjang in 2015, 2020 and 2030 due to predicted development in the upper catchment for both wet and dry seasons. InfoWorks models of water quality along the river in 2015, 2020 and 2030, which included extraction at the Batang Berjuntai barrage, predict little change in the WQ (Class II/III boundary) below the barrage during the dry season but a rapid deterioration in the wet season (down to Class III/IV by 2030) showing the importance of water extraction to the water quality of the river. Overall, because of its relative simplicity and ease of operation, InfoWorks is considered to be a useful tool for river management in Malaysia.

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LIST OF SYMBOLS/TERMINOLOGY

BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DID	Department of Irrigation and Drainage
DO	Dissolved Oxygen
DOE	Department of Environment
InfoWorks RS	InfoWorks River Simulation
IRBM	Integrated River Basin Management
IWK	Indah Water Konsortium Sdn. Bhd.
KeTTHA	KementerianTenaga, Teknologi Hijaudan Air (*Ministry of Energy, Green Technology and Water*)
LUAS	Lembaga Urus Air Selangor (*Selangor Water Management Authority*)
NAHRIM	National Hydraulic Research Institute of Malaysia
NH_3-N	Ammoniacal nitrogen
NRE	Ministry of Natural Resources and Environment
NO_2-N	Nitrite as nitrogen
NO_3-N	Nitrate as nitrogen
NWQS	National Water Quality Standard
RF	Rainfall
TCGs	Tidal Control Gates
TKN	Total Kjeldahl nitrogen
TSS	Total Suspended Solids
USACE	United States Army Corps of Engineers
WQI	Water Quality Index

CHAPTER 1

INTRODUCTION

1 The demand for water in Malaysia

The demand for fresh water is increasing in many parts of the world, primarily as a result of population growth and socio-economic development. The world's population, currently estimated at 7.2 billion (US Census Bureau, 2010) and growing by some 77 million people each year (United Nations Population Fund, 2003), is projected to increase the demand for freshwater by 64 billion cubic metres a year. Yet 90% of the population growth of the three billion expected by 2050 will be in developing countries, many in regions which already are water-scarce. In Malaysia alone, with an annual growth rate of 2% (Department of Statistics, 2007) the domestic and industrial water demand is expected to increase more than 20% in 50 years (Embassy of Denmark, 2009); the domestic demand will rise from 5.6 million m^3 per day in 2000 to 16.2 million m^3 in 2050 and the industrial demand from 3.9 million m^3 per day in 2000 to 15.5 million m^3 per day in 2050 (Embassy of Denmark, 2009).

Most of the water currently used comes from surface water sources. Malaysia at present is highly dependent on the surface water which comes from more than 150 river systems and contributes more than 90% of the total national water supply (Department of Statistics, 2007). As reported by Malaysian Department of Statistics (2007), until 2005 raw water supply in Malaysia as a whole increased at the rate of about 30% (about one billion m^3) annually, while Selangor State, which has a population growth rate of about 6% (Department of Statistics, 2001) consumed 576 million m^3yr^{-1} of water for domestic purposes and 261 million m^3yr^{-1} for non-domestic uses. The production capacity is estimated to increase at a faster rate in the future (Department of Statistics, 2007). The increasing water demand which parallels the population growth not only puts pressure on water sources but also results in more sewage discharge and industrial/agricultural contaminants which can finally drain into the river systems. Can the river systems, a major source of water, adequately continue to provide good quality water for the people of Malaysia?

People in Selangor State need clean water. Almost all the four million people in Selangor rely on rivers for their drinking supply. Public water companies draw water from reservoirs on different river intakes of which many are located in northern Selangor. Among the seven major rivers in the Selangor State (Figure 1-1), the Selangor River has nine water intake points and has become the main water source for the State of Selangor, the Klang Valley and Kuala Lumpur, providing 60% of water supply. It supplies two thirds of the industrial and domestic water needs within Selangor and Kuala Lumpur.

Water extraction from the Selangor River began in the 1990's (Department of Irrigation and Drainage, 2007a) and occurred in three phases. Initially the Sungai Tinggi Dam (reservoir capacity 103 x 10^6 m^3) and a water treatment works with a capacity of 950 million litres per day (11 m^3s^{-1}) were constructed; later the water treatment capacity was expanded to 22 m^3s^{-1}. Following the construction of the Selangor Dam (reservoir capacity 235 x 10^6 m^3) the total treatment capacity increased to 35 m^3s^{-1} (Department of Irrigation and Drainage, 2007b). The majority of the water extraction takes place at the Batang Berjuntai barrage. In dry years, such as 1990 and 1998, the water extraction capacity can exceed the water yield; when the river flow is low the flow is supplemented with water from the reservoirs, although the flow into the downstream part of the rivers is still significantly diminished.

The demand for the water is continuing to grow and plans have now been made to transport water from the other side of the Titiwangsa mountain range through a 45 km tunnel from Pahang (KeTTHA, 2009) but this will only be sufficient for a few more years. Future projects to satisfy the water demand are at this stage still uncertain.

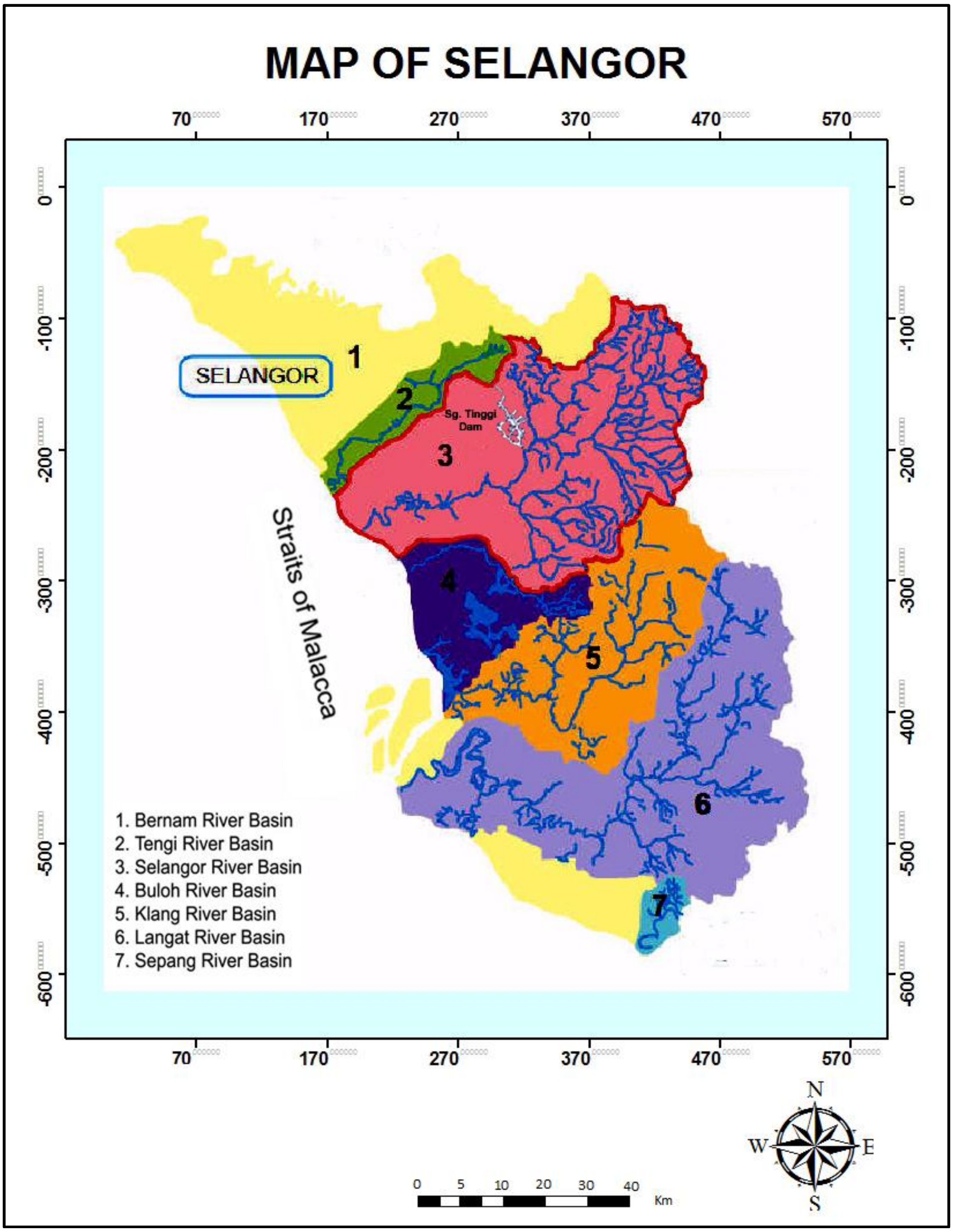


Figure 1-1: The river basins in Selangor State (source: LUAS, 2010)

Much of water flowing into the Selangor River comes from pristine corners of the State. Relatively untouched areas like the highlands area of the upper basin are home to the headwaters of hundreds of brooks and streams that fill aquifers and reservoirs across the state and eventually supply Selangor homes and businessess with valuable water. Pristine rivers also provide recreational opportunities, and important flora and fauna habitats. The upper Selangor River basin provides waterfalls, hot springs and also provides the world-renowned white water rafting, while the downstream areas have a natural wonder, the internationally-known firefly (*Pteroptyx tener*) colonies with their unique host trees (*Sonneratia caseolaris*). Part of the estuary is home to a number of large bird species like herons and endangered Milky Storks, as well as primates, namely silver leaf monkeys and macaques.

Unfortunately, Selangor River's most pristine waterways are becoming polluted. They face contamination from rapidly expanding developments. The quality of river water is often referred to as the 'pollution condition' and the 'health level' of the waters. Development within the river catchment can effect the water quality of the river systems. Land-use change and human activity have long been understood as the main contributors to many environmental issues including deterioration of river water quality. Hydraulic structures such as dams can block natural stream and river routes and reduce the volume of freshwater to lower reaches of rivers and estuaries. When that happens, the fresh and saltwater balance of the estuary is changed and the estuary can be seriously damaged. Development can damage or even destroy ecosystems. For instance, Yang et al. (2006) found that, with the increased number of dams being contructed in the Yangtze River catchment, the sediment supply to the sea decreased due to more sediment being deposited in reservoirs. As a result, the total growth rate of intertidal wetland in the Yangtze delta decreased from about 12 km^2yr^{-1} in the 1970s to 3.3 km^2yr^{-1} in 1998 (Yang et al., 2006). From data compiled by the Malaysian Department of Environment (DOE) in 2004, the overall trend points to a slow but steady deterioration in the water quality of rivers around Malaysia. Of the 120 rivers monitored, 9 rivers were categorised as 'highly polluted' and 53 as 'slightly polluted' (Department of Environment, 2005). A large percentage of the highly polluted rivers are located in highly urbanised or industrialised regions on the west coast of Peninsular Malaysia. In 2004 the DOE recorded 17,991 water pollution point sources comprising mainly of sewage treatment plants (54%), followed by manufacturing industries (38%), pig farms (5%) and agro-based industries (3%). Of the total number of effluent sources identified, Selangor State had the second highest number.

The Selangor River has experienced substantial changes in water quality. According to an analysis of the water quality for the rivers in Selangor River basin the water in the upper basin, which is surrounded by forest, is generally good but the quality starts deteriorating from Class II (defined by DOE as water 'requiring conventional treatment') to Class III ('extensive treatment required') in the middle and lower basins due to development pressures arising from converting areas into residential and industrial use (Ranhill Bersekutu Sdn Bhd and Sepakat Setia Consultant Sdn Bhd, 2002). Encroachment into tidal areas especially riparian reserves may become a major threat to sensitive ecosystems like the belt of firefly colonies' host trees that may spell the demise of the colony if trees are degraded and obliterated. Many people in the past thought tidal inlets or estuaries were 'waste land' and many were filled in and built on as pressure for land for growing food or housing increased as population grew. Estuaries are now amongst the most heavily populated areas throughout the world; 22 out of 32 largest cities in the world are located on estuaries (Ross, 1995). The Selangor River estuary is expected to be loaded with more pollutants due to on-going rapid urbanisation from the upper part of the basin and resulting in many environmental problems and conflicting interests of water users.

As the Selangor River catchment is adjacent to that of the Klang River (the Federal Territory of Kuala Lumpur and Putrajaya are situated on the Klang River) the pollution problems that occurred in the Klang River basin are a lesson to ponder. The status of the Klang River now lies between critical and bad (Class V). The Selangor State government had spent about RM50 billion on rehabilitation projects for the Klang River. It is estimated that the entire clean-up and rehabilitation of the 120 km long river will take 15 years to complete. A similar problem is potentially confronting the Selangor River basin which is the next intensive growth centre of the nation after the Klang basin. In the face of rapid growth, the State of Selangor faces the big challenge of accommodating new residents while preserving the natural resources that make Selangor a great place to live, including clean water supplies. The State should protect the water resources it already has while working to clean up waters that have been degraded.

1.1 Malaysian Vision for Water 2025

The Malaysian Government has fomulated the Malaysian Vision for Water 2025 as *"In support of Vision 2020 (towards achieving developed nation status), Malaysia will conserve and manage its water resources to ensure adequate and safe water for all (including the environment)"* and therefore the implementation of Integrated River Basin Management (IRBM) concept in both the Eighth Malaysian Plan (2001 to 2005) and the Third Outline Perspective Plan (2001 to 2010) was laid out to meet the challenges related to water resources beginning with the three rivers, including the Selangor River. The Ministry of Natural Resources and Environment is determined to increase efforts to ensure that water resources are managed efficiently and effectively for future prospects. Therefore, the water-related departments and agencies under the Ministry such as the National Hydraulics Research Institute of Malaysia (NAHRIM), is strengthening its research into understanding what controls the water quality of rivers and estuaries. One of the strategies is to upgrade the River Basin Decision Support System (RB-DSS), a computerised information system encompassing a number of databases, so that this database can function in an integrated manner in supporting the management of the country's river basins (Ministry of Natural Resources and Environment, 2005). However, the development of a database by itself will not be sufficient for sound management. There must also be development of good modelling and decision-making tools to aid in making choices and trade-offs. Besides the decision-making rules or guidelines and the procedures for taking action, one of the methods needed is predictive numerical modelling tools.

1.2 River water quality management in Malaysia

1.2.1 Organisation and legislation

The administration and management relating to river water quality in Malaysia currently involves a number of departments and agencies who operate independently of one another according to the specific responsibilities assigned to them. Figure 1-2 shows the organizational arrangement.

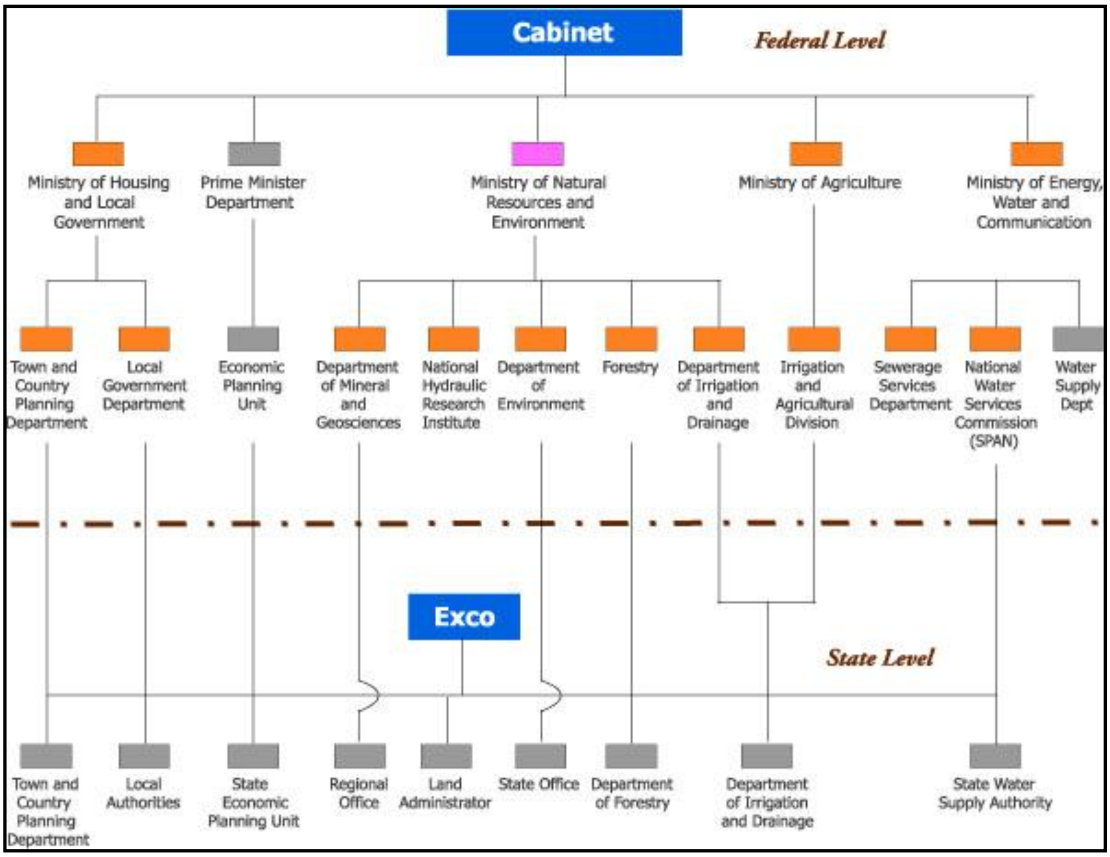


Figure 1-2: Water quality management structure in Malaysia. In 2009 the Ministry in charge of water supply became the Ministry of Energy, Green Technology and Water (KeTTHA)

The jurisdiction and legislative powers in all aspects of water are distributed between Federal and State Governments in accordance with Legislative Lists of the Federal Constitution. Items enumerated in the Federal List are: hydropower; navigation, maritime fisheries; estuarine fisheries (Peninsular Malaysia); factories, federal works and power including water supplies, rivers and canals except those wholly within one State or regulated by an agreement between States concerned. Items under the State List are: rivers; public nuisances; riverine fisheries and water (including water supplies, rivers and canals if they are wholly within one State). Table 1-1 shows the respective roles of each department/agency. In the past, there has been no single agency, State or Federal level entrusted with overall responsibility for holistic planning and management of water at river basin level. Conflicts involving water resource allocation, flood management, environmental protection, etc. are resolved mainly through ad-hoc inter-agency consultations. Therefore, the establishment of the National Hydraulic Research Institute of Malaysia (NAHRIM) in 1995 was approved during the Cabinet Meeting with the primary objectives to “*build a pool of experts and provide research service needed in planning, designing, building and implementing research related to development of water resources in particular and environment in general; and to set up as a National Focal Point that coordinate research on hydraulic engineering in Malaysia”* (NAHRIM, 2009). In addition, its function was documented in the “Ministerial Function Act 1969 (Minister of the Federal Government (No. 2) Order 2008) as follows:

i) to conduct basic and applied research in hydraulic engineering, coastal engineering, water resources and water quality for public and private sector;

ii) to provide experts/specialised consultancy services to public and private sectors;

iii) to co-operate with local universities and institutes in hydraulic engineering research;

iv) to function as Government advisor on matters relating to hydraulics, and

v) to act as the National centre in hydraulic engineering research and become the coordinator of all research in the country” (NAHRIM, 2009).

Table 1-1: water-related departments and agencies

Function	**Department/Agency**	**Role**
Water supply	Department of Irrigation and Drainage	Irrigation water source development. Monitoring stream flow and irrigation water supply
	Waterworks Department	Water supply source works. Treatment and supply of drinking water.
	Tenaga Nasional Berhad	Hydropower source works development. Use of water for hydropower.
Water Pollution Control	Department of Environment	Control of industrial pollutants
	Local authorities/Indah Water Consortium	Control and treatment of sewage

	Department of Irrigation and Drainage	Control of pollution from irrigation areas
	Mineral and Geoscience Department	Control of pollutants from mining operations
Water Quality Management	Department of Environment	Monitoring of water quality
	Fisheries Department	Prohibition of use of poisoning or destructive methods for fishing
	Chemistry Department	Analytical services on water samples monitored
	Department of Irrigation and Drainage	Planning, construction and maintenance of drainage works
Watershed Management	Forestry Department	Protection of forests. Watershed management within forest reserves
	Town and Country Planning Department	Land use planning and control
	Tenaga Nasional/Waterworks Department/ Department of Irrigation and Drainage	Protection of watershed upstream of reservoirs

1.2.2 National Water Quality Standards

In Malaysia river water quality management systems are monitored and controlled by Malaysian Department of Environment (DOE) which is responsible for providing the river classification standards called National Water Quality Standards (INWQS). Under these standards, there are 22 parameters that define the desired water quality for inland surface waters as listed in Appendix A. Accordingly, a river must meet all criteria of each applicable parameter 100% of the time to maintain its designated classification. The qualitative descriptions of water quality classifications (Table 1-2) are based on a series of qualitative indices and formulae developed by Mustafa (1981) and have been used as the National Quality Index for Malaysia.

Table 1-2: Water classes and their uses (National Water quality Standards, NWQS)

CLASS	DESCRIPTION
I	Conservation of natural environment Water Supply I (practically no treatment necessary), Fishery I (very sensitive aquatic species)
IIA	Water Supply II (conventional treatment required), Fishery II (sensitive aquatic species)
IIB	Recreational use with body contact
III	Water Supply III (extensive treatment required), Fishery III (common, of economic value, and tolerant species livestock drinking)
IV	Irrigation
V	None of the above

1.3 The importance of this study

Appropriate management strategies are needed to ensure that water supplies are adequate and the water quality is appropriate for the intended use. To evaluate potential management strategies for the basin, a robust computer model capable of simulating a wide variety of complex physical, chemical and biological processes is needed.

In addition to conducting important research into what controls the water quality of the lower reaches of the Selangor river, and making some predictions about the likely effects of industrial and urban developments in the upper reaches of the Selangor river in the next 15-20 years, this study is the one of the first steps in developing a decision support system which will help river authorities all over Malaysia to manage river basins and estuaries and to develop strategies for the management of the river water quality. Therefore, this study will be the foundation for other river basin studies mainly in providing useful information on cause-and-effect relationships in order to anticipate the limit of pollutant loads that can be assimilated by the river system based on Malaysian National Water Quality Standards and the relationship with the changes of development activities in the river basin. It is important that decisions on what to do in one part of a river basin should at least be based on knowledge of consequences for the river system, if not for the whole country.

A wide range of numerical models has been used to assess water quality in Malaysian rivers (Mohamed, 2001; Suliman, 2010) and numerical modelling appears to be useful tool for water quality management. However, the selection of the right model for a given management problem represents a hard task for decision makers: the more accurate and realistic the model, the more expensive is the monitoring programme needed to justify its use, and the more skill and experience that is needed to get the most from the model. The challenge has been to determine the optimal combination of project components that can provide maximum improvement at the best price. This study uses the commercial InfoWorks^{TM} river modelling suite, initially developed by HR Wallingford Ltd.

1.4 Research objectives

The overarching objectives of this thesis are

i) to set-up a one-dimensional hydrodynamic model of the Selangor River and its estuary, and calibrate it against measured data,

ii) to set-up a one-dimensional water quality model that integrates with the hydrodynamic model,

iii) to evaluate the effects of run-off from oil-palm plantations through the Tidal Control Gates (TCGs) on the water quality of the lower reaches of the Selangor River, and

iv) using data and estimates of future land use change, to estimate how severely the water quality of the lower reaches of the Selangor River will be the impacted by urban and industrial developments planned for the upper reaches (above the gauging station at Rantau Panjang) by 2015, 2020 and 2030.

The water quality results from the InfoWorks model simulations were classified quantitatively using Malaysia’s Water Quality Index (WQI), and into five levels of Malaysia’s national water quality class (Table 1-2).

1.5 Thesis structure

This thesis is divided into nine chapters.

The first chapter (**Chapter 1**) provides a general view of the research. The chapter begins with introduction to the topic of the research. This includes an explanation on the emerging water quality issue and the challenges that Malaysia is facing and how important this water quality study is for rivers in Malaysia. The river water quality management in Malaysia is then described, followed by defining the technical and scientific objectives of the research.

Chapter 2 describes some of the different ways that water quality in river basins and estuaries are regulated around the world, some of the numerical modelling tools that are available to assist in the management of river basins, and some of the very many studies that have been conducted around the world. The Chapter begins with Europe and the USA before moving on to tropical water quality modelling and studies in SE Asia. Finally previous experimental and modelling water quality studies in Malaysia and Selangor are described.

In **Chapter 3** a description of the InfoWorks™ modelling system is given. The equations in the model and the related water quality parameterisations are presented and discussed. The chapter also describes how the hydrodynamic and hydraulic components of the river model for the Selangor River were set-up, including the river cross-section and the catchments controlled by the tidal control gates.

Chapter 4 focuses on how the data for this study were collected and prepared for modelling of the Selangor River lower basin. This includes the description of the study area, the methodology used for water quality and quality assurance analyses. Primary data were collected during field trips, such as water quality measurements around the tidal control gates and at a number of locations along the river which provide input data and calibration data for the model.

Chapter 5 gives a description of the hydrodynamic model calibration which results in a realistic model of the water elevations in the estuary over spring and neap tidal cycles. The hydrodynamic calibration begins with the initial tidal stage set-up and is followed by calibration of the mixing processes using salinity as a conservative tracer.

In **Chapter 6**, the present water quality in Selangor River is analysed to know what the water quality is likely to be along the river in a typical dry and wet season during both spring and neap tides. Dissolved oxygen (DO) is the parameter used to calibrate and validate the InfoWorks™ water quality module by varying the re-aeration parameter. The impact of run-off of water from the plantations through the tidal control gates (TCGs) on river water quality is examined, and ‘worst case’ scenario (low-flow) analysis is also conducted.

Chapter 7 presents an analysis of the likely water quality in the Selangor River over the short term – 2015, mid-term – 2010 and long term – 2030. A model is constructed which uses GIS land-use maps for 1997, 2005 and 2008 together with concurrent water quality data to estimate the water quality entering the river at Rantau Panjang in 2015, 2020 and 2030 in the wet and dry seasons. A Monte Carlo method is used to estimate the uncertainties in the water quality parameters. The InfoWorks models are run for these scenarios to look at the change in WQI down the river; water extraction at the Batang Berjuntai barrage is also included.

The results of this study are discussed in **Chapter 8**. This includes a discussion of the findings and experiences from the study, and the limitations of the present research and the InfoWorks™ model and finally suggests further works which are required in in order to obtain reliable results for water quality along the Selangor River and to move towards a fully comprehensive management research tool suitable for this river and other rivers in Malaysia.

Chapter 9 gives a brief summary of the main results of this study and the overall conclusions of this study.

CHAPTER 2

WATER QUALITY MANAGEMENT AND MODELLING

2 Introduction

This chapter describes some of the ways that water quality is managed and modelled around the world and previous work that has been conducted, as well as detailing the more local water quality studies in tropical rivers in Southeast Asia that are relevant to the work that has been carried out in this dissertation. Water quality management is important in controlling water pollution and in river basin planning. Cohon (1978) referred to this as a large scale and complicated system, involving three components: the water system (quantity and quality), an economic system (national income and cost of waste water treatment), and a political system (equity and decision making). Water quality standards and regulatory environments differ around the world. There is also a wide variety of numerical models that have been used to simulate and predict water quality in rivers, estuaries and coastal seas. This review concludes with a description of the literature around river water quality management and research in Malaysia and summarises the research into water quality done in Selangor River and other Malaysian rivers and their major findings. A more detailed description of the Malaysian water quality regulation and standards are given in Chapter 1.

2.1 Water quality management and modelling in Europe

In Europe water quality is governed by the European Water Framework Directive (WFD) which looks at 30 measures of the water environment, grouped into a) chemical and b) ecological status; the WFD covers ground-water, lakes, rivers, estuaries and coastal waters. The WFD resulted from demands from European citizens and environmental groups for action to be taken to improve the quality of rivers, lakes and beaches. The WFR was finally adopted in 2000 (European Commission, 2000).

The European Commission (2012) gives a complete overview of the evolution of the EU Water Framework Directive. The purpose of the WFD is to establish a framework for the protection of inland surface waters (rivers and lakes), transitional waters (estuaries), coastal waters and groundwater and “ensure that all aquatic ecosystems and, with regard to their water needs, terrestrial ecosystems and wetlands meet 'good status' by 2015” (European Commission, 2000). It does not prescribe the acceptable levels of contaminants or combinations of contaminants but instead requires Member States to establish basin management plans for each river basin district and envisages a cyclical process where river basin management plans are prepared, implemented and reviewed every six years. The four distinct elements to the river basin planning cycle in the WFD are a) characterisation and assessment of impacts on river basin districts, b) environmental monitoring, c) the setting of environmental objectives and d) the design and implementation of the programme of measures needed to achieve them (JNCC, 2010).

There are a variety of models developed in Europe which allow water quality simulations to be made, varying from the 1-D InfoWorks model used in this thesis, to complex 2D and 3-D models such as TELEMAC (Hervouet, 2000), MIKE-21/3 (Geils et al., 2001) and DELFT3D (Roelvink and Van Banning, 1994) which are hydrodynamic models with water quality and flood-plain modules. Until recently these three latter models were only available commercially but recently components have become free-to-download. MIKE11 (DHI, 1998) is the 1-D equivalent of InfoWorks, including a hydrographic simulation engine, and can include hydraulic structures such as weirs, culverts bridges and sluice gates. It has been used extensively around the world including Thailand (Sriwongsitanon et al., 2003) and in the Cameron Highlands, Malaysia (Malakahmad et al, 2008) for a water quality simulation. In the context of the Water Framework Directive, Tsakiris and Alexakris (2012) reviewed and discussed the utility of eight of the more commonly used water quality models.

2.2 Water quality management and modelling in the US

In the US the Water and Water Quality Modelling Support Centre, part of the US Environmental Protection Agency (EPA 2013a), provides technical tools to assist States and Local Governments with the implementation of the Clean Water Act. They provide a number of watershed, hydrodynamic and water quality models. The water quality models available are

1. Water Quality Analysis Simulations Program (WASP)
2. River and Stream Water Quality Model (QUAL2K originally QUAL2E)
3. Aquatox
4. 1-Dimensional Riverine Hydrodynamic and Water Quality Model (EPD-RIV1)

QUAL2K (or Q2K), a river and stream water quality model based on the earlier version of the QUAL2E (or Q2E) model (Brown and Barnwell 1987), is the US de facto ‘community’ river water quality model in the US (EPA, 2013b). It is similar in many ways to InfoWorks, the UK-based model used in this study; QUAL2K is a 1-D model that assumes the channel is well-mixed vertically and laterally. It uses steady state hydraulics; non-uniform, steady flow is simulated and it includes a diurnal heat budget; heat and mass inputs are allowed through point and non-point loads and abstractions. In common with InfoWorks it divides the river into a series of unequally-spaced reaches but it does not explicitly include structures such as weirs or tidal control gates which are features of InfoWorks. QUAL2K models carbonaceous BOD speciation (through slow- and fast-BOD), anoxia denitrification, sediment-water interaction, bottom algae, light extinction and pathogens. pH is simulated through alkalinity and total inorganic carbon (EPA, 2013b). The output of QUAL2K is structured around the computation of Total Daily Maximum Load (TDML) as required by the Clean Water Act. It also includes a number of modules for assessing the uncertainty in the output predictions based on uncertainties in the input parameters (not available in InfoWorks).

QUAL2K software (latest version 2.11b8, 2009) and manuals can be downloaded from the US Environmental Protection Agency website (EPA, 2013a). The free nature of this software has resulted in its widespread use around the world (e.g.

Melching and Yoon, 1996; Drolc and Koncan, 1999; Ning et al., 2001; McAvoy et al., 2003; Paliwal et al., 2007). Ghosh (1997) and Ghosh and McBean (1998) used the QUAL2E model and its uncertainty modules to examine the BOD and DO profiles of the Kaliriver (India) where they found that turbidity was a useful measure of benthic oxygen demand in a region where there were a combination of industrial inputs and municipal sources.

Other models listed above are more complex. For example WASP7 can be used in 1, 2 and 3 dimensions for compartment-modeling of aquatic systems, including both the water column and the underlying benthos incorporating a variety of pollutant types. It is designed to help users interpret and predict water quality responses to natural phenomena and manmade pollution for various pollution management decisions (Ambrose et al. 1993).

For some complex watershed water quality management regions in the USA various models have been integrated into suites of modules. An example of this is the Chesapeake Bay Phase 5.3 Watershed Model, a collaboration between the US Environmental Protection Agency, the Chesapeake Bay Program, the U.S Geological Survey and the University of Maryland (EPA, 2010;Voinova and Gaddis, 2008).

2.3 Water quality management and modelling in the Southeast Asia

In SE Asia a two-year project (2009-2011) was funded by International Human Dimensions Programme on Global Environmental Change at United Nations University to establish a Centre of Excellence in the field of sustainable urban water quality management in Southeast Asian countries. Research was conducted in South East Asian countries on (1) current and future urbanization expansion (2) current water management policies (3) water quality impacts caused by urban activities and climate change and (4) the development of a strategic plan including capacity building programmes. The locations of the research were four urban cities, located in Cambodia, Indonesia, Thailand and Vietnam.

Hydrologically, the Mekong River is one of the most complex river systems in the world. It is the longest river in South East Asia, stretching 2,703 miles through six countries, and is nearly twice the length of the Colorado River. Its watershed supports between 65 and 80 million people, providing over $2 billion dollars in revenue from wild fisheries alone (White 2002). The Mekong River Commission (MRC) is an intergovernmental body charged with promoting and co-ordinating sustainable management and development of water in the Mekong Basin (Jacobs, 2002; Backer, 2007)

The large flows of the Mekong, nearly as large as those of the Mississippi, vary widely according to available precipitation. The basin has a wet and a dry season. In the wet season ~16% of the flows come from China while in the dry season, this rises to 40% (Evers et al. 2010). Fuji et al. (2003) modelled the Cambodian floodplain of the Mekong River with Mike 11. Due to the complexity and extent of the Mekong system, drought and flood events rarely affect the entire region equally. There are also interests in the effects of possible climate change on water quality as well as water availability. Prathumratana et al. (2008) concluded that TSS, alkalinity and conductivity were the most sensitive water quality parameters for monitoring impacts of changing climate in the lower Mekong River. In terms of water quality in the Mekong, using available data from the region, Campbell (2007) found that there was no evidence that water quality was poor except in the delta region.

Simachaya (2002) modelled water quality in Thailand using monitoring data. He modelled the major rivers of Chao Phraya and Tachinin the central region of Thailand, to estimate the potential effect of different percentages of waste load reduction and compared these with the no-action scenario, for years 2010 and 2020; Simachaya (2002) found that the water quality deteriorated most in the lower reaches of the rivers.

Tkalich et al. (2002) predicted the hydrodynamics and eutrophication processes in the Singapore Straits using output from 3-D Princeton Ocean Model, coupled with water quality from eutrophication model, NEUTRO. The water quality simulation output was used to the baseline level for generic condition of Singapore coastal waters.

Further calibration and validation refinement was still going on at the time their paper was submitted.

A study of land use and water quality relationships was done by Ferianita-Fachrul et al. (2001) in the Ciliwung River basin, Indonesia. 30 years (1970 to 2000) of land use data and 12 years (1993 to 2005) of water quality data were used to assess the relationships and the changes. The water quality in Ciliwung River was found to have decreased to 33% while the sizes of wetland area and water body decreased to 55%. There were no details of information, or findings on the relationship mentioned in this study.

2.4 Water quality management and modelling in Malaysia

A number of water quality studies have been conducted in Malaysia with the aim of improving knowledge of the rivers systems and their management. Sultan and Shazili (2009) conducted a study of the hydrochemistry of the Terengganu River which flows eastwards from the Central Range into the South China Sea. They sampled the surface waters from the river's source at Lake Kenyir and its five other tributaries for major, minor and trace elements plus eight anions and cations. They identified three water types, Ca-Cl-HCO_3 from the lake, Na-Cl-HCO_3 from the river and Na-Cl from the estuary. The eastern side of Peninsular Malaysia is much less developed than the western side and the hydrochemistry mainly relates to the geology through which the rivers flow, the chemistry of the regional rainfall and inflow of salt water from the estuary. A small number of polluted sites were identified, thought to be due to untreated waste water and agricultural runoff. The highest level of nitrate (NO_3) was 14 mg/l which is higher than the maximum values measured in the Selangor River (5.6 mg/l at Rantau Panjang and 4.9 mg/l at Kuala Selangor); nitrate levels in the four rainfall samples analysed averaged 2.4 mg/l.

A study of water quality of the Bertam River and its tributaries in Cameron Highlands by Eisakhani and Malakahmad (2009) found high levels of nitrogen and phosphorus resulting from agricultural practices and the "*presence of E. coli causing severe* *micro-biological contamination*" due to the use of chicken manure and to "*poorly treated or untreated sewage*" entering the river.

Haris and Omar (2008) assessed the tidal effects on water quality in the Petani River coastal area. Higher values for salinity and nitrite were recorded during high tide compared to total suspended solids (TSS), ammonia and pH which were higher during low tide. They claimed that most changes in water quality during neap tide were due to anthropogenic factors and the diurnal cycle rather than the influence of the tides. Mah (2006) applied the InfoWorks River System model to the Kanan River in Sarawak to construct the flood hydrograph for this river system. Salapour et al. (2011) also used the InfoWorks model to map the extent of flooding in the Skudai river basin in Johore State. Salapour et al. (2011) used a GIS to create the flood plain topography and simulated the flooding that would occur from a 100-year flood event and generated a flood risk map for the basin. Toriman et al. (2011) modelled dissolved oxygen (DO) along a 15 km length of the Juru River, a highly-polluted (Class IV and V), 'dying' and tidally-influenced river, using the InfoWorks model. DO values at 8 km and 11 km from river mouth were found to range between 0.5 and 10.5 mg/l and increased at 8 km during low tide and at 11 km during high tide.

2.5 The Integrated River Basin Management (IRBM) concept

In Malaysia, in order to counter the deterioration of water quality and to meet the future challenges, the Integrated River Basin Management (IRBM) concept has been chosen. The IRBM was laid out in the Eighth Malaysia Plan (five years project plan, 2005-2010) and in the Third Outline Perspective Plan. This is a joint project between the Malaysia Government and Denmark, which is assisting in the process, to be fully implemented in Malaysia, focusing on capacity building of institutions to allow for the implementation of the IRBM approach. A number of related agencies are involved, which will explore methodologies and facilitate communication and coordination. Each is encouraged to take advantage of new strategies and opportunities provided by IRBM and respond better to environmental challenges.

One of the main State components of the IRBM project is Selangor River basin; the Selangor basin is the main source of water for drinking for Kuala Lumpur and the Klang Valley area. The main focus is on practical implementation of activities within the basin of the Selangor River to reduce environmental problems and improve water management. The project is operated by Selangor Water Management Authority (SWMA) and the activities involve various agencies and stakeholders. However this is not just a technical study but a collaborative effort among selected agencies which is more on recognizing the vital link between Federal policies and State actions. Implementation of this IRBM started in 2008 by establishing policies and the strategies. The four policies identified were 1: to ensure sufficient water, 2: to ensure water was clean, 3: to protect against flood, and 4: to conserve the fireflies.

2.6 Water quality and management in the Selangor River basin.

Typically, research on river water quality is conducted in order to improve the quality of water of the river. The results of the research are often used to make recommendations for improving river management programs. Selangor River itself has been studied by several researchers. KadirIshak, (2000, 2002), Kheong (2002), Nelson (2002), Hassan (2006) and Maarten (2008), have investigated the dynamic behaviour of Selangor river and its estuary, particularly its salt budget and suspended sediment transport, but none considered the impact of run-off from oil-palm plantations through hydraulics structures on the river system, or assessed the likely effects of future developments planned for the upper reaches of the Selangor river on the water quality of the lower reaches and its estuary.

Engelsman (2002), in a report written as part of a research thesis, applied the CLUE-S model to the Selangor River basin to look at the impact of proposed developments up to 2014. The CLUE-S model is a tool designed to support the land use management decisions in developing countries (Verburg et al., 2001). The model simulates the land use changes that are related, for example, to a new town, including the clearance of forest around such a new town. Engelsman’s (2002) report is a test of the CLUE-S model and the conclusions more relevant to future use of model; one of his conclusions is to “Pay more attention to the social driving factors of land use change in future applications of CLUE-S.”

Mohamed (2002) carried out a modelling study for upper catchment (non-tidal influence area) of Selangor River using the steady-state flow water quality model QUAL2E of the dissolved oxygen and biological oxygen demand.

Hassan (2006) was the first to use the 1-D InfoWorks River System model on the Selangor River. The objective of his model study was to generate the flood risk map in Selangor river floodplain area. Model development involved three stages which were a hydrological model, a hydraulic model and a 3-D terrain model. Calibration was done at a tidal-influenced river node and in the middle reaches of the river. Input data and information used were the river catchment map, river cross section, flood plain, sub-catchment characteristics, rainfall and river flow. The hydrodynamic model covered 106 km of the river, starting at the estuary mouth; the flood map was generated between 53 km and 67 km upstream where he observed the flood prone area to be after doing the analysis. Hassan (2006) used the hydrodynamic module of the InfoWorks system, with the river flow defined through the daily gauging values at Rantau Panjang and the tides at the mouth of the Selangor River defined via the tidal constituents for the Straits of Malacca provided by the Royal Malaysian Navy. Hassan (2006) did not include the impacts of the tidal control gates (TCGs), which control the flow of water from the (mainly) oil palm plantations along much of the lower reaches of the Selangor river, on the flooding or general hydrodynamics of the river. In this dissertation the effects of the TCGs have been included and the tidal constituents computed from tide gauge measurements made in the Selangor estuary near its mouth. Although this dissertation uses the same bathymetric data-base as Hassan (2006) for the river cross-sections in the hydrodynamic model, some errors in the levels of some cross-sections were identified. In this dissertation care was taken to ensure that the river cross-sections were related to Malaysia's National Geocentric Datum (GDM 2000), introduced by the Department of Survey and Mapping Malaysia in 2002.

Van Breemen (2008) modelled the salt intrusion into the Selangor estuary using the Delft-3D model. The study was a collaboration between the National Hydraulic Research Institute of Malaysia (NAHRIM), the University of Twente and Alcyon Hydraulic Consultancy & Research in the Netherlands, and the report was presented as a research degree at the University of Twente. The study was particularly concerned with the possible impact of the extraction of water from the Selangor River (to meet the increasing requirements for domestic and industrial uses in Selangor and Kuala Lumpur) on the distance that saline water extends upstream. The model showed that the 6.5 ppt salinity point moves up the estuary by an average of 3.4 km assuming a pre-extraction dry-season flow of 30 m^3/s and a minimum baseline flow (post extraction) of 3.5 m^3/s. The 6.5 ppt point was chosen as this is the level at which ecosystems such as the trees on which the Selangor River fire-fly colony rely can be permanently affected by salinity greater than this.

Van Breemen (2008) concluded that his modelling strategy to derive boundary conditions for the Selangor Estuary was very accurate, but time-consuming. It used two nested tidal models, the Malaysia Overall Model and the Malacca Strait Model but these did not appear suitable for a detailed, small scale model like the Selangor Estuary. The Malacca Strait Model is capable of generating a very accurate tidal flow model but when the focus is solely on the estuary, "*boundary conditions derived from surrounding tidal stations could provide a fast alternative*" (Van Breemen, 2008); this was the approach used in this research. The calibration of tidal flow models with Delft-3D requires considerable "*experience with tidal models, knowledge of tidal waves and a good portion of luck*" (Van Breemen, 2008). He also concluded that his model of the Selangor Estuary was complicated by the lack of accurate bathymetry for the whole modelled area although the available cross-sections (the same cross-sections as those used in this research) did "*provide a good indication but for numerical modelling more dense depth measurements are required*".

Leong et al. (2007) have observed the occurrence of organochloride and organophosphate pesticides in the Selangor River. Surface water samples were collected in 2002 and 2003 for nine locations of sampling sites from river mouth to upstream where the Selangor Dam is located. The pesticide levels at the river upstream were found to be >500 ng/l and above the European Economic Community Directive water quality standards. Pesticide levels at the downstream location of the fire-flies attraction were lower but still were greater than 100 ng/l and exceeded EPA limits for freshwater aquatic organisms. Leong et al. (2007) concluded that these residual pesticides in the Selangor River came from agriculture and urban activities.

2.7 Summary

There is a wide variety of water quality regulatory environments around the world and a great number of studies conducted to measure, model and manage the quality of water in rivers, lakes, estuaries and coastal seas. Most countries have their own regulations which have been developed to suit their particular requirements and geographical locations. There are a considerable number of models available to assist scientists and managers to plan river basin development; these models vary considerably in complexity but the majority was developed for use in temperate regions. As described above they have been used in tropical regions but experience in the tropics is limited.

The InfoWorks model has been used for a number of water quality applications in Malaysia and this study builds on these studies, particularly the work of Hassan (2006). The present study is an effort to assess the water quality of Selangor estuary and estimate possible impacts of land use on it, in the coming years. The data obtained will be useful for planning a strategy to sustainably maintain the Selangor River and its estuary while providing clean water to a growing population.

CHAPTER 3

MODEL DESCRIPTION

3 Introduction

This chapter describes the mathematical formulation available in the commercial one-dimensional InfoWorks^{TM} River Simulation (RS) model which was used and applied to this study. The InfoWorks^{TM} model was selected by NAHRIM, after an evaluation of a number of commercial and free-ware modelling packages, to provide the broad combination of modelling tools, at the best price, needed for optimal application across HAHRIM's requirements in Malaysia as a whole, not simply this study of the Selangor River. It includes access to a help-desk to aid model set-up and configuration.

The InfoWorks^{TM} software models the hydrodynamics of water in the open channels and rivers, based on the one dimensional Saint-Venant equations, which express the conservation of mass and momentum of the water body. Results from the hydrodynamic model are then linked to the InfoWorks^{TM} Water Quality (WQ) module which models the transport of pollutants along the river reaches through an advection-diffusion equation. The modules are integrated through a series of input and outputs. Beginning with the simulation of flows and pollutant loads from land at sub-catchment scales, the model generates inputs for the routing of flows and pollutant loads along the main river of the catchment. Likewise, outputs from the routing component are inputs for the water quality component.

The hydrodynamic modelling to simulate the dynamic flow in the lower part and estuary of the Selangor River is first discussed before proceeding to water quality simulation. The governing hydrodynamic equations, data required and the application to the study area are also included. The following section presents the mathematical formulation of the water quality component that simulates pollutants transfer (in the presence of flows) from land to the river. The general work-flow for this modelling is shown in Figure 3-1.

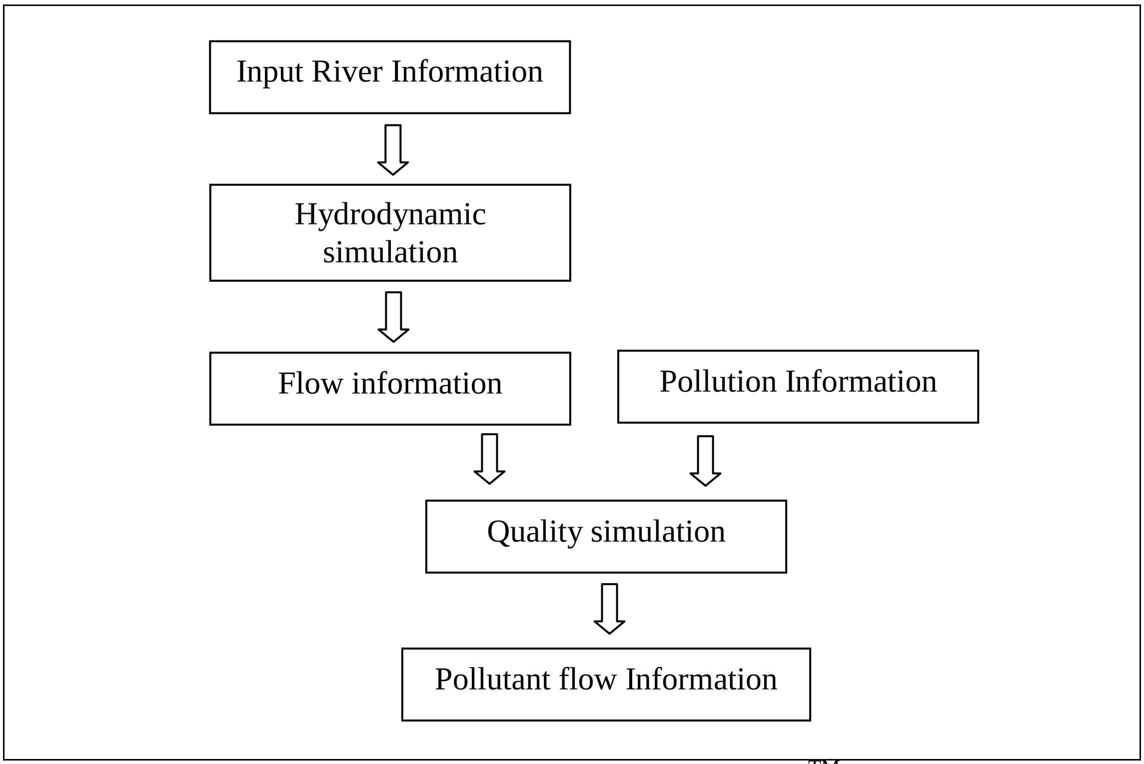


Figure 3-1: The work-flow diagram of the HR InfoWorks^{TM} river simulation and water quality model

3.1 The Hydrodynamic Model

In order to determine ‘where the water goes’ and how water movement affects the concentrations of water quality constituents, knowledge and understanding of the motion of water and the forces acting on water (Ji 2008), referred to as the ‘system hydrodynamics’, are required. The magnitude of flow dilutes contaminant loadings, affects the travel time of contaminants, and the amount of contaminants that can be produced or degraded; it also alters the degree of mixing, which in turn affects chemical gradients that can impact the water quality and will thus affect the assimilative capacity of a river (Martin and McCutcheon 1999).

3.1.1 Hydrodynamic Equations

The hydrodynamic component of the InfoWorks^{TM} RS model used for the Selangor River is a one-dimensional unsteady flow model that computes flow depths and discharges based on Saint-Venant equations which express conservation of mass and conservation of momentum. The river system is represented by a series of nodes (~ 1 km apart in the case of the Selangor River) at which the cross-sectional shape of the river and banks are defined. Conservation of mass is expressed in a mass balance equation or "continuity" equation (Eq. 3-1) which establishes a balance between the rate of rise of water level and wedge and prism storages (InfoWorks^{TM} RS Manual).

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \qquad \text{(Eq. 3-1)}$$

where Q is discharge (m^3s^{-1}), A is the area of cross section of the river (m^2) at the distance x and time t, and q is lateral inflow ($m^3\, s^{-1}\, m^{-1}$).

Conservation of momentum (Eq. 3-2) leads to the dynamic equation which establishes a balance between inertia, diffusion, gravity and friction forces (InfoWorks^{TM} RS Manual)

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{\beta Q^2}{A}\right) + gA\frac{\partial H}{\partial x} - gAS_f = 0 \qquad \text{(Eq. 3-2)}$$

where β is momentum correction coefficient, g is gravitational acceleration ($m\ s^{-2}$), H is water surface elevation above datum (m), S_f is called the friction slope:

$$S_f = \frac{Q[Q]}{K^2} \qquad \text{(Eq. 3-3)}$$

and K is the channel conveyance calculated according Manning's equation:

$$K^2 = \frac{A^2 R^{\frac{4}{3}}}{n^2} \quad \text{and} \quad R = \frac{A}{P} \qquad \text{(Eq. 3-4)}$$

where R(m) is the hydraulic radius, P (m) is the length of the wetted perimeter and n is Manning's roughness coefficient.

3.2 Water Quality

The water quality component of InfoWorks^{TM} RS used to model water quality has a separate simulation engine from the hydraulic engine (which provides the hydrodynamics). Water quality simulations therefore require two separate simulations; first the hydraulic model is run, then one or more water quality simulations are made, utilising the hydrodynamic data.

InfoWorks^{TM} Water Quality computes concentrations using a finite difference approximation to the advection-diffusion equation. An explicit implementation of the *Sharp and Monotonic Algorithm for Realistic Transport by convection* or SMART algorithm, developed by Gaskell and Lau (1988), is used to approximate the advection term. Although InfoWorks^{TM} RS is a depth-averaged model, for water quality modelling an element is divided into four vertical sub-components as shown in Figure 3-2 below.

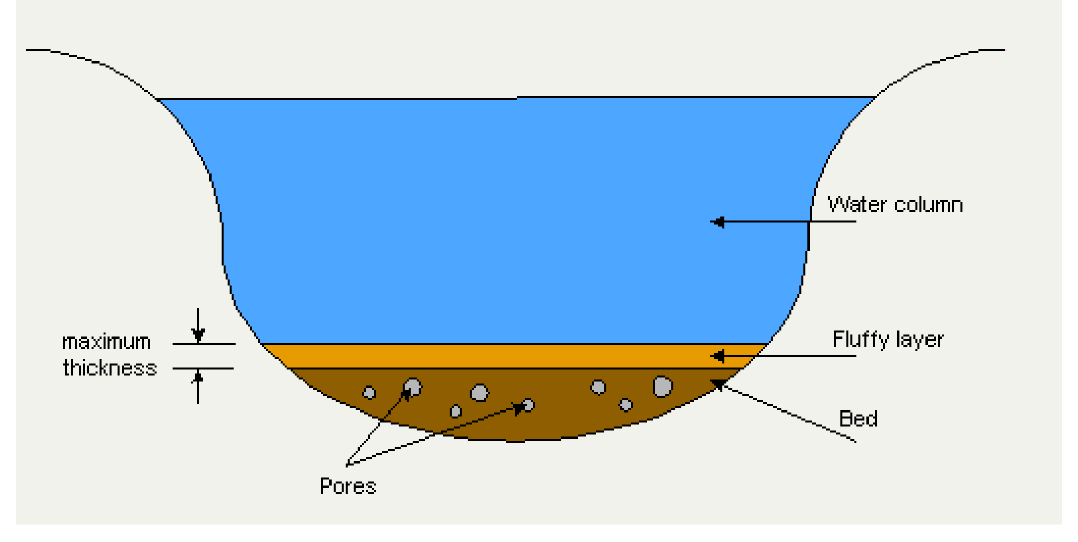


Figure 3-2: Vertical structure of the water quality component of the InfoWorks^{TM} RS model

The water column is the main body of water through which dissolved and suspended substances are transported. All the consolidated mud that has settled out of the water column and can be re-suspended forms a ‘bed layer’. However, settled matter initially falls into a fluffy layer where mud lies on top of the consolidated bed and is less dense with limited thickness. Once the layer has filled to its maximum thickness, any additional settled material causes an equal amount to pass into the bed. As mud consolidates into the bed layer, water is trapped within its pores. The rate of transfer of dissolved substances into the pore water is proportional to the deposition rate.

The contents of the fluffy layer can interact biochemically and biologically with the water column. The material in the bed and pore-water can interact but are isolated from the water column until resuspended. Erosion of the fluffy layer and bed material returns their contents and that of pore water to the water column.

InfoWorks^{TM} Water Quality is capable of modelling a range of water quality variables and processes simultaneously (Figure 3-3).

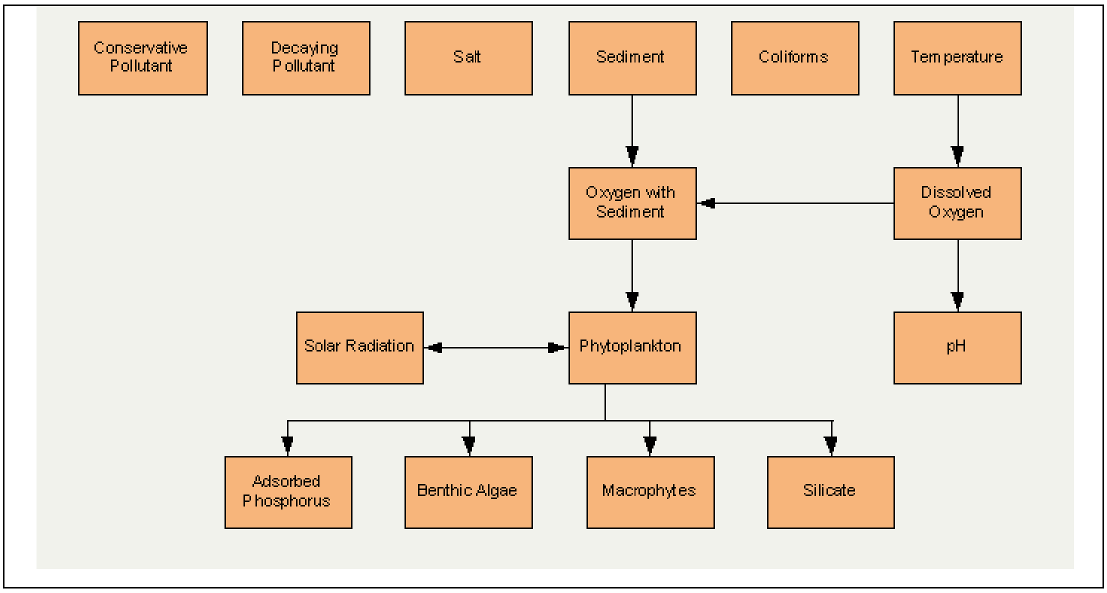


Figure 3-3: Components and inter-dependency of processes and variables included in InfoWorks^{TM} Water Quality

Since the InfoWorks^{TM} Water Quality is written in a modular style not all the processes need to be studied at once. However some modules are dependent on one another e.g. the 'Dissolved Oxygen' module must be run in conjunction with the 'Temperature' module and, since the oxygen balance is being simulated in an estuary (in this study), the 'Salt' module must be run as well because of the impact of salinity on the saturated dissolved oxygen concentrations.

3.2.1 Advection-Diffusion Equation

InfoWorks^{TM} Water Quality models the transport of pollutants along river reaches by the one-dimensional advection-diffusion equation:

$$\frac{\partial(CA)}{\partial t} = -\frac{\partial(uCA)}{\partial x} + \frac{\partial}{\partial x}\left(DA\frac{\partial C}{\partial x}\right) + S \qquad \text{(Eq. 3-5)}$$

where C is pollutant concentration (kg m^{-3}) of the species at the specified coordinate x(m) and time t(s), A is cross-sectional flow area (m^2), u is cross-sectional averaged flow velocity (m s^{-1}), D is diffusion coefficient ($m^2 s^{-1}$) and S represents source or sink terms which is representing the net gain or loss of a substance by physical, chemical or biological reactions (kg $m^{-1}s^{-1}$). Equation 3-5 is effectively a mass conservation equation with an added source term, S. The first term represents the rate of change with time of pollutant at a point. The second term is called the advection component and, when combined with the first term, represents the rate of change of pollutant in a unit of fluid along a streamline (considering the carrying fluid as incompressible). This is then balanced by the third term, the diffusion term, which represents the flux of pollutant out of a small unit of fluid travelling with the flow. As the equation is one dimensional all the variables represent are cross-sectional averaged quantities.

Due to the complexity of the river network boundary conditions, Equation 3-5 is solved numerically. The finite difference approximation to Equation 3-5 used in InfoWorks^{TM} Water Quality is:

$$\frac{\varphi_i^{n+} - \varphi_i^n}{\Delta t} = -\frac{u\varphi_{i+1/2}^n - u\varphi_{i-1/2}^n}{\Delta x} + D\left[\frac{(A_{i+1}^n + A_i^n)(C_{i+1}^n - C_i^n) - (A_i^n + A_{i-1}^n)(C_i^n - C_{i-1}^n)}{2(\Delta x)^2}\right] + S$$

(Eq. 3-6)

where n is time index, i is position index, Δx is the mean of the element lengths adjacent to node i(m), Δt is time step (s) and $\varphi = C \, x \, A$ is the scalar transport variable (kg m^{-1}).

3.2.2 Dissolved oxygen module

The model for dissolved oxygen in the river is related to the decomposition of pollutants in the water. The development of a dissolved oxygen (DO) model has evolved over the years since the effort pioneered by Streeter and Phelps (1925). Nowadays, the model complexity depends on the number of sinks and sources of DO. In the InfoWorks^{TM} Water Quality model, the dissolved oxygen (DO) module utilises the following variables: dissolved oxygen (kg m^{-3}), fast BOD (kg m^{-3}), slow BOD (kg m^{-3}), suspended particulates, COD (kg m^{-3}), total COD (g m^{-3}), fast nitrogen (kg m^{-3}), slow nitrogen (kg m^{-3}), ammoniacal nitrogen (kg m^{-3}), Nitrite-N (kg m^{-3}), Nitrate-N (kg m^{-3}). The following equations are taken from the InfoWorks^{TM} manual and cannot be altered by the user. Throughout the InfoWorks manual concentration is referred given as 'mg/l'; values are entered into the module in 'mg/l' and will be referred to as such throughout this Chapter.

3.2.2.1 Dissolved Oxygen

Dissolved oxygen concentration is often used as the main indicator of the health of a river or estuary. It represents the ability of the water body to support plant and animal life. The concentration of oxygen which can be dissolved in water is a function of temperature and salinity (Equation 3-7). Oxygen is utilised by the decay of organic material and the nitrification of ammonia and can be added to the water body by re-aeration. Saturated dissolved oxygen concentration (*DOS*) is determined as a function of temperature and salinity (InfoWorks manual):

$$\begin{aligned} DOS = 1.43[&(10.291 - 0.2809T + 0.006009T^2 - 0.0000632T^3) \\ &- 0.607S(0.1161 - 0.003922T + 0.0000631T^2)] \end{aligned} \tag{Eq. 3-7}$$

where *T* is temperature (Celsius) and *S* is salinity (ppt).

3.2.2.2 Re-aeration

Re-aeration is the process by which oxygen from the air dissolves in water and is limited by the saturation concentration (Equation 3-8). The rate of re-aeration is proportional to the oxygen deficit, which is the difference between the saturation concentration and the actual concentration. Re-aeration can be a function of temperature (Equation 3-9). Re-aeration is represented in the InfoWorks^{TM} model by the equation:

$$\frac{dDO}{dt} = K_{air}(DOS - DO) \qquad \text{(Eq. 3-8)}$$

where DO is dissolved oxygen concentration (mg/l), DOS is dissolved oxygen concentration at saturation (mg/l) and K_{air} is the rate constant (h^{-1}). The rate constant may calculated from

$$K_{air} = f_{air}\ \frac{b}{A} \qquad \text{(Eq. 3-9)}$$

where f_{air} is transfer velocity (m h^{-1}) and represent the speed at which a front of oxygen penetrates through the water depth. The stronger the mixing processes are, then the higher this value will be. b is water surface width (m) and A is cross sectional area of flow (m^2).

3.2.2.3 Biochemical Oxygen Demand (BOD)

BOD normally refers to a measure of the total amount of oxygen removed from water biologically or chemically in a specified time and at a specific temperature. It indicates the total concentration of DO utilised either during degradation of organic matter (decomposition by aquatic microbes) or the oxidation of inorganic matter. InfoWorks^{TM} Water Quality calculates oxygen demand in terms of the ultimate oxygen demand, which is the amount of oxygen that would be consumed if the material decays completely over 5 days. This is referred to as the standard 5-day BOD test or BOD_5. When modelling BOD, the ultimate biochemical oxygen demand (BOD_u) is used; this is where the pool of organic matter that could potentially be hydrolysed and broken down is represented in terms of its oxygen-consuming capacity. Organic matter consists of readily-hydrolysed organic matter (called the fast-BOD) in the water column and in the sediment, and more slowly hydrolysed components (slow BOD) in the water column and in the sediment. Settling of particulate organic matter from the water column into the sediment is another of factor influencing the BOD as it will remove both the readily-hydrolysed and slowly-hydrolysed BOD from the water column to the sediments.

The ultimate oxygen demand, BOD_u (mg/l) is calculated by

$$BOD_U = \frac{BOD_5}{1 - \left[(1-\alpha) exp(-5K_f) + \alpha exp(-5K_s)\right]} \qquad \text{(Eq. 3-10)}$$

where α is the proportion of slow BOD, K_f is the reaction rate constant for fast BOD and K_s is the reaction rate constant for slow BOD. Since BOD_5 is measured during sampling campaigns in the Selangor River conducted by NAHRIM and the Malaysian Department of Environment (DOE) the BOD_5 measured in the water samples collected at the surface of water column is taken as the total BOD (fast + slow). Hence from a practical implementation of the InfoWorks model the proportion of slow BOD is set to zero and removed from Eq. 3-10. BOD_u becomes

$$BOD_U = \frac{BOD_5}{1 - exp(-5K_f)} \qquad \text{(Eq. 3-11)}$$

The amount of oxygen removed from waters varies with the concentration of organic matter and many other factors (Ji, 2008). The decay of organic matter is represented in InfoWorks^{TM} Water Quality by temperature-dependent, first-order kinetics. Organic matter will decay whether the surrounding water is fully oxygenated or anoxic. In practice, the rate of decomposition of organic matter is often assumed proportional to the amount of organic matter (Ji, 2008)

$$\frac{dC}{dt} = -KC \qquad \text{(Eq. 3-12)}$$

where K is reaction rate constant (time^{-1}) and expressed as a function of temperature and C is concentration of the organic material (kg m^{-3}). However, most of reactions rates in natural waters increase with temperature. A general rule of thumb is that the rate will about double for a temperature rise of 10°C (Chapra, 1997). The InfoWorks^{TM} Water Quality model applies the following equation (which originally comes from the Arrhenius equation)

$$K_\theta = K_{20}\left(1 + \frac{\alpha}{100}\right)^{\theta - 20} \qquad \text{(Eq. 3-13)}$$

where K_θ is rate constant (time^{-1}) at θ℃, K_{20} is rate constant (time^{-1}) at 20℃ and α is temperature dependent factor (a constant fixed in InfoWorks model).

3.2.2.4 Chemical Oxygen Demand (COD)

Generally COD is a measure of the amount of oxygen reduction due to chemical oxidation of pollutants in the system: it involves the addition of a chemical oxidising agent such as potassium permanganate or dichromate to a water sample for a standard period of time (5 days) at 20^{o}C and measuring dissolved oxygen concentrations as for BOD; this provides a more complete oxidation of both organic and inorganic compounds in the water than BOD and is widely used to represent the overall level of organic contamination in waste water. In InfoWorks there is no conversion of COD to ultimate oxygen demand which it is taken as the equivalent to BOD_U.

$$COD \equiv BOD_U \qquad \text{(Eq. 3-14)}$$

3.2.2.5 COD or BOD?

The InfoWorks^{TM} Water Quality model calculates BOD and COD separately. A user has to choose which to use; both cannot be run simultaneously. When BOD and COD are run sequentially these result in different values for the DO in the river. In the Selangor River, COD values are higher than the BOD values, as COD includes both biodegradable and non-biodegradable substances whereas BOD contains only biodegradable. The main land-use within the catchment is oil palm plantations where the use of fertiliser containing phosphate is actively applied. The COD value tends to be higher when the phosphate concentration is high. As it is therefore believed that the chemical assimilation of pollutants within the Selangor river system is likely to be more important than biological processes, the COD module has been used in this study. Tchobanoglous et al. (2003) suggested that BOD could be assumed to be 0.6 * COD but as both BOD and COD are routinely measured by DOE as part of their bi-monthly water quality measurements just downstream of Rantau Panjang the average ratio of BOD to COD of 0.13 from these measurements was used.

3.2.2.6 Ammoniacal Nitrogen

Organic nitrogen represents nitrogen which is present in organic matter in the form of compounds such as proteins and amino acids. These compounds are hydrolysed by bacteria to form ammonium compounds. As with BOD, the organic nitrogen hydrolyses at a fast and a slow rate represented by temperature-dependent, first-order kinetics. Ammoniacal nitrogen represents nitrogen which exists in the form of ammonia or ammonium ions. It can be formed by the hydrolysis of organic nitrogen, as described above, but also enters the river system directly from industrial or sewage effluent. Ammoniacal nitrogen is oxidised to nitrite by nitrosomonas bacteria. This oxidation is modelled as a first-order process which is temperature, salinity and suspended sediment dependent (Equation 3-13 and Equation 3-15). The process consumes dissolved oxygen. Nitrite is in turn oxidised by nitrobacter to form nitrate consuming more dissolved oxygen.

In the case of the oxidation of ammoniacal nitrogen to form nitrite, the reaction rate constants are a function of salinity and suspended sediment concentration as well as temperature:

$$K_{AM\theta} = K_{AM20}\left(1+\frac{\alpha}{100}\right)^{\theta-20}\left(1+\frac{\beta}{100}\right)^{S-S_0}\left(1+\frac{Y}{100}\right)^{SS-SS_0} \qquad \text{(Eq. 3-15)}$$

where S_0 is reference salinity (ppt), SS_0 is reference suspended solids concentration (ppt), β is salinity dependence factor, Y is suspended solids dependence factor, $K_{AM\,\theta}$ is nitrification rate constant at θ°C and $K_{AM\,20}$ is nitrification rate constant at 20°C.

3.2.2.7 Denitrification

Under low oxygen or anoxic conditions the nitrification of ammonia ceases. Nitrates and nitrites are then used as a source of oxygen in order to satisfy BOD by denitrification. The nitrogen which is released during the process is released to the atmosphere and plays no further part in the model. Once all the nitrate and nitrite have been consumed BOD is then satisfied by the reduction of sulphates which leads to the formation of hydrogen sulphide. The model will keep a track of the amount of hydrogen sulphide which is formed as an indication of the severity of anoxic conditions.

It is assumed that both nitrate and nitrite can be used as sources of oxygen when oxygen concentration falls below 5% saturation. The demand of oxygen is completely satisfied by the denitrifying process. Nitrate concentration is set according to the Equation 3-16

$$\frac{dN0_3}{dt} = -0.35\,\frac{N0_3}{N0_3+N0_2} \tag{Eq. 3-16}$$

and nitrite concentration is reduced according to

$$\frac{dN0_2}{dt} = -0.58\,\frac{N0_2}{N0_3+N0_2} \tag{Eq. 3-17}$$

when there is sufficient oxidised nitrogen to satisfy oxygen demand then any remaining dissolved oxygen is utilised. When all the dissolved oxygen has been used, any further demand is satisfied by the reduction of sulphates to form hydrogen sulphide. The equivalent amount of oxygen released by this process is stored in the variable ‘hydrogen sulphide’. The net rate of change in dissolved oxygen concentration when modelling BOD is given by:

$$\begin{aligned}\frac{dDO}{dt} = {} & -K_f BOD_u(fast) - K_s BOD\,(slow) - 3.43K_{AM}AM - 1.14K_{NO_2}NO_2 \\ & + K_{air}(DOS - DO)\end{aligned}$$

where K_{NO_2} is the oxidation rate constant for nitrite.

The net rate of change in dissolved oxygen concentration when modelling COD is given by:

$$\frac{dDO}{dt} = -K_{COD}COD - 3.43K_{AM}AM - 1.14K_{NO_2}NO_2 + K_{air}(DOS - DO)$$

whereK_{COD} is the oxidation rate constant for COD.

3.3 The Malaysian Water Quality Index (WQI)

The Malaysian Department of the Environment defines an overall Water Quality Index (WQI) based on just six parameters, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), ammoniacal nitrogen (AN), suspended solids (SS) and pH. The concentration of each parameter is used to calculate a sub-index, and the sub-indices are combined as shown below

$$WQI = 0.22(SIDO) + 0.19(SIBOD) + 0.16(SICOD) + 0.15(SIAN) + 0.16(SISS) + 0.12(SIpH) \quad \text{(Eq. 3-18)}$$

where *SIDO* is the sub-index for DO, *SIBOD* is that for BOD, *SICOD* for COD, *SIAN* is for AN, *SISS* for SS and *SIpH* is for pH.

The sub-indices are calculated as follows:

Sub-Index for DO (x in % saturation):
$SIDO = 0$ for $x \leq 8$
$SIDO = 100$ for $x \geq 92$
$SIDO = -0.395 + 0.03\, x^2 - 0.00020\, x^3$ for $8 < x < 92$

Sub-Index for BOD (x in mg/l):

$SIBOD = 100.4 - 4.23x$ for $x \leq 5$
$SIBOD = 108 * e^{-0.055x} - 0.1x$ for $x > 5$

Sub-Index for COD (x in mg/l):

$SICOD = -1.33x + 99.1$ for $x \leq 20$
$SICOD = 103 * e^{-0.0157x} - 0.04x$ for $x > 20$

Sub-Index for NH_3-N (x in mg/l):
$SIAN = 100.5 - 105x$ for $x \leq 0.3$
$SIAN = 94 * e^{-0.573x} - 5\,|x - 2|$ for $0.3 < x < 4$
$SIAN = 0$ for $x \geq 4$

Sub-Index for SS (x in mg/l):
$SISS = 97.5\, e^{-0.00676x} + 0.05x$ for $x \leq 100$
$SISS = 71 * e^{-0.0061x} - 0.015x$ for $100 < x < 1000$
$SISS = 0$ for $x \geq 1000$

Subindex for pH

$SIpH = 17.02 - 17.2x + 5.02x^2$ for $x < 5.5$
$SIpH = -242 + 95.5x - 6.67x^2$ for $5.5 \leq x < 7$
$SIpH = -181 + 82.4x - 6.05x^2$ for $7 \leq x < 8.75$
$SIpH = 536 - 77x + 2.76x^2$ for $x \geq 8.75$

The WQI value obtained is then used to classify a river or water body based on the DOE water quality classification (Table 3-1, 3-2 and 3-3) below

Table 3-1: Water quality based on DOE Water Quality Index

SUB INDEX & WQI	**INDEXRANGE**		
	CLEAN	**SLIGHTLY POLLUTED**	**VERY POLLUTED**
BOD	91 - 100	80 - 90	0 - 79
Ammoniacal Nitrogen	92 - 100	71 - 91	0 - 70
Suspended Solids	76 - 100	70 - 75	0 - 69
WQI	81 - 100	60 - 80	0 - 59

Table 3-2: DOE water quality classification

Parameters	**Classes**				
	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
BOD (mg/l)	< 1	1 – 3	3 - 6	6 - 12	> 12
COD (mg/l)	< 10	10 – 25	25 - 50	50 - 100	> 100
DO (mg/l)	> 7	5 – 7	3 - 5	1 - 3	< 1
pH	> 7	6 – 7	5 - 6	< 5	< 5
SS (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

Table 3-3: Water classes and uses

CLASS	**DESCRIPTION**
I	Conservation of natural environment Water Supply I (practically no treatment necessary), Fishery I (very sensitive aquatic species)
IIA	Water Supply II (conventional treatment required), Fishery II (sensitive aquatic species)
IIB	Recreational use with body contact
III	Water Supply III (extensive treatment required), Fishery III (common, of economic value, and tolerant species livestock drinking)
IV	Irrigation
V	None of the above

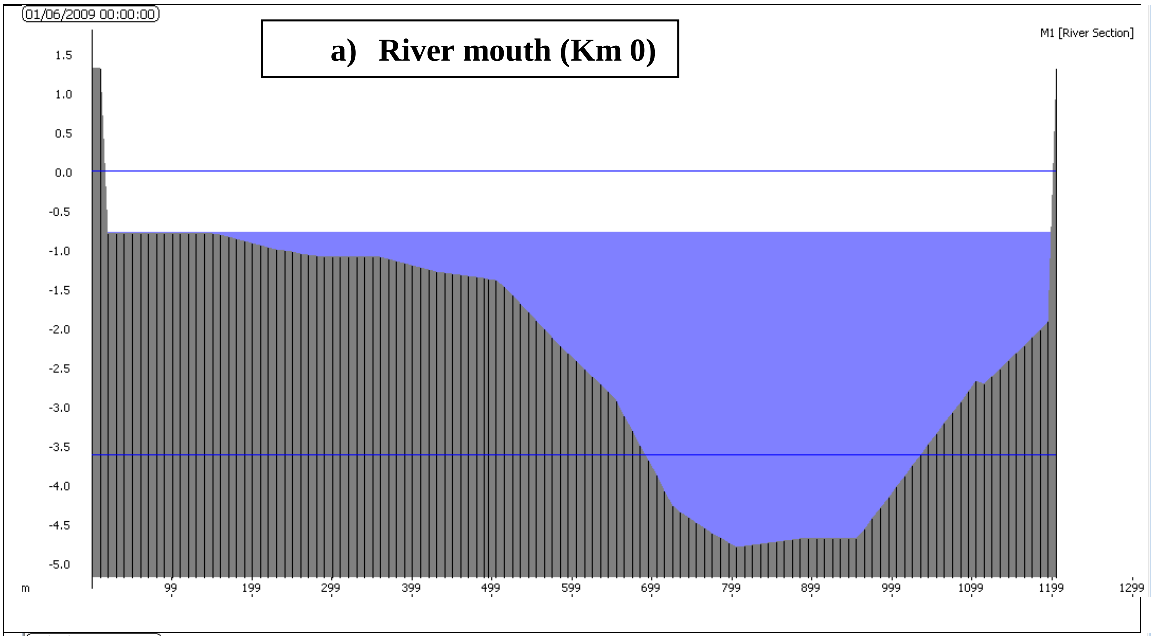
The above qualitative descriptions of water quality classifications are based on a series of qualitative indices and formulae developed by Mustafa (1981) and have been used as the National Water Quality Index for Malaysia.

3.4 Setting up the river model

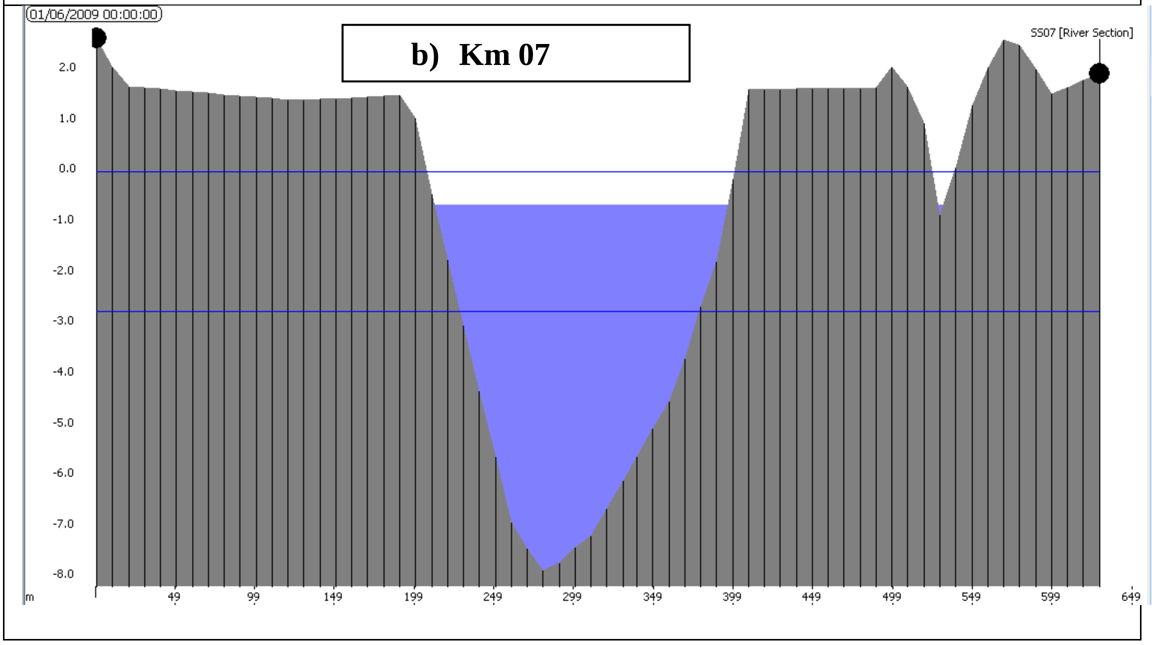
In practice the InfoWorks^{TM} RS model is applied to a reach of ~57 km from the mouth of the Selangor River as shown in Figure 4-6 to the gauging station at Rantau Panjang. The modelling was restricted to this reach because the only gauging station for river discharge (installed and maintained by Department of Irrigation and Drainage (DID)) is at Rantau Panjang and represents the discharge from the upper part of Selangor River catchment, providing an upstream boundary condition for the river model.

3.4.1 River cross sections

All hydrodynamic models (Martin and McCutcheon 1999) require the information about the geometry of river channel, both the cross-section shape and bottom slope. In this 1D model the cross-sectional data are used to determine the relationships among velocities, flows and volumes. The river system network is discretised into a number of river nodes which are defined such that the input parameters for river cross-section remain constant within a node. Each node is defined by its distance from the river mouth and referred to as, for example, “km 10”. The river cross-section data for Selangor River were provided by DID (Section 4.2.1 and Figure 4-9). Figure 3-4(a) to (d) are the examples of cross sections at four river cross-sections (at the river mouth, km 7 and km 20; and further upstream at km 57) respectively used as inputs to the model.



a) River mouth (Km 0)



b) Km 07

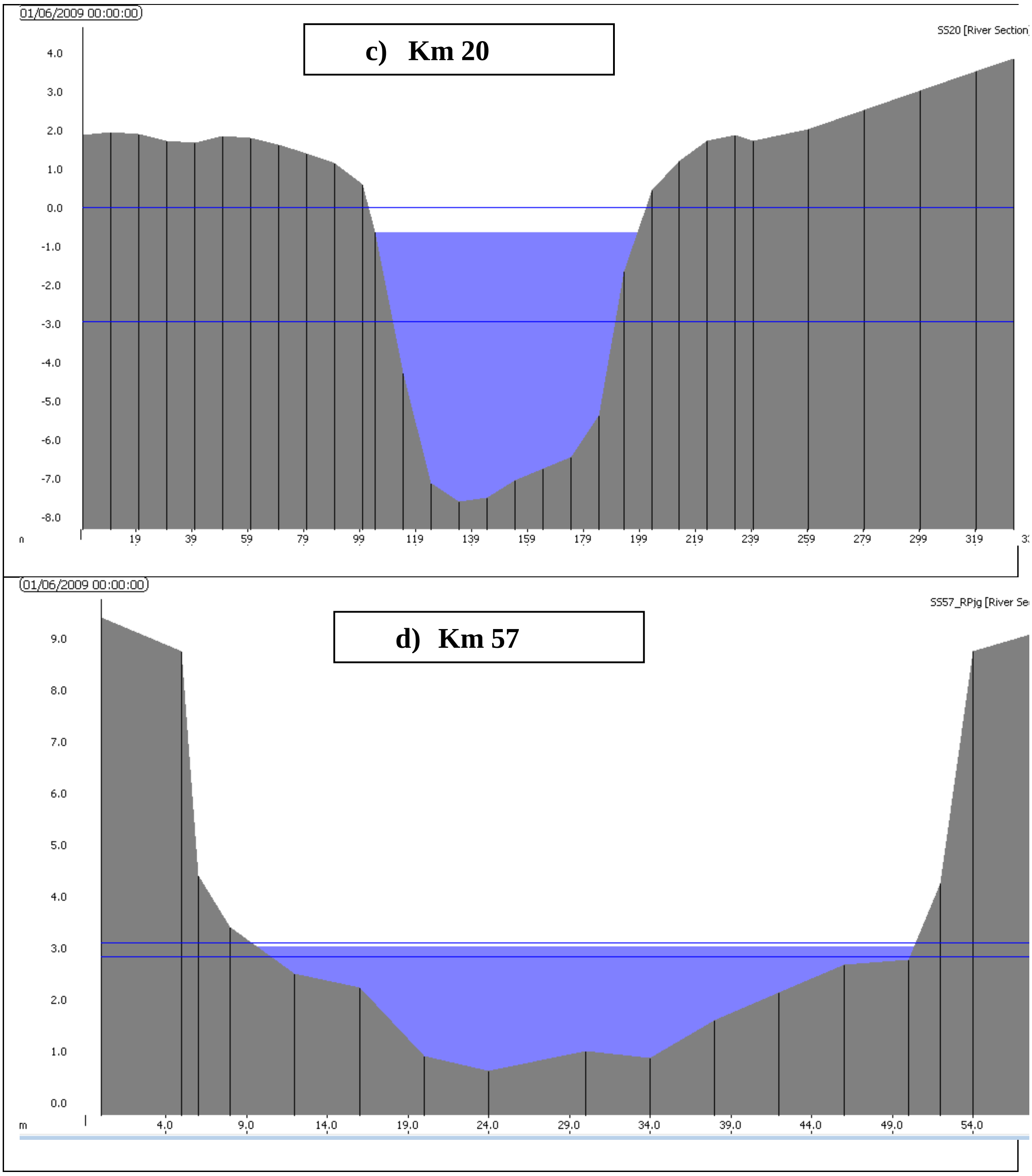


Figure 3-4: A diagram illustrating four of the cross-sectional surveys used in the model. Cross-sections are from (a) the river mouth (km 0), (b) from km 7, (c) from km 20 and (d) from the upper boundary at Rantau Panjang at km 57. Scales are in metres. The two blue horizontal lines show the maximum and minimum water level reached due to tidal forcing.

The channel slope affects the acceleration of water due to gravity (Martin and McCutcheon 1999). However, flows are also affected by bottom friction, which opposes flow. Therefore, data are required to estimate the degree of friction. In this case, an empirical coefficient, Manning *n*, is used to estimate the effects of friction or roughness.

3.4.2 Manning's Roughness Coefficient, *n*

Manning's equation (Equation 3-4) is one of the most commonly used methods to characterise river bed roughness in river modelling and is used in the InfoWorks^{TM} model. Suggested values for Manning's *n*, tabulated according to factors such as vegetation, changes in cross sectional shape and size, surface irregularities, obstruction and channel alignment, that affect roughness are found in Chow (1959), Henderson (1966), and Streeter (1971). As distinct differences in bed material were difficult to identify along the Selangor River, the river bed roughness was estimated based on Manning's *n* roughness value from Chow (1964); sensitivity tests are described later (see Section 5.2.3). Table 3-4 shows a range of n values for various channels and rivers suggested by Chow (1964). The value of 0.03 was used throughout the catchment after trying various values.

Table 3-4: Values of the Manning roughness coefficient, *n* for various channels and rivers (Chow, 1964)

Type of channel	**Manning roughness coefficient (*n*)**
Smooth concrete	0.012
Ordinary concrete lining	0.013
Earth channels in best condition	0.017
Straight unlined earth canals in good condition	0.02
Natural rivers and canals	0.020 – 0.035
Mountain streams with rocky beds and rivers with variable sections and some vegetation along banks	0.040 – 0.050
Alluvial channels without vegetation	0.11 – 0.035

3.4.3 Tidal Control Gates

Hydraulic structures can affect river flow (Martin and McCutcheon 1999) and can be expected to influence river hydrodynamics and, (depending on the type of structure) water quality. Along the Selangor River the most important hydraulic structures are the tidal control gates (TCG) that are used to control the flow of water between the river and the surrounding land, which are mainly oil-palm plantations (Section 4.3).

In InfoWorks^{TM} RS the opening and closing of vertical sluice gates are controlled by 'logical rules' in either "automatic", "manual" or 'mixed' mode of operation. When in "automatic" mode, the gates are driven entirely using logical rules and move depending on the relative levels of water in the river and behind the gates; instructions can be updated when a time interval has elapsed. Instructions are interpreted as a command to move a gate to a "target" position, between fully-closed and the maximum opening value, and the gates will be moved to this target position at the maximum movement rate allowed in the subsequent time interval. In "manual mode" the target gate positions are specified directly irrespective of water levels. When the simulation time reaches or exceeds the time value defined, the gates will move to the corresponding gate-opening value, moving at the maximum rate possible.

For this study purpose, all the 10 TCGs (see Table 4-6 in Chapter 4) the operation of the gates uses a mix of logical rules, where manual and automatic modes are combined. Initially the gates are manually set to "closed" for the first six hours and then operated automatically (Table 3-5) based on the logical rules set-up (Table 3-6). The rules are repeated and applied throughout the simulation using a polling time of 60 seconds.

Table 3-5: Gate setting-up data; All gates remain closed, (irrespective of water levels) for the first 6 hours of model operation (starts with gate closed manually for first 6 hours) followed by gate operating (opening and closing) automatically after 6.00 am in the morning every day.

	Date-Time (hours) After 2007 00:00:00	**Opening (m)**	**Operating Mode**
1	0.00	Closed	Manual
2	6.00	0.00	Automatic
3	24.59		Automatic
4	Sequence 1-3 repeated daily		Manual/Automatic

Table 3-6: The two logical rules used for the TCGs. Rule 1: when the water level at the upstream node of gate (HEAD_upstream) is more than 0.4 m greater than the water level at downstream node (HEAD_downstream), the gate will be moved up 0.05 m. Rule 2: when the water level at the upstream node of gate is less than 0.4 m greater than the water level at downstream node, the gate will be moved down 0.05 m.

	Available Rules	**Rule Condition**	**Setting**
1	Rule 1	(HEAD_upstream) – HEAD_downstream).GT.0.4	MOVE = 0.05
2	Rule 2	(HEAD_upstream) – HEAD_downstream).LT.0.4	MOVE = - 0.05

All TCGs have the same logical rules but may have a different *mode of flow* through the gate at a particular time. The *mode of flow* through each gate, and hence the rate of water flow through the gate, is predicted by the model. InfoWorks^{TM} identifies 11 different modes of flow which are shown and described in Table 3-7. Logically, the TCGs should never appear in Mode 2, 3, 8, 9 or 10 which are the flow over the gate.

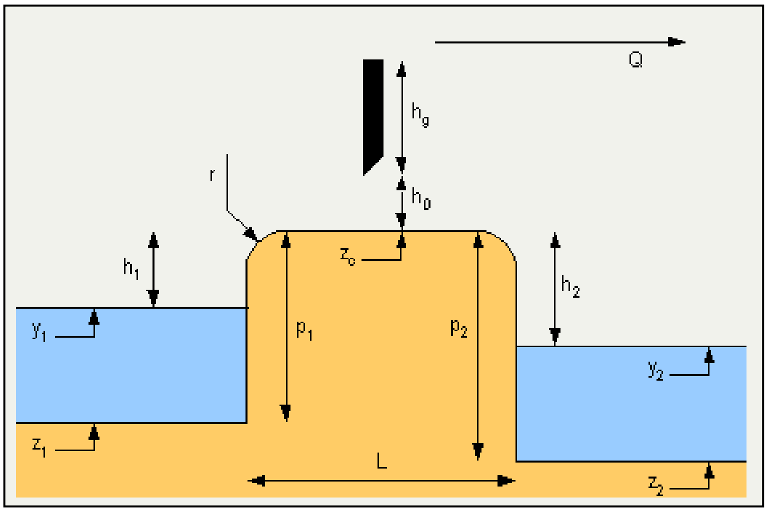
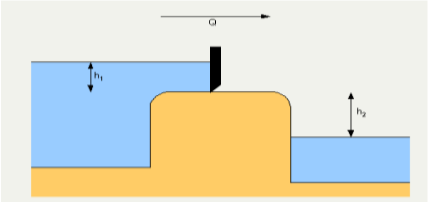
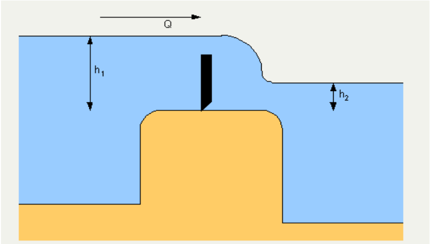
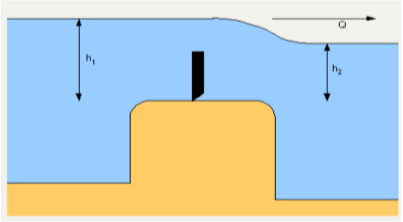
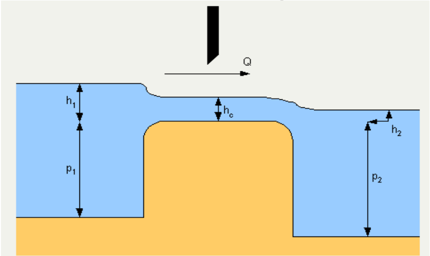
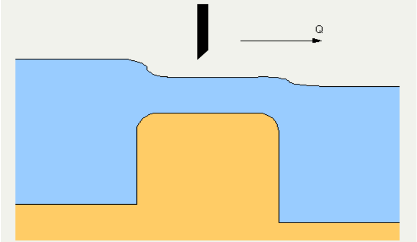
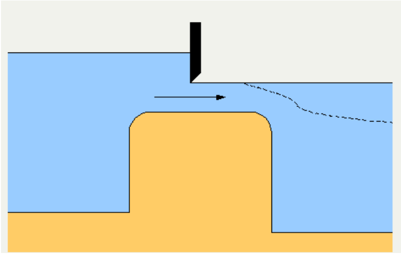
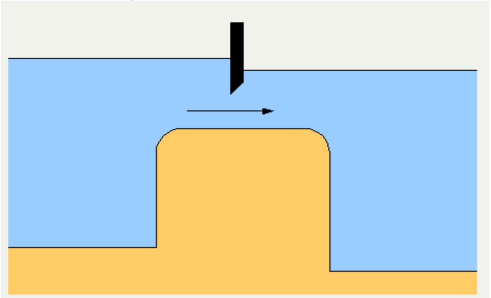
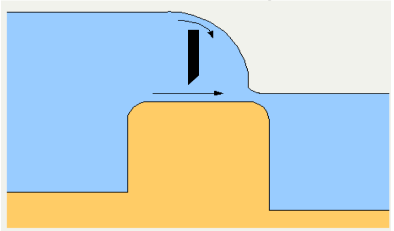
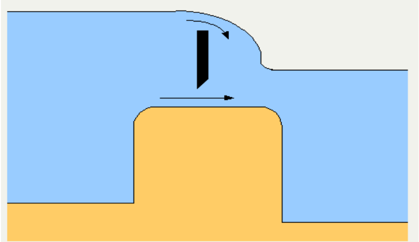


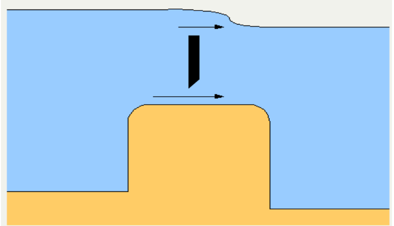
Figure 3-5: A schematic of the gate parameters used in the InfoWorks^{TM} manual (from Harrison 1967) which have been used in this model for the Tidal Control Gates

Table 3-7: The possible modes (states) of the gate (from InfoWorks^{TM} Manual).

Mode	State	Condition	Equation
0	Dry crest	$h_1 \leq 0.005$ (L-r)	$Q = 0$
1	Gate closed, upstream and downstream level below gate top  	$h_0 < 0.001$ $h_1 – h_g \leq 0.005$ (L-r)	$Q = 0$
2	Gate closed, free flow over gate  	$h_o < 0.001$ $(h_1 – h_g) > 0$ $(h_2 – h_g) / (h_1 – h_g) \leq 0.1$	$Q = C_{vs}C_e\, 2/3\, (2g)^{0.5}\, b(h_1\text{-}h_g\text{-}h_o)^{1.5}$ where C_{vs} is coefficient of surface velocity (ratio of surface water velocity to depth-average water velocity), $Ce = 0.602 + 0.075(h_1\text{-}h_g\text{-}h_o) / (p_1 + h_g + h_o)^{1.5}$ b is height of gate opening and g is gravitational acceleration (m s^{-2})
3	Gate closed, drowned flow over gate  	$h_o < 0.001$ $(h_1 – h_g) > 0$ $(h_2 – h_g) / (h_1 – h_g) > 0.1$	$Q = C_{rf}\, C_eC_{vs}\, 2/3\, \sqrt{(2g)}^{0.5}\, b(h_1\text{-}h_g\text{-}h_o)^{1.5}$ where $Ce = 0.602 + 0.075(h_1\text{-}h_g\text{-}h_o) / (p_1 + h_g + h_o)$; $C_{rf} = [1 – (h_2\text{-}h_g\text{-}h_o)^{1.5}]^{0.385}$ and g is gravitational acceleration (m s^{-2})

4	Free weir flow under gate  	$h_o \geq 0.001$ $(h_2 - h_1) \leq m$ $0.005(L - r) < h_1 < 1.5h_o$ $h_2 < h_o$	$Q = C_d\,(2/3)^{1.5}\,\sqrt{g}bh_1^{1.5}$ where $C_d = [1 - \delta\,(L - r)/b][1 - \delta\,/2h_1)(L - r)]^{1.5}$ and $r = 0.1$; $\delta = 0.01$ g is gravitational acceleration (m/s^2)
5	Drowned weir flow under gate  	$h_o \geq 0.001$ $(h_2/h_1) > m$ $0.005(L - r) < h_1 < h_o$	$Q = C_d\,(2/3)^{1.5}\,\sqrt{g}bh_1[(h_1 - h_2)/(1 - m)]^{0.5}$ where $C_d = [1 - \delta\,(L - r)/b][1 - \delta\,/2h_1)(L - r)]^{1.5}$ where $r = 0.1$; $\delta = 0.01$ and g is gravitational acceleration (m/s^2)
6	Free gate flow 	$h_o \geq 0.001$ $h_1 \geq 1.5h_o$ $h_2/h_o < (\alpha/2)\ \{\sqrt{}(1 + 16\ [h_1/(\alpha h_o) - 1]) - 1\}$	$Q = 0.60\sqrt{2g}bh_o^{1.5}\sqrt{\left(\frac{h_1}{h_o}\right) - \alpha}$

7	Drowned gate flow 	$h_o \geq 0.001$ $h_1 \geq 1.5h_o$ $\frac{h_2}{h_o} =\geq \frac{\alpha}{2}\left\{\sqrt{\left(1+16\left[\frac{h_1}{\alpha h_o}-1\right]\right)}-1\right\}$	$Q = 0.16bh_o\sqrt{2g}(h_1 - h_2)^{0.5}$
8	Free over and under gate 	As mode 6 and: $(h_1 - h_o) > 0$	Sum of Mode 6 and Mode 2 equations
9	Free over gate and drowned under 	As Mode 7 and: $\left(h_1 - h_g\right) > 0$ $\left(h_2 - h_g\right) \leq 0$	Sum of Mode 7 and Mode 2 equations

10	Drowned over gate and drowned under gate flow 	As Mode 7 and: $(h_1 - h_g) > 0$ $(h_2 - h_g) > 0$	Sum of Mode 7 and Mode 3 equations

3.5 Summary

The 1-D InfoWorks river simulation system comprises two modules, a hydrodynamic module and a water quality module. The water quality module can be configured in a number of ways but options based on Dissolved Oxygen have been used in order to calculate the parameters needed for the Malaysian Water Quality Index, namely dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), pH, suspended solids and ammoniacal nitrogen. This module describes the physical, chemical, and biological processes that affected the DO in the Selangor River. The model can compute either COD or BOD; it was set to calculate COD while BOD was then derived from COD using the measured BOD/COD ratio from water quality measured near Rantau Panjang. The processes of setting up the model from the river cross sections and operation of the tidal control gates, and the sequence of operation of the hydrodynamic and water quality modules, are described.

CHAPTER 4

DATA COLLECTION AND PREPARATION FOR MODELING OF THE SELANGOR RIVER

4 Introduction

This chapter describes study area including the location, climate, characteristics of the river system, soil, land use, human activities and the river pollution within the basin. This is followed by a description of the data sets that were utilised in this study, some of which were collected specifically for this study. These include important primary data such as the cross-sectional surveys of the river between the mouth of the Selangor estuary and Rantau Panjang, river elevation measurements, daily discharge from the Rantau Panjang gauging station, water quality data, longitudinal boat transects of the lower reaches on the river for water quality during both wet and dry seasons as well as measurements from around the tidal control gates. Secondary data sources (e.g. rainfall) are also described.

4.1 Description of study area

4.1.1 Location

Selangor is situated on the west coast of the Malaysian Peninsular between longitudes 101º 15’ and 101º 25’ East and latitudes 3º 20’ and 3º 25’ North. Its geographical position on the west of the Malaysian Peninsular has contributed to the State’s rapid development as Malaysia’s transportation and industrial hub, which in turn attracts migrants from other States as well as abroad. In 2002 Selangor had a population of 4.8 million. The population growth rate of Selangor from the period 1991 to 2000 was estimated at 6.02% making it the highest in Malaysia (Department of Statistics, 2001).

4.1.2 Climate

Similar to other parts of the west coast of Peninsular Malaysia, Selangor experiences an equatorial climate which is influenced by the regime of the north-east monsoon from approximately mid-November until March and a south-west monsoon between May and September. The monsoons are not severe in Selangor because the region is sheltered by the Main Range during the north-east monsoon and by the land mass of Sumatra during the south-west monsoon. During the inter-monsoon periods (April-May and mid-September - October) rainfall occurs due to thunder-storm activity in the afternoon and evening. According to 10 years (1998 to 2007) of rainfall data from the Malaysian Department of Irrigation and Drainage (DID), the average annual rainfall amounts to about 2000 mm. The highest numbers of rain-days at Kuala Selangor are found in the first and last one-third of the year. May to August have least rain and June is the driest month.

The average temperature throughout the year in Malaysia is constantly high and uniform. The annual variation is less than 2ºC but the daily range of temperature is large, being from 5ºC to 10ºC in the coastal areas and from 8ºC to 12ºC inland (Malaysian Meteorological Department, 2006). However, the high daytime temperatures found in continental tropical areas are never experienced. It may be noted that an air temperature of 38ºC has very rarely been recorded (Malaysian Meteorological Department, 2006). Although days are frequently hot, nights are reasonably cool everywhere. May and June have the highest average monthly temperature in Kuala Selangor, and November to January are the months with the lowest average monthly temperature (Malaysian Meteorological Department, 2006). The humidity is consistently from 70% to 90% and the average evaporation rate is between 4 mm and 6 mm per day (Department of Irrigation and Drainage, 2002).

4.1.3 The Selangor River system and its characteristics

The Selangor River is one of the major rivers in the State of Selangor. The river rises from a mountainous spine known as the Main Range of Malaysia (Banjaran Titiwangsa); the main channel of the Selangor River is ~110 km in length (LUAS, 2007); it flows in a south-westerly direction before draining into the Straits of Malacca. The boundaries of the catchment and the river’s main tributaries are shown in Figure 4-1. Selangor River basin, which has an area of ~2,200 km^2, covers nearly a quarter of the total area of the Selangor State. For the purpose of this study, the basin is divided into two catchments; the upper and the lower catchments. In the upper catchment, the Selangor River has three main tributaries, each of them comprising many other small tributaries connected in a dendritic pattern. The headwaters of the Selangor River originate from the hilly forest reserves, and flow westward and meeting at Rantau Panjang. In the upstream stretches, the river runs down steep slopes where ground elevation changes from 240 m to 20 m within 50 km length. In the lower catchment the river mostly passes through rural areas including rubber and oil palm estates before draining into Malacca Straits.

The lower catchment of the Selangor River has the total area size of about 500 km^2 (below Rantau Panjang); the river over this stretch is about 57 km in length and has no significant tributaries. This lower section of the river is flat with several meandering reaches. The settlements and townships are more developed in the lower catchment; the major town is Kuala Selangor (Figure 4-1).

4.1.4 Soil

According to Hamzah et al. (2007) the lower reach of Selangor River flood plain is covered by alluvial soil which mainly contains clay and sand layers underlain by meta-sedimentary rock. The clay, sand and gravel layers are thicker towards the coastal area increasing from 15 to 38 m (Hamzah et al. 2007). These alluvial soils tend to erode and, during the rainy season, this river will carry high sediment loads. Figure 4-2 shows the soil classification in details where generally the upper catchment is mostly covered by sedimentary soil while the lower catchment is dominated by clay.

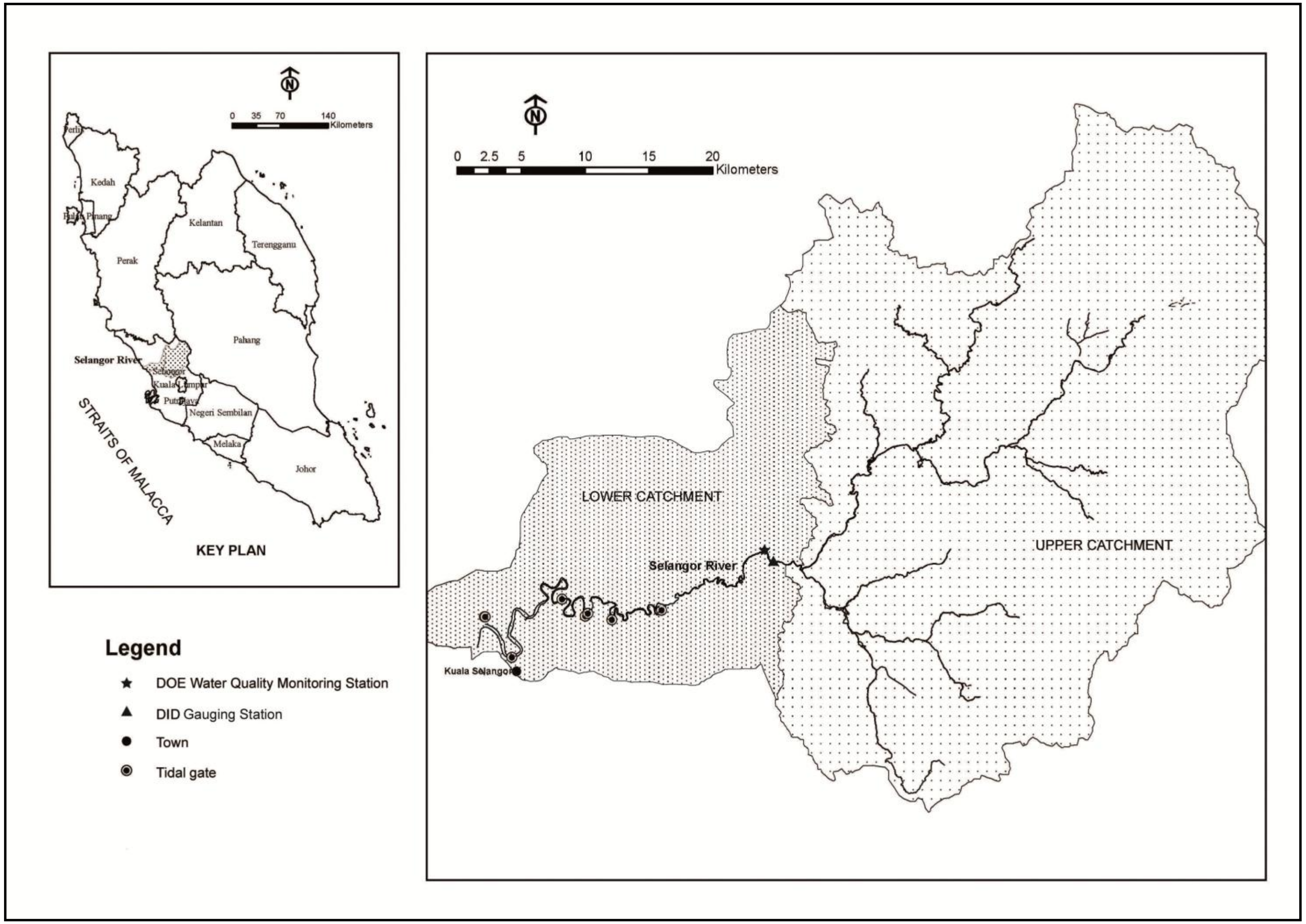


Figure 4-1: The location of Selangor River basin on the west coast of Malaysia (left panel) and the division of the basin into an upper and lower catchment (right panel)

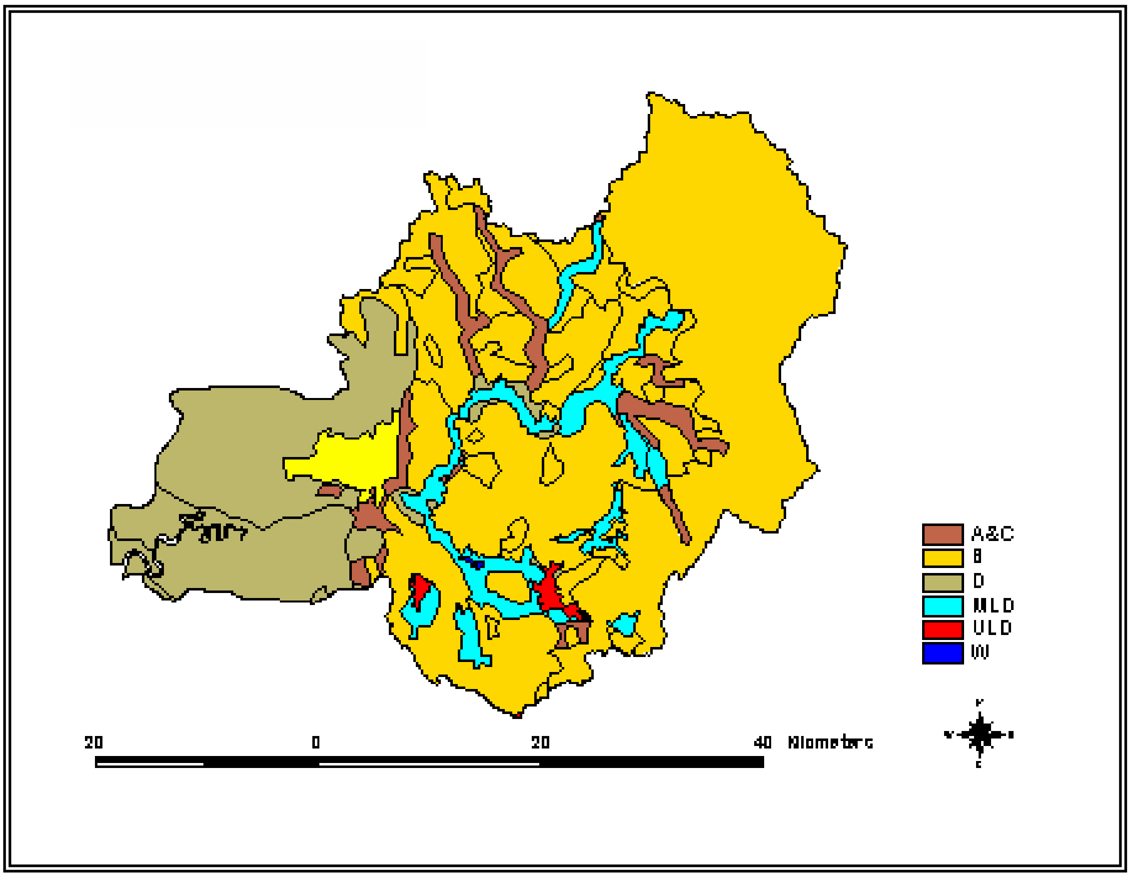


Figure 4-2: Soil type classification in Selangor River basin. Alluvial soil (*Telemong-Akob-Local Alluvium*) (A & C); sedimentary soil (*Serdang-Kedah, Serdang-Bungo Munchong, steepland, Munchong-Seremban and Renggam-Jerangau*) (B); Clay (*Kranji*and *Selangor-Kankong*) (D); mined land (MLD); urban land (ULD) and water (W) from Hamzah et al. (2007).

4.1.5 Land-use

The river basin in its present state supports upland tropical forest and some lowland swamp forest, but agriculture, largely oil palm and rubber, occupy much of the lowlands. However, urban development shows a growing trend especially in the middle and lower parts of the basin. Agricultural land use is declining and mining is stagnant, and much of the land used for these activities will be converted to urban development in the next decades. Rivers are now contaminated by drainage and run-off from multiple sources such as factories, mining, palm oil mills, pig farms and also agricultural runoff from oil palm and rubber plantations.

The sub-catchment characteristics are generally related to human activities. Table 4-1 below shows the land use in 1990 and 1997, and its change over that period; forest areas constitute the maximum portion of the basin followed by agriculture. However, forested and agricultural areas have decreased 6.8% and 6.2% respectively, while urban areas have increased by around 340% with an additional 8728 hectare being developed. This shows that residential construction was the greatest land use change between 1990 and 1997.

Table 4-1: Land use change in the basin for 1990 and 1997 (source: Department of Agriculture, 2001)

Land use Category	**Area (ha)**		**Change**	
	1990	**1997**	**(ha)**	**(%)**
Forest reserve	89,900	83,800	-6,100	-6.8
Cleared area	286	4,067	3,781	1,320
Swamp	16,900	16,100	-800	-4.8
Grassland	1,140	1,610	470	42
Town/urban	2,580	11,310	8,730	340
Mining	13,660	10,460	-3,200	-23
Agriculture	70,400	66,000	-4,400	-6.2
water	-	1,250	-	-

Land use in 1997 showed a clear increase in urbanisation (red) at the expense of agriculture (green) and ex-tin mining land (purple) particularly in the middle of the basin (Figure 4-3). Industrial growth within middle part of basin is expected to be low due to the present oversupply of industrial land. The Local Plan for Kuala Selangor (2005 – 2015) however shows a significant potential increase in industrial areas especially in the north-eastern part the basin. The change of land use is projected to be 73% within the planning period. The summary of land development is shown in Table 4-2.

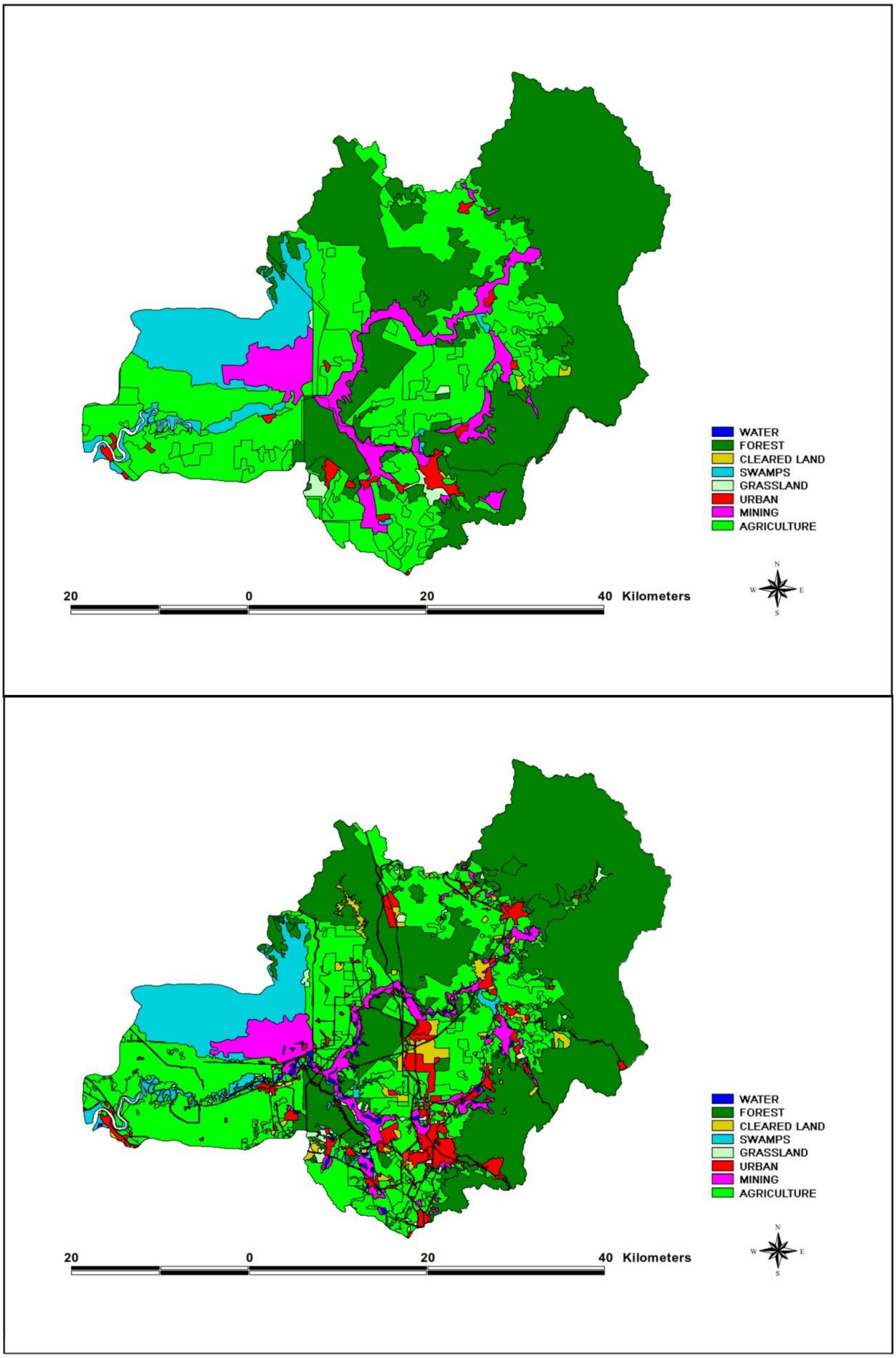


Figure 4-3: Land use in 1990 (upper panel) and 1997 (lower panel).
(Source: Department of Agriculture, 2001)

Table 4-2: Projection of land development in the lower Selangor River basin, 2005 – 2015 (Local Planning for Kuala Selangor District 2015 Report, 2007)

Type of development	Area (hectare)			
	2005	2010	2015	% change
Housing	2,410	2,850	3,390	40
Community Facilities	707	910	889	26
Trading	35	46	61	75
Industry	417	601	949	127
Recreational	353	1,135	1,493	323
Cumulative Total	**3,925**	**5,545**	**6.782**	**73**

4.1.6 Human activities by the coast and their impact

The area is an important base for sea fishing and the estuary is one of the largest producers of aquaculture products in Malaysia. Abstraction of river sand for commercial use has been an important economic activity for more than 50 years. Based on the 1997 Department of Irrigation and Drainage (henceforth DID) records, 10 of the 19 sand mines in Malaysia are located in the Selangor River catchment. About 12 million tonnes per year of sand and gravel were extracted from the Selangor River and the river bed has lowered at a rate of 0.07 to 0.15 m y^{-1} over the past two decades (Ashraf, 2010).

4.1.7 River pollution

In Malaysia, the Department of Environment (henceforth DOE) had 18,956 registered water pollution sources in 2006 consisting mainly of sewage treatment plants (47.8%), followed by manufacturing industries (45.1%), animal farms (4.6%) and agro-based industries (2.6%). The number of sewage treatment plants under the management of the Indah Water Konsortium Sdn. Bhd. (IWK) increased to 9,060 in 2006 compared to 8,782 plants in 2005. Selangor had the largest number of sewage treatment plants (2,563:28.3%). Of the total number of sources from manufacturing and agro-based industries, Selangor state was identified as having the highest number of water pollution sources (20.5%). The major issues associated with each source in the Selangor River Basin are listed in Table 4-3.

Table 4-3: The pollution sources in the Selangor River Basin and the main issues associated with each (Department of Irrigation and Drainage, 2002).

Source	Issue
Animal Waste	There are many pig farms located within the upper part of Selangor river basin. When the holding ponds for solid waste retention are overloaded, the waste will normally be discharged into water courses without proper treatment causing high ammoniacal nitrogen, *E.Coli*, BOD and COD. Other animal husbandry activities are also contributing.
Industrial effluent	Untreated industrial effluent discharged into waterways is one of the main sources of pollution and occurs mainly from the industrial areas.
Construction and Earthwork Activities	Although the effects of these activities on the river are only transient, the increase in total suspended solids in the Selangor river is evident. Erosion assessment in the whole Selangor River basin indicated overall soil losses of about 19 tonnes per hectare per year (Department of Irrigation and Drainage 2002)
Sewage Discharge	As most of the areas within the Selangor River catchment are still rural, these areas have not been served with centralised sewage treatment. Partial and raw sewage have caused high BOD and *E.Coli* in many segments of the river system.

According to a DID report (Department of Irrigation and Drainage, 2002), the quality of the water has deteriorated from Class II (conventional treatment required) to Class III (extensive treatment required) in the middle and lower basin of the Selangor River.

4.2 River hydraulic data

4.2.1 Bathymetric (river cross section) data

Bathymetric data are the most important in developing the river model (see Section 3.4.1). According to U.S. Army Corps of Engineers (1996), appropriate bathymetry data is the factor (besides boundary conditions and mesh design) that contributes 80% of the ability of a numerical model to produce accurate results. Bathymetric data in the form of XYZ coordinates for the study sites were obtained from Selangor Department of Irrigation and Drainage (DID, 2000) from river surveys conducted between 1986-1989 and digitised in 1999. A combined operation between the DID and four appointed land surveyors resulted in a survey that generated 106 cross-sections at one km intervals for a distance of 106 km up the river. The widths of cross-sections were in the range of 500-1000 m and included the flood plain as well as the river channel; measurements of the underwater bathymetry of the Selangor River were collected by boat with a fathometer and geo-referenced to a mapping-grade global positioning system (GPS). These data were then digitised in a geographic information system (GIS). For this study the 58 cross-sections between the mouth and Rantau Panjang (km 57) are used to define the river dimensions in the hydrodynamic model. The river slope for first 40 km from the mouth is 1:10,000 and the remaining upper 17 km is 1:3,500.

4.2.2 Tidal data

Measurement of tides is essential to provide information on water levels via amplitude and phase of the tidal harmonics at the downstream boundary as the tide is the dominant forcing mechanism at the estuary mouth of the Selangor River. An automatic recording tide gauge (model TGR-2050) was installed by the National Hydraulic Research Institute of Malaysia (NAHRIM) five kilometres upstream from the river mouth at Kampung Pasir Penambang (Figure 4-4) which gave 32 days (15 November to 16 December 2007) of continuous recording of tidal stage with an interval logging period of 10 minutes (Figure 4-5). These data were used to compute the 25 harmonic constituents of the tide using a tidal analysis software package ‘Tidal

Analysis TAN' (a commercial package distributed by Geomatics) which applies a least-squares method and followed by Fourier transformation analysis. This software is extensively used by The Royal Malaysian Navy which is responsible for the prediction of the harmonic constituents at the standard ports in Malaysia. The dominant seven harmonic constituents were used to force the downstream boundary (the estuary mouth) of the hydrodynamic model. The amplitudes and phase of these seven largest constituents are shown in Table 4-4. The mean tidal height in the estuary is +2.05 m relative to Malaysia's National Geocentric Datum (GDM 2000), introduced by the Department of Survey and Mapping Malaysia in 2002. The fortnightly spring tidal range measures 3.80 m and the neap tidal range is 1.5 m. Note that the water levels around lowest spring tides shown in Figure 4-5 are truncated due to the tide gauge drying; no corrections have been applied to allow for this.

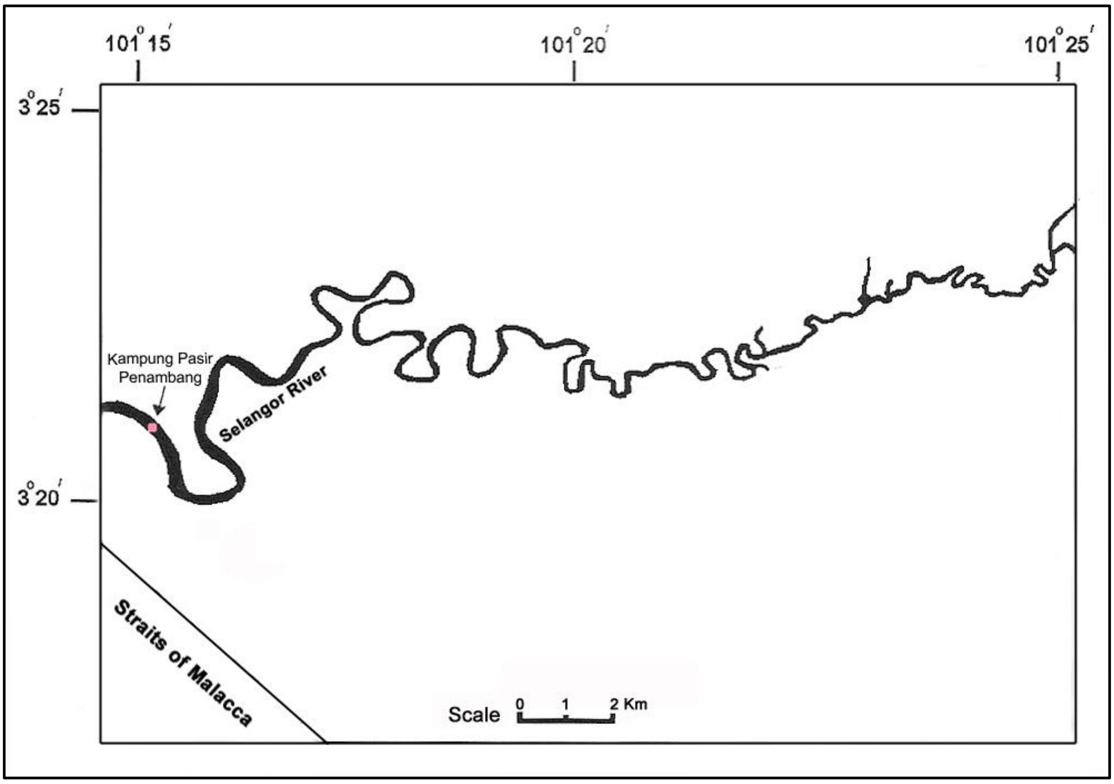


Figure 4-4: Location of tidal stage measurement at Kampung Pasir Penambang (km 5), Selangor River.

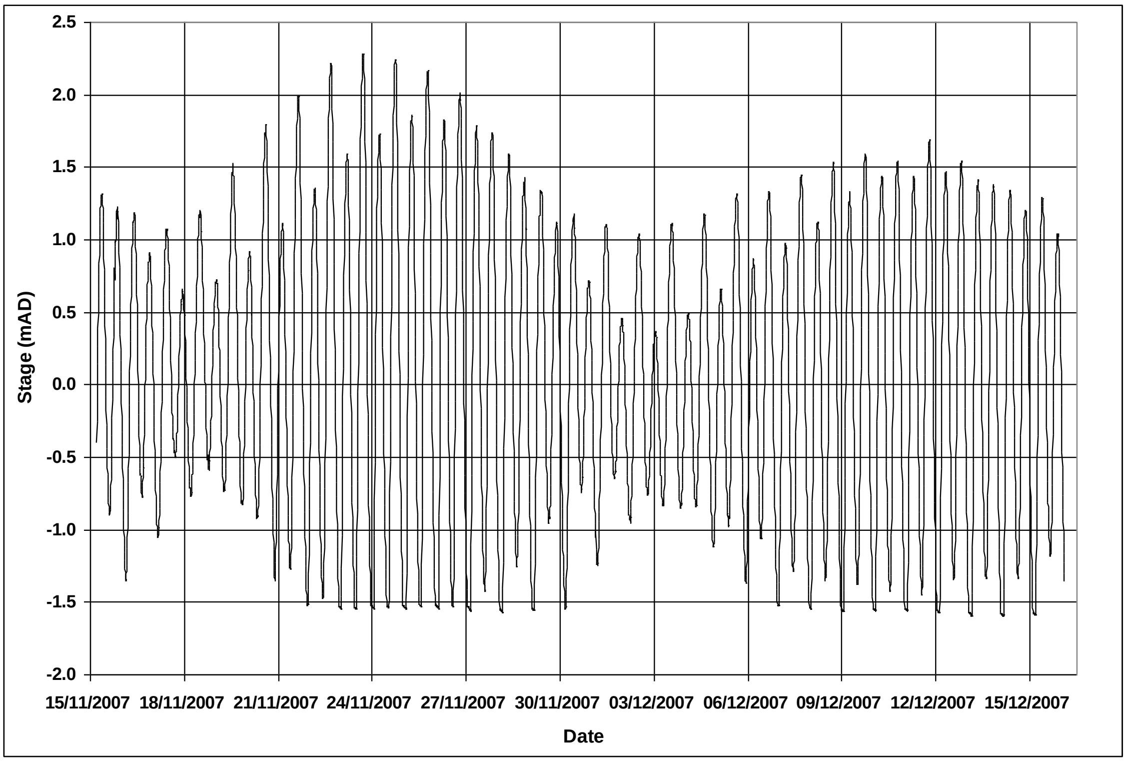


Figure 4-5: Tidal stage at Kampung Pasir Penambang (km 5), Selangor River from 15 November to 16 December 2007.

Table 4-4: The seven largest harmonic constituents for Selangor River estuary from measured water levels Kampung Pasir Penambang (km 5) for the period of 32 days (15 November to 16 December 2007).

Name	**Amplitude, H (m)**	**Phase, g (degree)**
M_2	**1.297**	**150.223**
S_2	**0.580**	**150.223**
K_1	**0.218**	**201.767**
O_1	**0.052**	**121.883**
N_2	**0.232**	**136.930**
K_2	**0.158**	**201.767**
Mm	**0.125**	**1.625**

4.3 River flow data at Rantau Panjang

Since 2000 the Department of Irrigation and Drainage has maintained an automated gauging station at Rantau Panjang (the upper boundary of the model – see Figure 4-6) which is 57 km from the river mouth. The daily river flow data covering the period from 2000 to 2009, used to represent the discharge coming from the upper catchment, are summarised in Table 4-5. These data were obtained from DID in Selangor but are only available approximately one year in arrears.

The volume of river flow (m^3s^{-1}) at Rantau Panjang is based on the measurement of the water level. Simultaneous measurements of the water level, flow velocity, and the river cross section at the gauging station were used to calculate the discharges at different stages of flow and hence to construct the stage – discharge curve, also known as the 'rating curve'. The rating curve may no longer valid when there are changes to the river cross section where the measurements took place. In order to make sure the rating curve is applicable, the DID produces a new curves for each gauging station whenever a change occurs, or at least once a year.

A submersible pressure transducer system is used to measure the water level and telemeter the data in real-time for recording in the Rantau Panjang gauging station (Figure 4-6). The sensor (Figure 4-7) measures the pressure head at the point in the water column and this pressure value is converted to water height above the sensor. The sensor has an accuracy of 0.02% of full-scale output and excellent long-term stability. A small stilling pipe is used to protect the sensor from damage by debris including bed load in the channel during high flow events. Data are transmitted to the DID office by telephone or satellite. The Master Telemetry Unit (MTU) in the DID office receives and displays the data for local use. An automatic e-mailer program in the DID office in each State sends all the data through the internet to the Hydrology and Water Resources Division of DID in Kuala Lumpur that operates a Centralized Flood Monitoring System.

Figure 4-6: Gauging station at Rantau Panjang

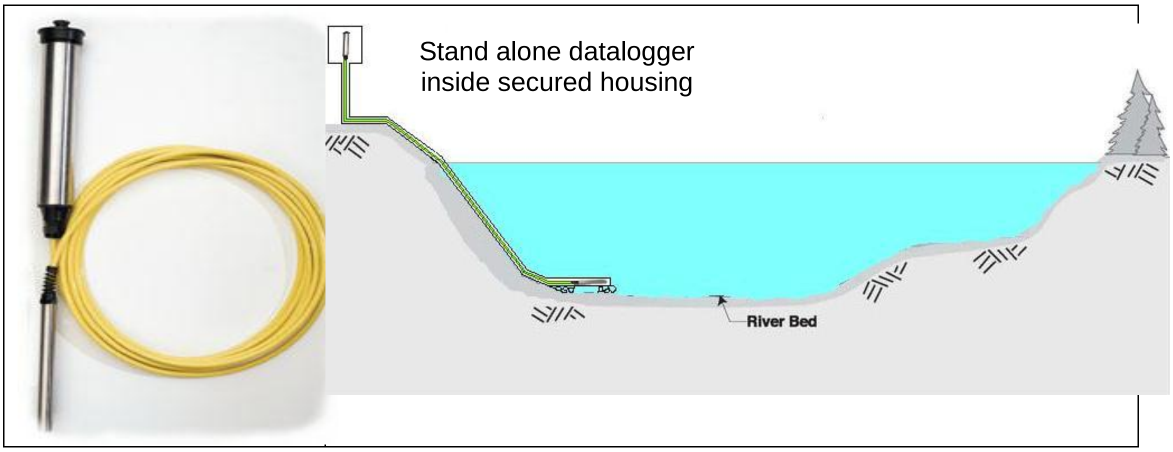


Figure 4-7: Submersible pressure sensor (left panel), shown here with external stand-alone data logger for water level measurement.

Bbiological growth and silt built-up occurs around both the sensor and stilling pipe (Figure 4-8) after a period of time so the underwater unit is serviced monthly, as is the rest of the system including, where used, the data logger and power supply. The solar panels used to provide power to the Rantau Panjang Gauging Station are checked and cleaned of any debris including bird droppings and leaves.

Figure 4-8: Submersible pressure sensor and stilling pipe before (left panel) and after (right panel) cleaning.

4.3.1 Discharge measurement

Records of stage (water level) are important in river gauging because the rate of flow is calculated directed from stage via the discharge or rating curve. After a rating curve has been established for a stable channel, the rate of flow can be directly determined from stage reading alone. Reliability of the stage reading is, therefore, of great importance.

The velocity-area method is the standard approach employed by the DID to measure discharge of a river and it depends on the measurement of velocities at various points across the river, using a current meter. The velocity-area method is built around the premise that the discharge, Q, can be derived if the vertical cross-sectional area and its respective flow velocity are known

$$Q = vA$$

where v is the mean velocity as measured by the current meter and A is the cross-sectional area. Usually the river cross-section is subdivided into segments and the discharge determined for each segment (Figure 4-9). By measuring the velocity at different depths in a sub-divided area, the mean velocity for the segment can be calculated. And thus

$$Q = \sum_{sumoverallsegments} v_{segment} A_{segment}$$

The velocity measurements required to calculate the volume flow at Rantau Panjang were made using a bank-operated cableway. Figure 4-10 shows a typical cableway installation of the type used at Rantau Panjang. A traveller carriage running on the main cable is used to move the current meter and sinker weight across the river. Velocities are measured at 0.2, 0.6 and 0.8 of the water depth for each segment of the cross-section then the values of velocity are averaged. The advantages of using the cableway method for gauging is personnel safety as no manpower is required on the water although some disadvantages are encountered when it is deployed over severely polluted rivers or where there are ongoing upstream logging activities. This cableway system is limited to a cross-section distance of approximately 400 m.

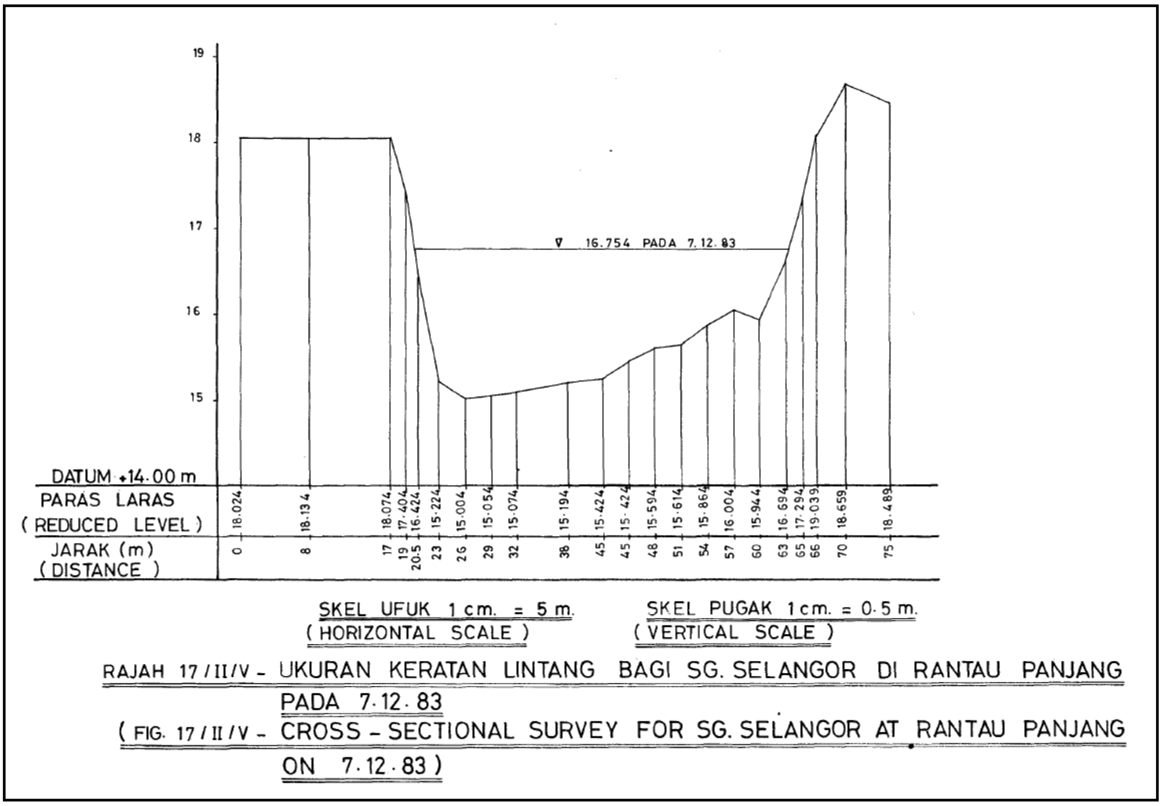


Figure 4-9: Cross sectional survey for Selangor River at Rantau Panjang 7 Dec 1983

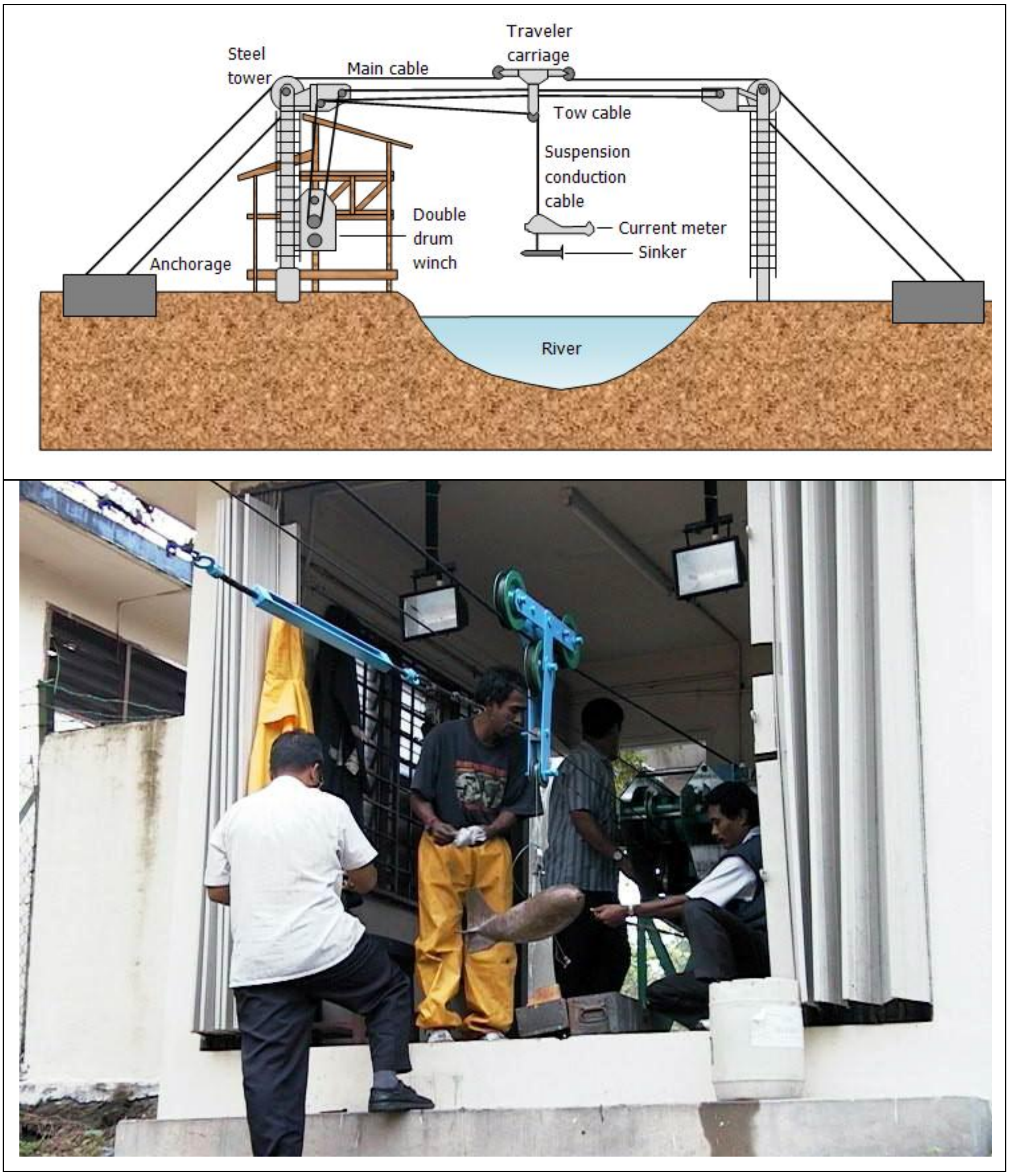


Figure 4-10: Typical cableway installation drawing (upper panel); cableway with weight attached for deployment

4.3.2 Stage-Discharge Relationship

The aim of the current-meter and the direct discharge measurements is to prepare a stage-discharge relationship which is also known as the rating curve. The measured values of the discharge are plotted against the corresponding stages (water level) enabling the rating curve to be constructed for the Selangor River at Rantau Panjang. This curve is then used to compute the discharges from the water depth. A typical rating curve is shown in Figure 4-11.

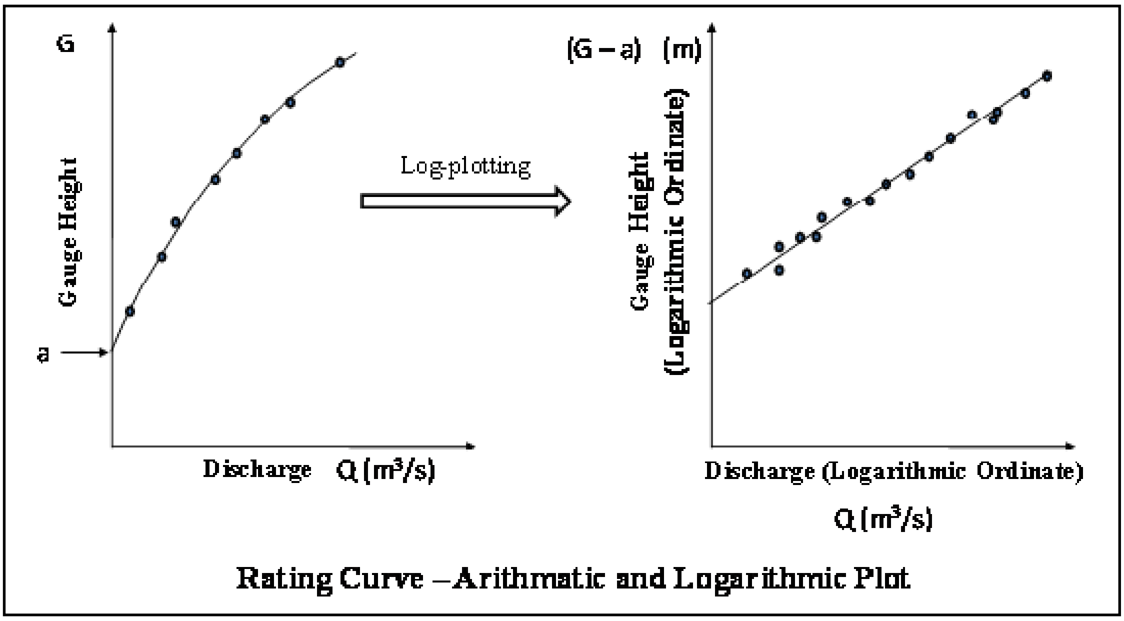


Figure 4-11: Stage Discharge Curve – Arithmetic Plot (left) and Stage Discharge Curve – Logarithmic Plot (right). Source: DID Manual

Table 4-5: Summary of daily river flow for the period of ten years (2000 to 2009) at Rantau Panjang in the Selangor River, Malaysia.

Year	Peak Flow ($m^3 s^{-1}$)	Minimum flow ($m^3 s^{-1}$)	Average Flow ($m^3 s^{-1}$)	Missing data (%)
2000	314	3	59	8
2001	210	14	46	2
2002	196	8	38	3
2003	214	13	50	3
2004	276	22	53	2
2005	196	17	35	6
2006	309	27	86	7
2007	372	28	94	2
2008	382	22	68	3
2009	287	27	65	3

4.4 Tidal Control Gates

The Selangor River has no significant tributaries downstream of Rantau Panjang. The lower catchment of the Selangor River is mostly covered by oil palm plantations. In order to prevent the brackish water from the river estuary flowing into the irrigation/ drainage canals and destroying the valuable crops, DID installed a total of 16 tidal control gates (TCGs) in the tidal area of the Selangor River system. The gates are designed to be closed around high tide when the water level at the downstream (river) side of the gate is higher than upstream (irrigation canal) side. When the water level in the river is lower than in the canals, the gates are opened, allowing water to drain off from the plantation canals; at this time any contaminants from the catchment also are discharged into the river through the gates. These hydraulic structures will contribute to the volume of river flow but can also be expected to impact on the water quality of the river through increases in the nutrient concentration, turbidity, heavy metals, or reduction in dissolved oxygen and pH (Portnoy et al. 1987; Vranken and Oenema 1990).

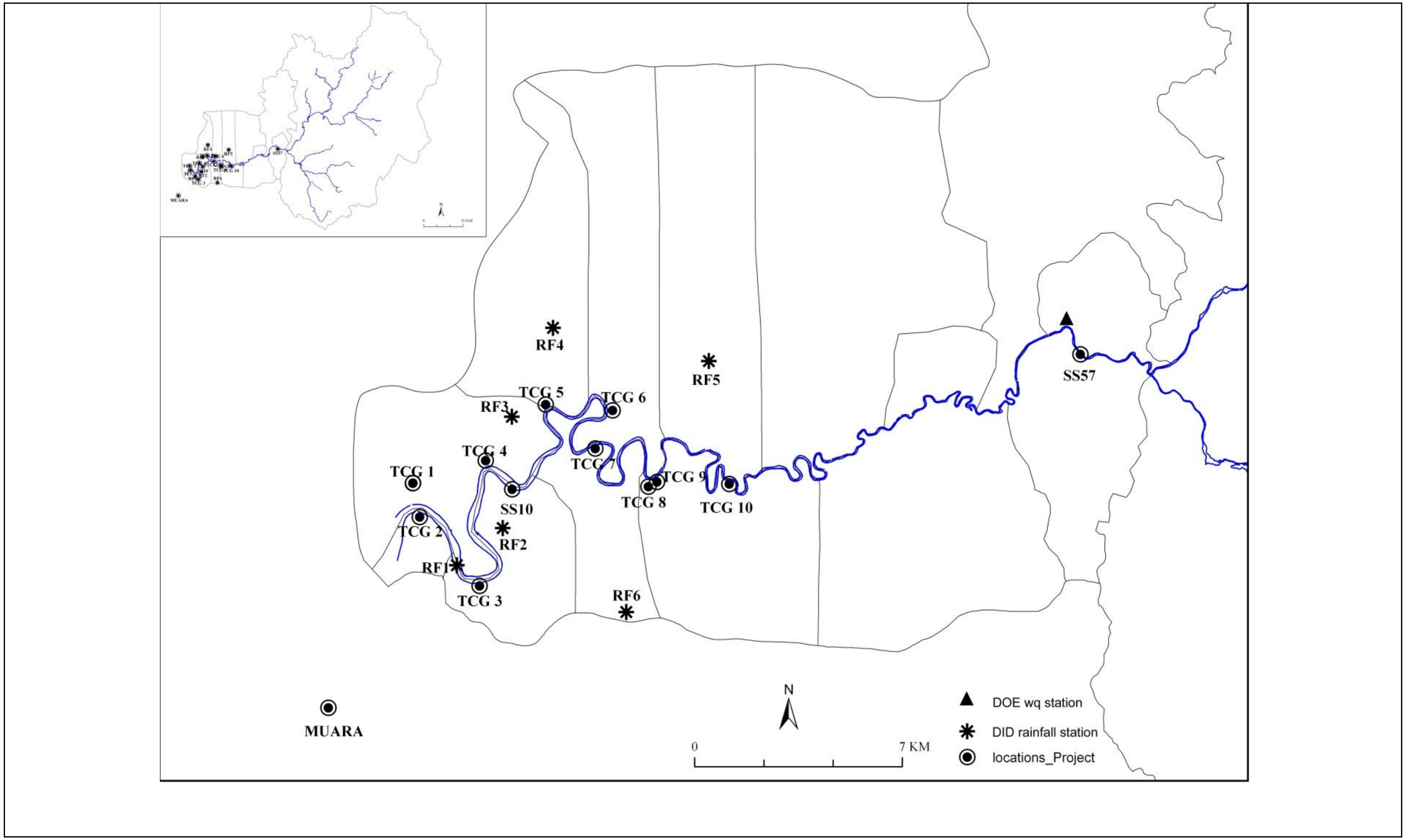


Figure 4-12: Map of lower reaches of the Selangor river showing the location of the sampling stations including the 10 TCGs used in the model, and the location of the rainfall stations (RF1-RF7). Also shown in the location of Rantau Panjang (SS57)

Figure 4-12 shows the locations of the 10 largest gates. Their distances from the river bank were measured using a Garmin 60CSX handheld GPS (Table 4-6). Accuracy achieved during the measurements was ±4m. Their crest levels, the height of each gate crest relative to the Geocentric Datum of Malaysia-GDM 2000 and mean sea level (MSL), were obtained from the DID. The measurement datum in Peninsular Malaysia is Kertau 1948.

Table 4-6: The tidal control gates, with their ID numbers and names, used in the model together with their locations, distances from the river and crest elevations.

MODEL ID	Gate Name	Distance from estuary (km)	Distance to river bank (m)	Elevation (m)	Notes
TCG1	Sg Yu	3	675	10	
TCG2	TgKeramat	5	245	21	
TCG3	TelukPenyamun	7	110	16	
TCG4	TiramBurok	12	226	11	
TCG5	Bukit Belimbing	17	165	10	
TCG6	Lubok Jaya	19	185	9	
TCG7	Jalan Kedah	23	137	13	
TCG8	Tg Siam	29	220	11	Triple gate
TCG9	PokokPauh	29	143	9	
TCG10	Kemsey	34	72	11	

These 10 tidal control gates, which were all of a similar design and mainly automatic, were incorporated into the model: there were a number of other smaller gates of various designs but these drained small areas (generally <1 km^2) and contributed only a small amount of water to the river. Figure 4-13a and Figure 4-13b show the design drawings for the 10 major TCGs. Most of the gates were operated automatically, controlled by the water levels on each side of the gate. Some were manual, notably the triple gate (three of the normal gates side-by-side) at Tanjong Siam (TCG8) and were operated by a gate-keeper. It has been assumed in the model that the opening and closing of the manual gates by the gate-keeper used the same criteria as the automatic gates but it is unlikely that the manual gates were always opened or closed at the correct times.

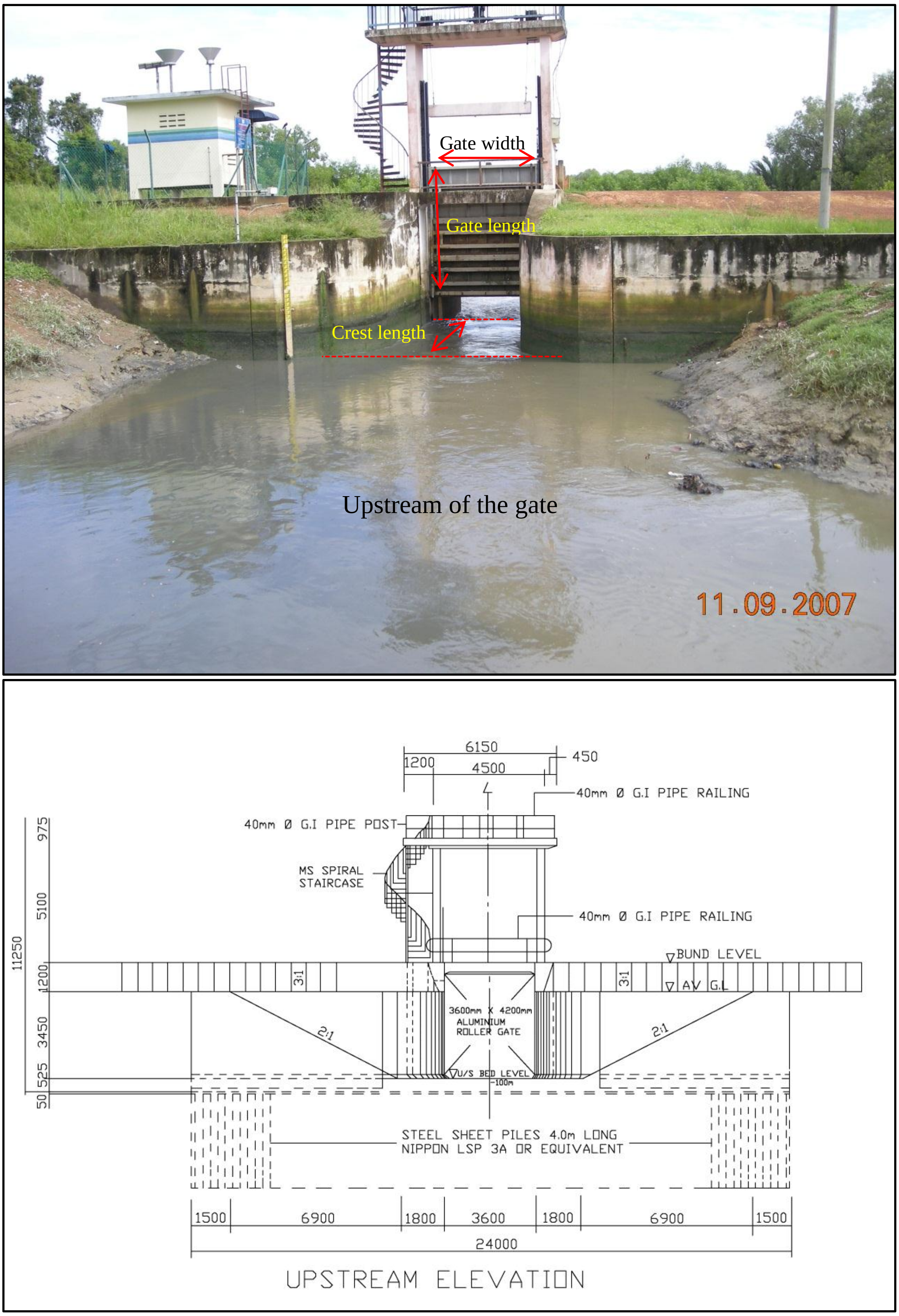


Figure 4-13a: Teluk Penyamun tidal control gate, (TCG 3) looking from upstream of the gate (upper panel) and the typical tidal control gate dimensions from upstream elevation (lower panel). Gate width, gate length and upstream crest length are also shown.

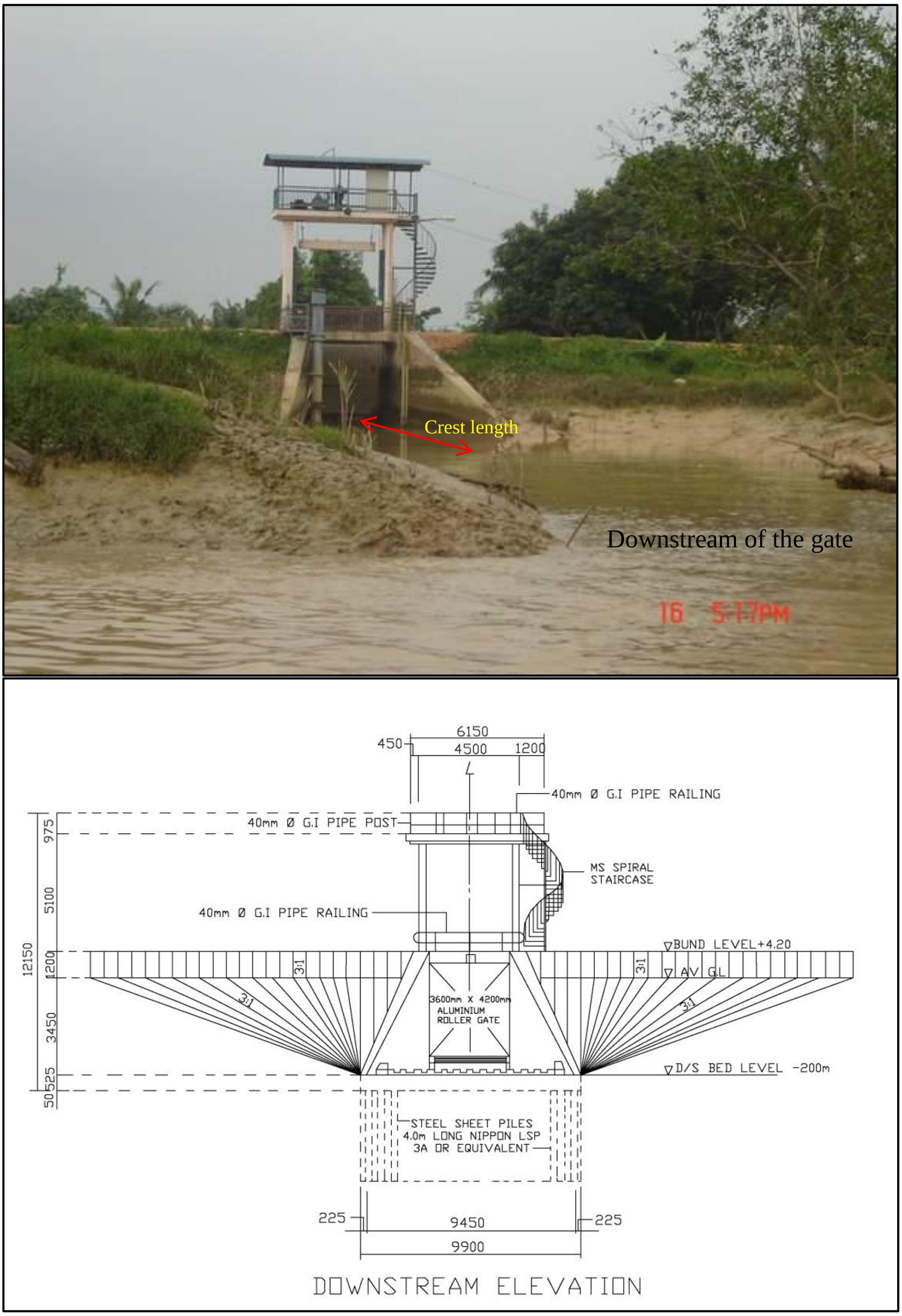
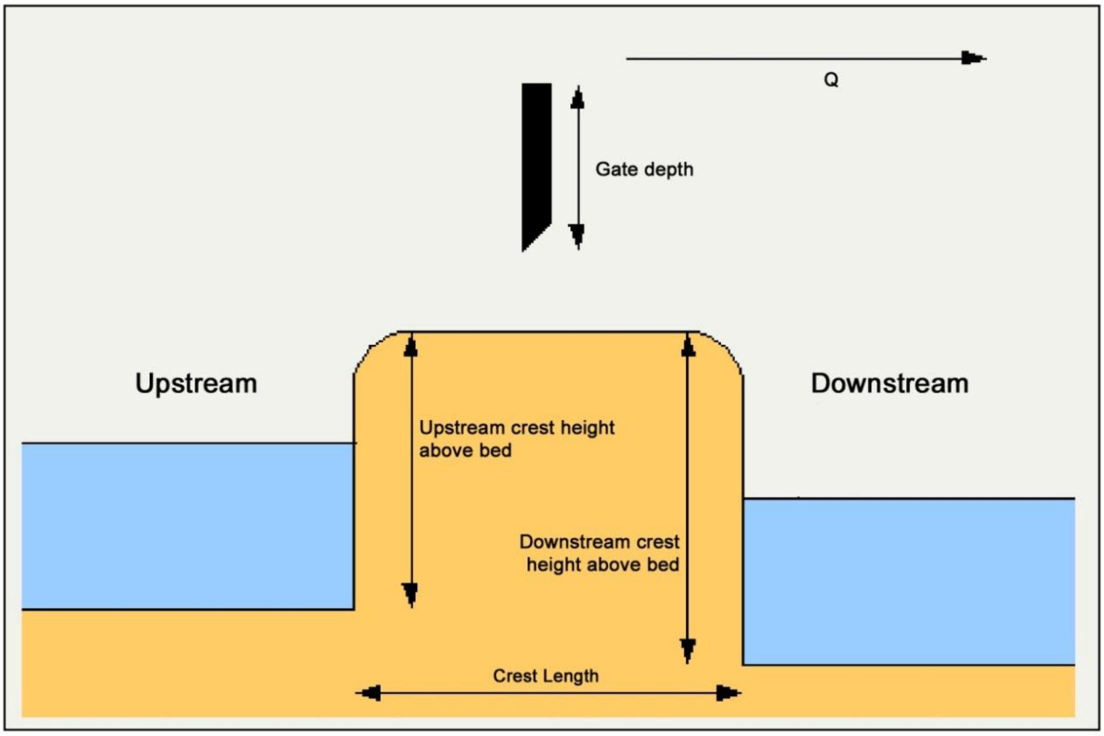


Figure 4-13b: Teluk Penyamun tidal control gate (TCG 3); looking from downstream of the gate (upper panel) and the typical tidal control gate dimensions from upstream elevation (lower panel). Downstream crest length is shown by the red arrow.

The tidal gate information applied in the model is shown as illustrated in Figure 4-14.



Gate geometry	i) Crest level (mAD) = -1.95 ii) Crest length (m), L = 30.0	i)The level refer to ii) As shown in Figure 4-14
Height of gate crest above bed	Upstream (m) = 0.286 Downstream(m) = 1.786	As shown in Figure 4-14
Gate Data	Depth (m) = 4.2 Gate width (m) = 3.6	As shown in Figure 4-13a

Figure 4-14: Gate geometry and dimension applied in the model. Diagram (not to scale) adapted and modified from the InfoWorks Manual.

4.4.1 Water Levels behind the TCGs

Operation of the model requires the level of the water in the canals behind the TCGs to be specified initially. No data were available so manual measurements of the water level were made at each of the TCG. Wet season water levels were measured between 19-21 November 2008, morning and evening, at every gate immediately prior to the gate opening. Where no gauge board was available levels were measured relative to a known gate feature using a tape measure.

Figure 4-15: Measurement tape used to determine the water level upstream of the gate (left panel) and existing gauge board at the downstream of the gate (right panel).

4.4.2 Canal dimensions and lengths

The model also requires. A representation lengths and cross-sections of the canals and drains within the area drained by each TCG is required by the model to allow the changes in water depth in the drained areas to be tracked over time. Access to the plantations was restricted and not available to scientists involved in this study. Therefore measurements were taken from a 2007 SPOT 5 satellite image of the area which has a 2.5 m resolution; this provided the required information on the lengths and width of each section of the drainage features. These have been divided into three type of features, primary ‘canals’ major drains and secondary drains. Primary canals are ~20 m wide and generally run around the boundary of each drainage area. The main drains (~10 m wide) usually run between the primary canals and smaller secondary drains. The depths of the primary canals and drains could only be measured at a few locations where access from public roads was available; based on these measurements a single depth was used for each of the three drainage features, 1.5 m, 1.0 m and 0.5 m respectively for the canals, major drains and secondary drains.

Table 4-7: The lengths and widths (± 2.5 m) of the major drainage features in the areas drained by each TCG.

Gate	Canal (m)			Main Drain (m)			Secondary Drain (m)		
	Length	Width	Depth	Length	Width	Depth	Length	Width	Depth
TCG1	6376	20	1.5	10340	10	1	5000	30	0.5
TCG2	9680	20	1.5	-	-	-	5000	7	0.5
TCG3	8200	20	1.5	-	-	-	7800	9	0.5
TCG4	7000	20	1.5	7000	20	1			
TCG5	120	20	1.5				2500	8.5	0.5
TCG6	205	20	1.5	15220	13	1			
TCG7	150	20	1.5				8625	4	0.5
TCG8	7000	20	1.5	13260	30	1	-	-	-
TCG9	120	20	1.5	5100	11.5	1			
TCG10	120	20	1.5	4580	10.6	1			

4.5 Water Quality Data

4.5.1 DOE Sampling Stations

The DOE has maintained seven water quality sampling stations in the Selangor river basin since 1978 (Department of Environment 2007). All but one of these seven stations is above Rantau Panjang. The station downstream near Rantau Panjang is at km 55; data from this station were used to define the water quality at the upper boundary of the model. Water samples are collected at these stations once every two months and returned to the DOE laboratories for analysis. The following water quality variables are measured: ammoniacal nitrogen (NH_3-N), dissolved oxygen (DO), Biochemical Oxygen Demand (BOD), pH, temperature, total suspended solid (TSS), Chemical Oxygen Demand (COD) and *Escherichia coli* (e.coli). The water sampling and maintenance for most of the DOE water quality monitoring stations throughout Malaysia, including stations in Selangor River basin, is done by Alam Sekitar Malaysia (ASMA) which has a 20–year contract with DOE that began in 1995. ASMA’s contract with the Malaysian Government requires at least 85 % accuracy; it was reported that the company has consistently met this requirement (YSI Incorporated 2007). ASMA maintains each station every two months. Technicians are assigned to specific stations so they learn the nuances of each one, carefully checking the site and equipment, and rotating-in fresh instruments that have been cleaned and re-calibrated in the laboratory. Data are transferred to Excel spread sheets and run through ASMA's rigorous quality assurance and control processes before being distributed to 'users'.

4.5.2 NAHRIM Sampling Campaigns

Four river water quality sampling campaigns were conducted (two in the wet season, two in the dry season) to collect physical and chemical data at 13 stations selected by scientists at NAHRIM; trips were limited to four due to budgetary constraints. The dates of the river sampling were 19 to 29 November 2008 and 13 to 23 December 2008 for the wet season, while the dry season was represented by data measured on 18 to 21 June 2008 and July 2008. Sampling was conducted from a boat. The 13 sampling sites were at the confluence of the outfalls from the 10 TCGs as listed in Table 4-6, at Rantau Panjang, at Kampong Sepakat and at the river mouth ("Muara"). All the sampling sites are listed in Table 4-8 and shown in Figure 4-12. A further set of salinity measurements was collected along the lower section of the river over spring tide around low water on 11 June 2009 and high water on 12 June 2009. These salinity data were used to calibrate the mixing values D0 and D1 in the model.

During each campaign a YSI Sonde 6600 multi-parameter water quality sensor (Figure 4-16) was used to measure pH, temperature, dissolved oxygen (DO) and salinity at 1.5 - 2 m depth. The YSI 6600 records data internally and was set up to do so during each campaign, but direct measurements were manually recorded at each of the sampling sites. At the same time as the YSI Sonde was being deployed and retrieved, grab samples were collected using a 4.2L Van Dorn water sampler (Figure 4-17). All the water samples were stored and preserved within 24 hours as recommended in the standard method based on Standard Methods for Examination of Water and Wastewater 21st Edition (2006) before being analysed in the laboratory.

Laboratory parameters for the grab samples consisted of Ammoniacal Nitrogen (NH_3-N), Nitrate Nitrogen (NO_3-N), Nitrite Nitrogen (NO_2-N), Total Kjedahl Nitrogen (TKN), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and Suspended Solids (SS) in the water column.

The same instrumentation was used to collect water quality samples from the canals behind the TCGs. As explained earlier scientist involved in this study were denied access to the plantations to sample the canal and drainage water so samples were restricted to places where there was public access.

Table 4-8: Locations of sampling stations in study area

No.	Model ID	Station name	Distance from estuary (km)	Latitude	Longitude
1	TCG1	Sg Yu	3	N3° 21.795	E101° 14.363
2	TCG2	TgKeramat	5	N3° 21.189	E101° 14.487
3	TCG3	TelukPenyamun	7	N3° 19.951	E101° 15.574
4	TCG4	TiramBurok	12	N3° 22.202	E101° 15.688
5	TCG5	Bukit Belimbing	17	N3° 23.209	E101° 16.779
6	TCG6	Lubok Jaya	19	N3° 23.103	E101° 17.997
7	TCG7	Jalan Kedah	23	N3° 22.418	E101° 17.681
8	TCG8	Tg Siam	29	N3° 21.735	E101° 18.647
9	TCG9	PokokPauh	29	N3° 21.818	E101° 18.802
10	TCG10	Kemsey	34	N3° 21.782	E101° 20.116
11	Muara	Estuary mouth	-5	N3° 17.762	E101° 12.828
12	SS10	Kg Sepakat	10	N3° 21.686	E101° 16.168
13	SS57	Rantau Panjang	57	N3° 24.109	E101° 26.502

Table 4-9: Summary of Methods used for analysis of physical, chemical and microbial parameters.

Parameter	Unit	Method	Reference Method of Analysis
Temperature	C	temperature meter	Temperature meter
Salinity	ppt	salinity meter	salinity meter
pH	unit	pH meter	pH meter
DO	mg/l	DO meter	DO meter
BOD	mg/l	Measurement of oxygen consumed in a 5day test period	APHA 5210B
COD	mg/l	Open reflux	APHA 5220B
NH_3-N	mg/l	Titrimetric	APHA 4500B
NO_3-N	mg/l		APHA 4500NO3 E
NO_2-N	mg/l		APHA 4500 NO_2 B
TKN	mg/l	Titrimetric	APHA-600/4-79/020
SS	mg/l	Gravimetric	APHA 2540D

Figure 4-16: YSI 6600 multi-parameter water quality sensor (left) and field laptop (right)

Figure 4-17: Water samples in the cool box (left) and Van Dorn water sampler for the lab samples collection (right)

4.5.3 Quality Assurance Analysis

Proper quality control is important for any sampling effort to assure that data collected are of high quality. Quality control procedures were practised in both field sampling and the laboratory analysis of various parameters. The quality of the information collected was assured in the following ways:

1) Laboratory and field duplicates. Duplicate grab samples were collected at one river site during each sampling trip. The representativeness of duplicate samples is measured by performing the relative percentage difference (RPD) analysis. The RPD in percentage is calculated as the absolute difference between two concentration value of samples (S_1 andS_2) and divided by the mean value of the pair; or summarised as follow:

   $$\text{RPD (\%)} = 100 \text{ x } \{(| S_1 - S_2 |) / ((S_1 + S_2) / 2)\}$$

   where S_1 is concentration of the original sample and S_2 is concentration of the duplicate sample. According to Standards Australia (2005), RPD values which are within 30 – 50% can be considered to be acceptable data. Only one duplicate was outside Standards Australia (2005) recommended limits (at 52%) but the data set as a whole was considered acceptable in view of the limited data available for this study.

2) The YSI multi-parameter sonde was verified by the following QA checks:

   a) In-house pre-calibration of dissolved oxygen, temperature, pH and salinity to known standards prior to deployment at the sampling site.

   b) Field measurements of temperature, dissolved oxygen, pH and salinity at the time of deployment and the time of retrieval.

   c) Post-calibration after travelling back from the site against known standards.

   All the sensor technology used in the YSI sonde was verified through the US EPA’s Environmental Technology Verification (ETV) Program. (YSI Incorporated, 2010). The performance of the YSI multi-parameter sonde was within the acceptable tolerance during pre- and post-fieldwork calibration. For the field measurements, the sonde was lowered into the water on a wire to the required depth, left to settle for 5 minutes, and then triggered by sending a weighted "messenger" down the wire. Most of the time the *in situ* parameter values monitored on the surface unit in the boat showed minimal changes in value during the settling time. All the retrieval data were checked for a pattern of the consistent values and outliers removed.

4.6 Run-off through the Tidal Control Gates

The volume of water in the catchments behind the TCGs (and therefore the water level and the rate at which water will flow through the gates) depends on the water balance of the catchment. The water balance was calculated as follows.

4.6.1 Estimating net flow using a simple Water Balance Model

The water balance for most drainage catchments may be summarized by a simple water balance based on Thornthwaite & Mather (1955)

$$P = Q + ET \pm \Delta S$$

where P is precipitation, Q is runoff or stream discharge (canal flow), ET is loss by evapotranspiration, and S is the changes in soil moisture storage. Stream discharge is therefore

$$Q = P - ET \pm \Delta S$$

The initial value of the soil moisture storage (S) was set to 40 mm (DID, 2009). The flow (Q) was then calculated on a daily basis, using the daily rainfall data (P) from DID and evapotranspiration rates (ET), also provided by DID (2009). The value of ET is calculated using the Penman equation, which is generated through a computer program, PEN 91.FOR (DID, 1991).

4.6.2 Run-off from sub-catchments

As the study area is divided into sub-catchments associated with each TCG, the run-off or discharge was generated for each of these sub-catchments; the method used for calculating the run-off was the 'Rational Method' (Corbitt, 1999). This method estimates the rate of run-off through the sub-catchment in the study area as a function of drainage area, run-off coefficient, and rainfall intensity for duration equals to the time of concentration (Corbitt, 1999).

$$Q = CIA$$

where Q is the rate of run-off (m^3s^{-1}), C is the run-off coefficient that represents how efficiently certain surfaces contribute to the run-off, I is the average intensity of rainfall in mm day^{-1} and A is the drainage area in m^2. When a sub-catchment consists of a number (i) of different surfaces the runoff is calculated by summing the run-off from each type of surface

$$Q_{Total} = \sum_i C_i I_i A_i$$

4.6.3 Run-off coefficient

In this study only two surface-types were involved – roofs and infrastructure in the residential areas, and soil in the plantation areas. The plantation area was around 70% of each catchment, with 30% housing and residential infrastructure. Table 4-10 shows runoff coefficient values recommended in theUrban Storm Drainage Criteria Manual, (Urban Drainage and Flood Control District, 2010). The runoff coefficients of 0.80 and 0.10 were used for the residential roofs and infrastructure, and plantation soil, respectively. Tekolla (2010) conducted an analysis of rainfall and flood frequency in Pahang, Malaysia and found 0.10 to be an appropriate runoff coefficient for areas of plantation. The daily values of Q were calculated in an Excel spreadsheet for the area drained by each TCG, before being transferred to the InfoWorks model. An example of these spreadsheets is shown in Appendix B.

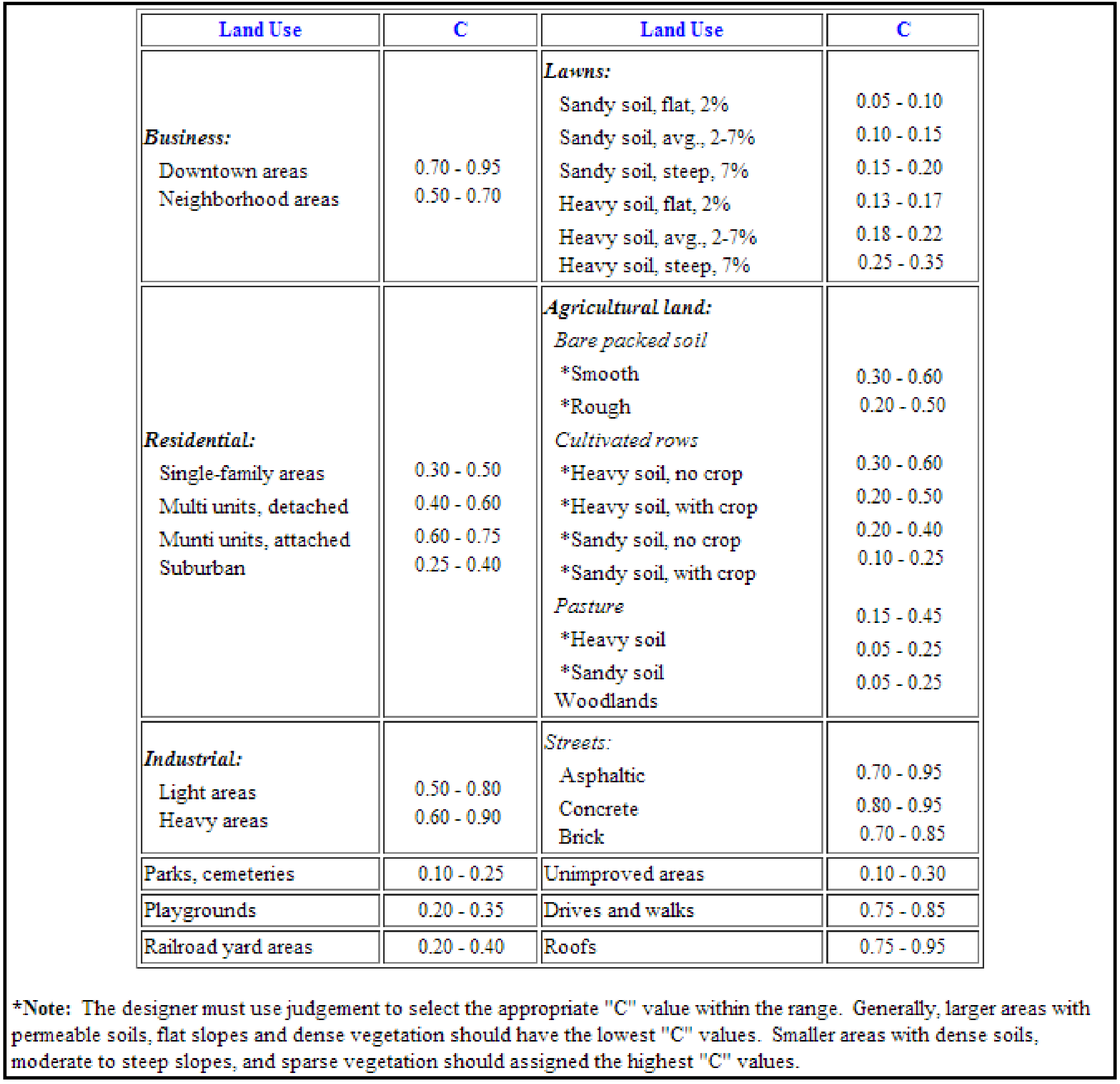
The area of each TCG catchment, and the division of the area between soil (oil palm) and residential, were calculated for using a GIS (Table 4-11).

The intensity of rainfall (I) was obtained from the daily rainfall data recorded at the nearest DID rain gauge station and was assumed to represent the rainfall over the whole catchment (Table 4-12). For modelling purposes rainfall was assumed to occur at a constant rate through the 24 hour period.

4.7 Rainfall Data

Rainfall can vary from county to county within the lower part of Selangor River catchment. Rainfall is from convective storms so daily rainfall is highly variable both temporally and spatially. Seven rainfall stations (Table 4-12) were selected and assumed to represent the lower Selangor River catchment. Rainfall is recorded by DID using a standard 0.5 mm tipping bucket rain gauge connected to a data logger and recording daily totals (mm/day); stations are maintained by DID from whom the data were obtained. The average monthly rainfall for one station (RF1) over the period 2000 to 2009, is shown in Figure 4-17. The wet season is from November and April with the heaviest rainfall in these months, while the dry period is between May and August; climatically June is usually the month with the lowest rainfall although between 2000-2009 May and July had lower rainfall than June.

Table 4-10: Runoff coefficient of different type of catchment (Urban Drainage and Flood Control District, 2010)



Land Use	**C**	**Land Use**	**C**
Business: Downtown areas Neighborhood areas	0.70 - 0.95 0.50 - 0.70	***Lawns:*** Sandy soil, flat, 2% Sandy soil, avg., 2-7% Sandy soil, steep, 7% Heavy soil, flat, 2% Heavy soil, avg., 2-7% Heavy soil, steep, 7%	0.05 - 0.10 0.10 - 0.15 0.15 - 0.20 0.13 - 0.17 0.18 - 0.22 0.25 - 0.35
Residential: Single-family areas Multi units, detached Munti units, attached Suburban	0.30 - 0.50 0.40 - 0.60 0.60 - 0.75 0.25 - 0.40	***Agricultural land:*** *Bare packed soil* *Smooth *Rough *Cultivated rows* *Heavy soil, no crop *Heavy soil, with crop *Sandy soil, no crop *Sandy soil, with crop *Pasture* *Heavy soil *Sandy soil Woodlands	0.30 - 0.60 0.20 - 0.50 0.30 - 0.60 0.20 - 0.50 0.20 - 0.40 0.10 - 0.25 0.15 - 0.45 0.05 - 0.25 0.05 - 0.25
Industrial: Light areas Heavy areas	0.50 - 0.80 0.60 - 0.90	*Streets:* Asphaltic Concrete Brick	0.70 - 0.95 0.80 - 0.95 0.70 - 0.85
Parks, cemeteries	0.10 - 0.25	Unimproved areas	0.10 - 0.30
Playgrounds	0.20 - 0.35	Drives and walks	0.75 - 0.85
Railroad yard areas	0.20 - 0.40	Roofs	0.75 - 0.95

***Note:** The designer must use judgement to select the appropriate "C" value within the range. Generally, larger areas with permeable soils, flat slopes and dense vegetation should have the lowest "C" values. Smaller areas with dense soils, moderate to steep slopes, and sparse vegetation should assigned the highest "C" values.

The river discharge measurements made at the permanent station installed by DID at Rantau Panjang effectively represents all the rainfall, run-off and evaporation occurring in the upper part of the Selangor river catchment, plus, in more recent years, additional flow released from the Tinggi and Selangor dams to maintain the flow at Batang Berjuntai barrage (km 50) at a level where water abstraction can occur while a low base-flow is maintained. Over the lower catchment rainfall data from the seven rainfall stations (Table 4-12) were used with the appropriate catchment areas associated with each TCG to estimate the inflow.

Table 4-11: The drainage area of TCG

Drainage area where the TCG located	Total area (km^2)	Residential area (km^2)	Soil area (km^2)
TCG 1	17.994	0.034	17.959
TCG 2	8.319	3.359	4.959
TCG 3	11.798	0.950	10.847
TCG 4	39.626	0.636	38.990
TCG 5			
TCG 6	12.400	0.380	12.019
TCG 7	3.056	<0.001	3.056
TCG 8	25.624	0.375	25.248
TCG 9	1.313	32,107.6	1.281
TCG 10	0.626	0.014	0.611

Table 4-12: Rainfall stations

Rainfall station	Station Name	Drainage areas covered
RF 1	Km 45.5 Jln Kelang/Selangor	TCG 1 and TCG 2
RF 2	Ladang Telok Piah	TCG 3
RF 3	Ladang Bukit Belimbing	TCG 4 and TCG 5
RF 4	Ladang Raja Musa	
RF 5	Ladang Bukit Talang	TCG 6
RF 6	Ladang Kuala Selangor	TCG 7, TCG 9, TCG 10
RF 7	Rumah Pam JPS Jaya Setia	TCG 8

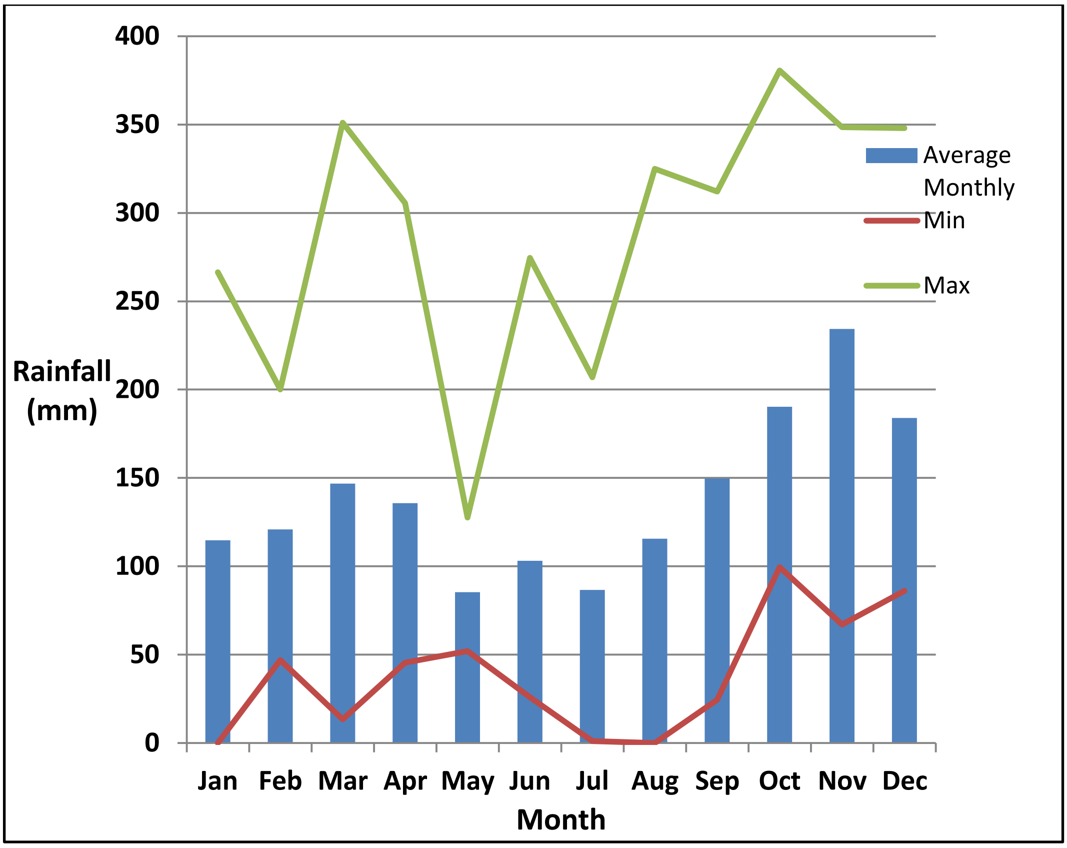


Figure 4-18: Average monthly rainfall for one station (RF1) over the period 2000 to 2009, with maximum (green) and minimum (red) monthly values.

4.8 Summary

In addition to a description of the geography, climate and land-use in the Selangor River basin, the data used in the modelling work are discussed. The method and analysis of the tidal data to produce the tidal constituents used to drive the boundary conditions are described. The flow rates at Rantau Panjang, the upper boundary of the model, are calculated from water levels at this gauging station through a rating curve; the instruments to measure the water levels together with their maintenance, and the methodology used by the Department of Irrigation and Drainage (DID) to establish the rating curve are explained. As there was no access to the oil palm plantations the lengths, widths and locations of the canals and drains in the plantations were derived from a 2.5m resolution SPOT satellite image. Water levels behind the TCGs were measured during the wet season by NAHRIM scientists.

The sampling station just below Rantau Panjang is maintained by a commercial company on behalf of the Department of Environment and they are responsible of the quality assurance of these data. The data collected by NAHRIM, using water sampling and a YSI multi-parameter sonde, are also subjected to similar quality assurance using standards and duplicate samples; the methodology used and standards applied are described

The water levels in the catchments behind the TCGs are updated using a simple water balance model based on Thornthwaite & Matter (1955) model, using rain fall from the nearest DID station and evapotranspiration from the Penman equation. Adjustments are made to account for differing run-off rates from residential areas and from oil-palm plantations, based on GIS-based calculations of areas in each catchment. Rainfall intensities, assumed to be uniform each day, were obtained from the nearest DID rain gauge station.

CHAPTER 5

MODEL BOUNDARY CONDITIONS AND CALIBRATION

5 Introduction

This chapter explains how the InfoWorks^{TM} RS and InfoWorks^{TM} Water Quality modules were set up, including the boundary conditions used, and how the River System module was calibrated before being used for analysis and simulation. For the River System module this involved a two-step procedure in which the tidal parameters were first adjusted to optimize the river elevation, followed by calibration using the salinity measurement from the water quality data assuming that salt was acting as a conservative tracer. Step one used the measured tidal stage data from 2007 and the adjustment of the amplitudes of the tidal harmonic constituents; step two then followed by calibration of the mixing processes using the measured salt data from 2009 for high and low water during neap and spring tide in the river system. The Water Quality module was then calibrated for the re-aeration coefficient using the measured dissolved oxygen data from 2008 for both wet and dry seasons.

5.1 Boundary conditions

The InfoWorks^{TM} model requires information on the inflows and outflows into the river, together with the ambient pollutant concentration at boundary nodes. Boundary conditions for a tidal river are required for the model at the both upstream and downstream boundaries as well as at “internal boundaries” which for the Selangor River are the controlled inflows from the plantation catchments through the tidal control gates.

5.1.1 Hydrodynamic Boundary Conditions

The daily flow rates measured at the gauging station at Rantau Panjang (km 57) are used as the upstream inflow boundary condition for the model (Section 4.2 in Chapter

4). Flow rates were assumed constant over each 24 hour period. The downstream boundary (the river mouth) was forced using the seven tidal constituents described in Table 4-4 (Chapter 4); the average water level at the river mouth was set to the value measured during the 31 days of water levels from the tide gauge deployment in 2007. The InfoWorks^{TM} RS hydrodynamic module computes the time-varying water levels from the amplitude and phase of the tidal harmonics for any defined starting date and time. The flows from the TCGs were controlled by the logical rules (Section 3.4.3 in Chapter 3).

5.1.2 Water Quality Boundary Conditions

The bi-monthly DOE water quality measurements taken from the DOE sampling station close to Rantau Panjang (Section 4.5.1 in Chapter 4) and other available samples taken by NAHRIM (Section 4.5.2 in Chapter 4) were used at the upstream boundary. Integration of these bi-monthly DOE measurements, and the other occasional measurements of water quality, with daily river flow data was difficult and is discussed later.

At the lower boundary, the estuary mouth, the only direct measurements available were the four made by NAHRIM in 2007 and 2008 so, for this study, the water quality concentration values at the downstream boundary (the estuary mouth) were based on previous water quality studies conducted in the Straits of Malacca (Hii, 2006), Yusoff & Peralta, 2008), Law et al. 2002). The WQI for the coastal waters is 85 which is Class II.

The water quality data from the DOE station at Rantau Panjang for wet and dry seasons (Table 5-1), averaged over the twelve years from 1997 to 2008, were used for initial condition at the upstream boundary (Section 4.5.1). The period 1997 – 2008 was used as these data were complete; post-2008 there was missing data. These data were examined for temporal trends but no significant trend was found. The water quality values for source pollutant nodes are based on the small number of observations conducted at the TCGs during the wet and dry seasons. These values were assumed to be constant with time and not to vary with the speed of the water flow. During the wet season the WQI is 77 (Class III, close to Class II) while in the dry season the WQI drops to 72 (Class III).

Over this period the water extraction from the barrage at Batang Berjuntai was begun. It is unclear exactly when and how much extraction occurred so the modelling of the present hydrodynamics and water quality described in the following Chapter does not include any extraction.

As described in Section 4.4.2 in Chapter 4, for reasons of access, only a limited number of water quality measurements were made in the canals behind the TCGs. All were taken close to the control gates. The data from all canals, for each wet and dry season, were averaged and applied to all the catchments. It is assumed in the model that all rainfall runoff (NOT the rainfall itself) entering all catchments has the same water quality. These have a WQI of 62 (Class III) during the wet season and 52 (Class IV) during the dry season.

Table 5-1: The boundary concentrations for the water quality components.

Variable (unit)	**Downstream (estuary mouth)**	**Upstream (Rantau Panjang)**		**TCG**	
		Wet season	Dry season	Wet season	Dry season
DO (mg/l)	5.3[a]	5.7[d]	5.5[d]	3.19[e]	2.8[e]
BOD (mg/l)	0.6[a]	2.6[d]	3.7[d]	15.6[e]	9.6[e]
Total Nitrogen(mg/l)	0.1[b]	1.23[d]	1.0[d]	1.0[e]	3.8[e]
NO_2-N (mg/L)	0.06[c] x 10^{-3}	0.25[e]	0.15[e]	0.3	0.70[e]
NO_3-N (mg/L)	1.34[c] x 10^{-3}	0.16[d]	0.54[d]	0.3	0.80[e]
NH_3-N (mg/L)	1.36[c] x 10^{-3}	0.22[d]	0.26[d]	0.82[e]	0.93[e]
COD (mg/l)	25.0[e]	26.8[d]	38.1[d]	44.1[e]	49.2[e]
pH (unitless)	7.8[a]	6.4[d]	6.5[d]	6.58[e]	2.9[e]
Salt (g/l)	32[a,]	0	0	0	0
Temp (^{0}C)	29[a,]	29[d]	29[d]	29[e]	29[e]
TSS (mg/l)	7.2[a]	153.7[d]	149.2[d]	53.8[e]	41.5[e]
WQI value	85	77	72	62	52
WQI Class	II	II	III	III	IV

[a]Hii et al. (2006);[b]Yusoff & Peralta (2008);[c] Law et al. (2002); [d]DOE; [e]Selangor River

The initial conditions for the water quality model runs were that all internal river nodes, i.e. the whole river, were set to the water quality values at Rantau Panjang and all the internal nodes in the catchments behind the TCGs were set to the same rainwater boundary values for each catchment.

The values of all the coefficients used in the InfoWorks^{TM} water quality model were based on the values taken from general ranges recommended by Brown and Barnwell (1987) and Chapra (1997) plus other published literature for tropical rivers (Zaki et al., 2010). The values of selected coefficients are summarized in Table 5-2. However, the dispersion coefficients D0 and D1 were calibrated as described below and set to be 10 (m^2s^{-1}) in this model.

Table 5-2: Values of major coefficients used in Selangor River water quality model

Description	Symbol	Unit	Range	Value used
Dispersion coefficient (shear velocity)	D0	m^2s^{-1}	-	10
Dispersion coefficient (tidal mixing)	D1	m^2s^{-1}	-	10
Re-aeration Coefficient	K_{air}	h^{-1}	0 – 4.2[a]	0.30
Re-aeration temperature factor		unitless	-	1.02
Re-aeration structure coefficient			-	0.8[d]
BOD/COD standard decay rate	K_1	d^{-1}	0.05 – 0.5[b]	0.65 [c]
BOD/COD decay temperature				4.7[d]
BOD slow decay rate fraction				0.2[d]
Nitrogen standard decay rate		d^{-1}	0.1 – 0.5[b]	0.23[d]
Nitrogen decay temperature coefficient				4.7[d]
Nitrogen slow decay rate fraction				0.2[d]
Ammonia standard oxidation rate		d^{-1}		0.26[d]
Ammonia oxidation temperature coefficient				0.47[d]
Nitrite standard oxidation rate		d^{-1}		1.0[d]
Nitrite oxidation temperature coefficient				5.0[d]
Critical deposition stress		N/m^2		0.1[d]

Fluffy mud critical erosion stress		N/m^2		0.2^d
Fluffy mud max thickness		mm		3.0^d
Fluffy mud dry density		kg/m^3		75^d
Consolidated mud critical erosion stress		N/m^2		0.3^d
Consolidated mud erosion rate		kg/N/s		0.001^d
Consolidated mud dry density		kg/m^3		300^d

[a]Brown and Barnwell (1987),[b]Chapra (1997), [c]Zaki (2010),[d]default value

	Oxidation of fast BOD	**Oxidation of slow BOD**	**Hydrolysis of fast organic nitrogen**	**Hydrolysis of slow organic nitrogen**	**Oxidation of ammoniacal nitrogen**	**Re-aeration through the water surface**
K_{20}	0.23	0.046	0.23	0.046	0.4	variable
α	4.7	4.7	4.7	4.7	8.8	1.6

$K_\theta = K_{20} (1 + \alpha/100)$

The concentration of suspended sediments in the Selangor River, required to calculate the values of the WQI, were not measured by the DOE at their sampling station, only the value of turbidity. It was therefore necessary to estimate the values of suspended sediment from the measured turbidity (*NTU*). This was done using the method in Packman et al. (2006) where turbidity and total suspended sediment (*TSS*), with natural-log transformations, were plotted and regressed using a simple linear regression analysis. The regression equation was then used to predict *TSS* from *NTU*. Figure 5-1 plots the natural log-transformed data from 1997 to 2006 (six samples a year) at 13 DOE water quality monitoring stations located in urban streams in the upper part of the Selangor River (above Rantau Panjang) (n = 416) with a simple linear regression model inset. The data show a strong positive log-linear relationship between turbidity and *TSS* with a correlation coefficient of 0.87 (R^2=0.75). The regression model (Equation 5-1)

$$\ln(TSS) = 0.64\ln(NTU) + 1.83 \qquad \text{(Eq. 5-1)}$$

is applied to predict TSS in this water quality model, but can be used to predict TSS for all streams in the Selangor River in the future.

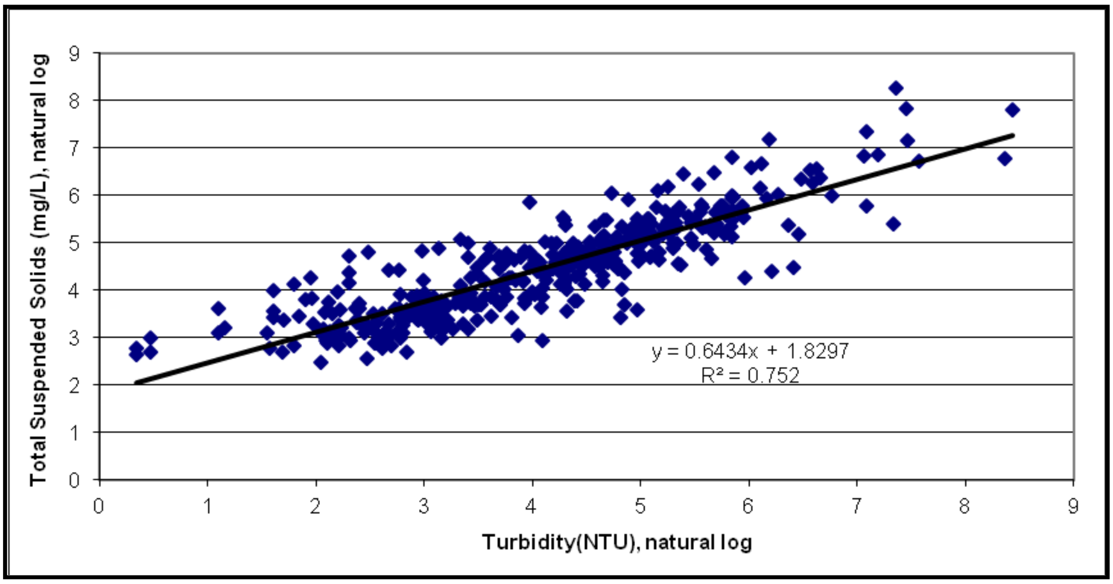


Figure 5-1: Total suspended solids (*TSS*) and turbidity (*NTU*) data (natural-log transformed) for all streams in the Selangor River.

5.2 Hydrodynamic model set-up and calibration

5.2.1 How good is the hydrodynamic model? – Model Evaluation

In order to assess the performance of a model, the statistical variables such as Relative Mean Square Error (RMSE) and Absolute Relative Mean Square Errors (RRMSE) (Ji, 2008) are often used to judge the effectiveness of model performance against data. Mean Absolute Error (MAE) is also commonly used as a measure of accuracy as it is not as heavily influenced by outliers as RMSE (Hedges, 2001) and is always lower than, or equal to, the RMSE. However Sutherland et al. (2004a, b) suggested that it is most appropriate to use the Relative Mean Absolute Error (RMAE) for hydrodynamic calibration purposes such as this study. The RMAE is expressed as:

$$RMAE = \frac{\langle |Y - X| \rangle}{\langle |X| \rangle} = \frac{MAE}{\langle |X| \rangle}$$

where the angular brackets represent an average, modulus sign is to make the values of either scalars or vectors as positive (absolute values), Y is a set of N modelled values (y_1,…,y_N) and X is a set of N observed values (x_1,…., x_N). MAE is equally applicable to both vectors and scalars so that this is particularly useful for evaluating hydrodynamic modelling (Sutherland et al, 2004a, b). The model performance results, according to the range of values of RMAE, are tabled below.

Table 5-3: Error classification and categorisation of results of model performance as suggested by Sutherland, et al. (2004a)

Classification	**Range of RMAE**
Excellent	< 0.2
Good	0.2 – 0.4
Reasonable	0.4 – 0.7
Poor	0.7 – 1.0
Bad	> 1.0

5.2.2 Initial tidal stage set-up

The hydrodynamic model is forced by the seven tidal constituents at the downstream open boundary as described in Section 4.4.2 in Chapter 4. The tidal stage measurements (30 days from 15 Nov to 16 Dec 2007) were conducted at km 5 so it was necessary to adjust the values applied at the boundary so that the tidal stage at km 5 was as close as possible to the measured water levels. The phases of the constituents were adjusted by the equivalent of 20 minutes; the time taken for a shallow water wave to propagate from the boundary to km 5 (~10 km) in water of ~7 m depth. It was also necessary to increase the amplitudes of all tidal components by 10% (Table 5-4) to get the best match between the water levels predicted by the model and those measured by the gauge tide at km 5.

Table 5-4: The initial amplitudes of the Tidal Harmonic Constituents used in the hydrodynamic model.

Harmonic Constituents	Amplitude	10% increase
M_2	1.297	1.427
S_2	0.580	0.638
K_1	0.218	0.24
O_1	0.052	0.057
N_2	0.232	0.255
K_2	0.158	0.174
M_n	0.125	0.138

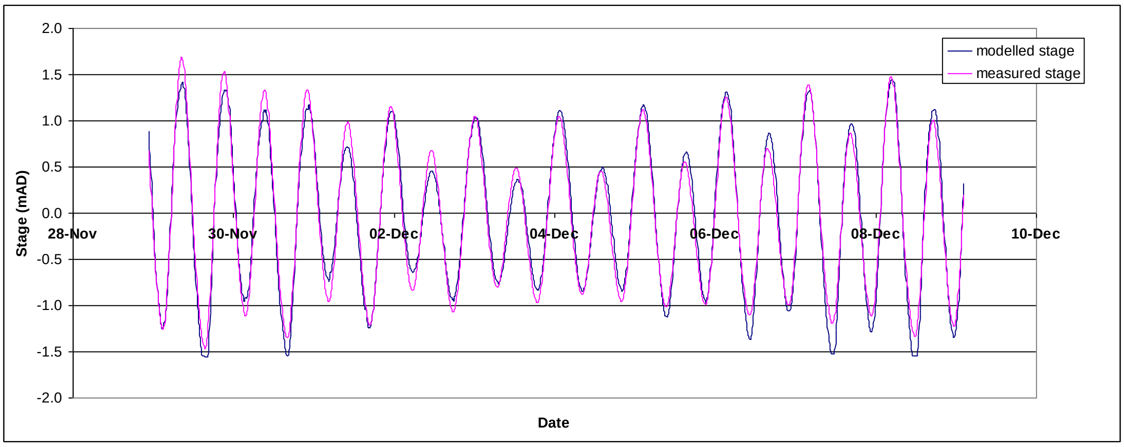


Figure 5-2: Comparison of stage between the modelled and measured values of 31 days period for hydrodynamic calibration (for clarity only 10 days are shown) at km 5 (location of the tide gauge).

As seen in Figure 5-2, the water level (stage) predicted by the model at km 5 closely follow the measured data suggesting that the stage is well represented by the model. However, the modelled phase differs slightly from the observed data; the modelled data slightly lags compared to the measured data. In statistical terms, the Relative Mean Absolute Error between the two series is less than 0.2 (RMAE = 0.17) which is considered by Sutherland et al. (2004) to be an ‘excellent’ match (see Table 5-3). Based on this initial adjustment and assessment, the tidal forcing of the hydrodynamic model at the downstream boundary can be of considered as acceptable.

5.2.3 Manning's Roughness coefficient, *n*

The model also allows the channel roughness to the changed via the Manning's Roughness *n* value (InfoWorks Manual). Chow (1959) determined the range of values of *n* for many types of river, including those in the tropics, relative to the type of bed. A value of *n* ranging 0.020 to 0.035 is suggested by Chow (1964) in Section 3.4.2 and, according to Dyhouse & Hatchet (2003), this value range is suitable for river-width less than 30 m. Hassan (2006) used a value of 0.02 for the lower part of Selangor River. However in this study a constant Manning's Roughness coefficient *n* = 0.03 was found to be most suitable. The model runs have been carried out using various bed roughness coefficients between 0.02 and 0.05 in order to calibrate the model with respect to the water level data measured at the tidal control gate at km 34 (Kemsey TCG). Values of *n* were tested by comparing the modelled water level with the measured water level at km 34 over the two-week period between 15 - 27 November 2005. The comparison that gave the best correlation (R^2 = 0.94) was that for *n* = 0.03 so this was used in the model.

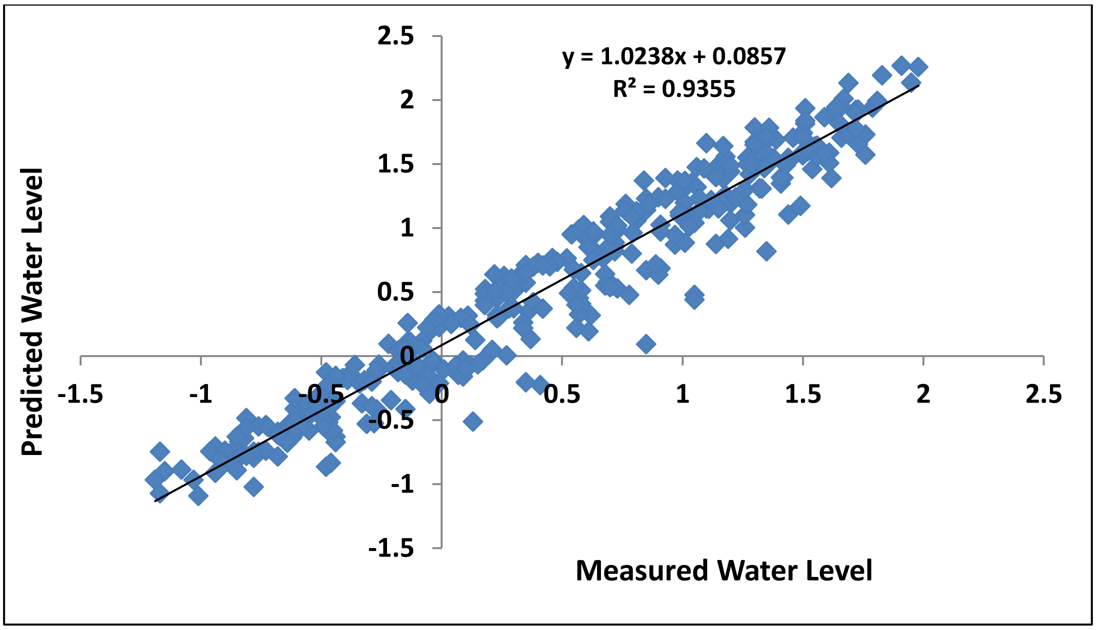


Figure 5-3: Correlation of measured and predicted water level at km 34 over the two-week period between 15 - 27 November 2005 with Manning's Roughness coefficient, *n* =0.03.

5.3 Calibration of the mixing processes

Mixing within the model is parameterised through empirical dispersion, or mixing, coefficients D0 and D1, which control the amount of longitudinal dispersion which occurs as a result of, for example, turbulent mixing processes. In most water quality modelling exercises in estuaries with a significant freshwater discharge, salinity is used as a longitudinal dispersion tracer for calibration of the mixing processes. In the Selangor River salinity effects are experienced up to ~15km from the estuary mouth and the longitudinal variation of salinity, which affects water density, will also affect the flow regime. Salt is a conservative substance so its variation in time and space will be solely due to its advection and dispersion by the water flow; its distribution is affected by the tidal currents, freshwater discharge, density circulation, as well as turbulent mixing processes. Salt can therefore be used to determine the values of the empirical longitudinal dispersion coefficients in the model. In addition, the amount of oxygen that can be dissolved in salt water is significantly less than that in fresh water. Salinity variations are therefore important when predicting the oxygen balance in estuaries.

The boat transects (section 4.5.2) conducted along the lower section of the river over spring tide around low water on 11 June 2009 and high water on 12 June 2009 were used to calibrate the values of D0 and D1 in the model. To allow the processes in interior of the model (which are initially static and uniform) to adjust to the boundary forcing, the model is run for a 14-day model period prior to 11 June, using measured river flows at Rantau Panjang and the actual rainfall occurring; this is referred to as the ‘spin-up period’. Because the boat transects took place over several hours it was necessary to select the modelled salinity values corresponding to the *time* the measurements were taken; hence the figures shown below are have some temporal changes within them. Figures 5-4 to 5-7 show a comparison of the modelled and measured (vertically-averaged) salinity with a range of values of D0 and D1 from 0.1 to 50.

Changes in salinity distribution due to different values of the dispersion coefficients were significant for D1 (Figures 5-4 and 5-5) but had very little impact for D0

(Figures 5-6 and 5-7). However the default value of D1=10 provided the best correspondence between the modelled and the measurement so the default values of D0 = 10 and D1 = 10 were used. The model performs very well around low water on the landward transect (when the tide was ebbing) but less well on the seaward transect when the tide was flooding after low water. Similarly the model performed less-well on the flood tide (landward transect) just before high water but better on the ebbing tide after high water. On the flood tide the salinity in the model is several kilometres further downstream than measured from the boat (e.g. in Figure 5.4 a salinity of 5 ppt is found between km 11 and km 12 but the model shows a salinity of 5 at km 9). The other differences are near the estuary mouth where the model shows salinity of 32 ppt (the open coast value) extending upriver to km 4 (flooding tide after low water) and to km 10 (flooding tide before high water); Figure 5.5 shows salinity dropping to 20 ppt by km 10. This discrepancy is believed to be due to brackish water leaving the outer boundary on the ebb but not being drawn back into the estuary in the model. See ‘ramp function’ below.

5.4 Ramp function

The InfoWorks manual states that a ‘ramp function’ can be defined which allows the water returning into the estuary through the outer boundary to reflect the salinity at the boundary at the time the tide reverses. The ‘ramp function’ allows salinity at the estuary mouth to vary linearly between the salinity at the time of low water, typically around 25 ppt, and the ‘open coast’ value of 32 ppt two hours later. However this was clearly not implemented in the code used for this dissertation as switching the ramp function on and off produced no effect on model output. This has been reported to InfoWorks but nothing has been implemented to date. Hence the sea water flowing back into the estuary after low water always has the characteristics of the ‘open coast’ (Straits of Malacca) and is thus too saline initially.

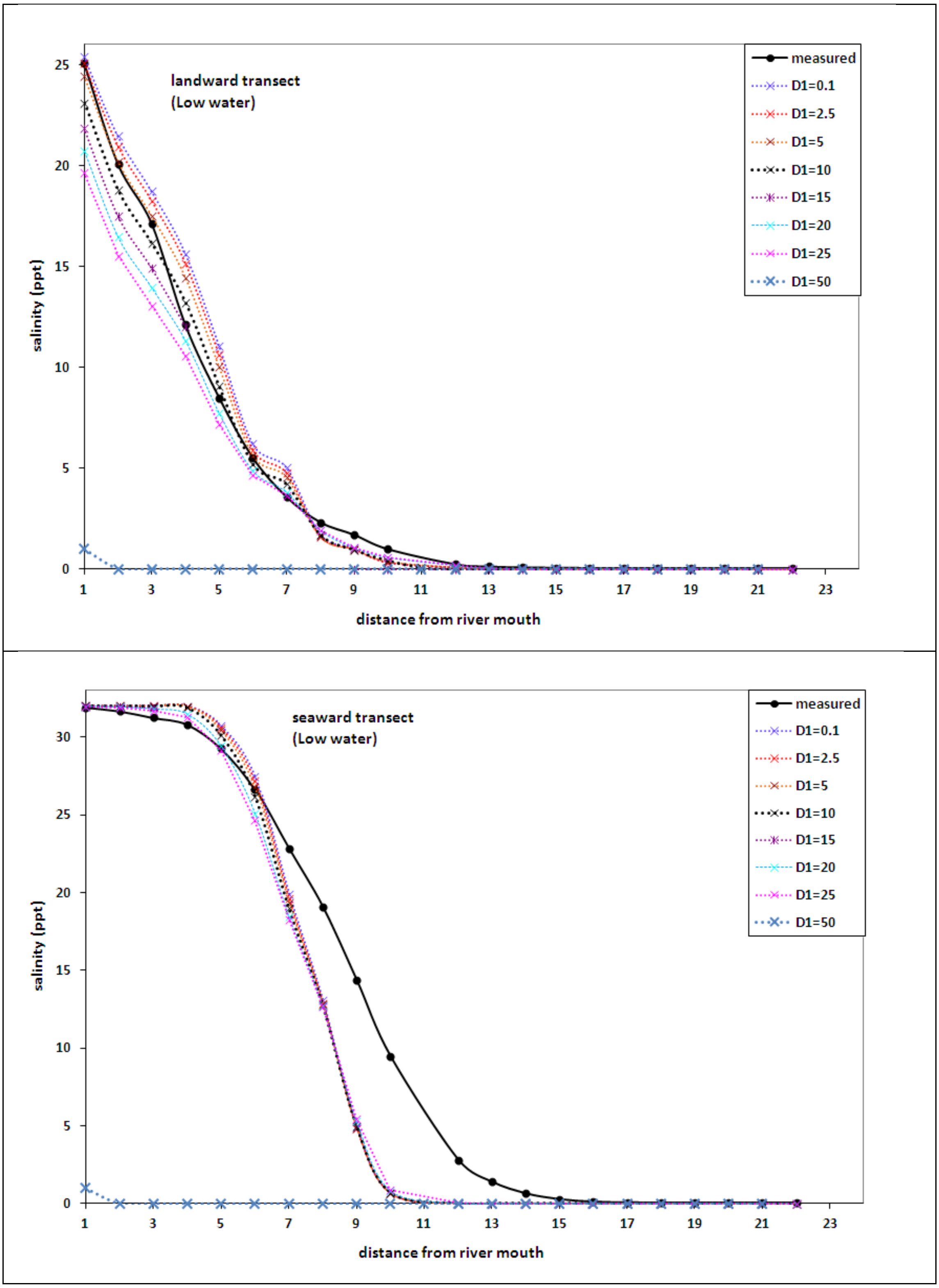


Figure 5-4: Measured and predicted salinity around low water during spring tide on 11 June 2009 (landward transect – upper panel; seaward transect – lower panel) with default D0 (10 m^2s^{-1}) with values of D1 from 0.1 to 50.

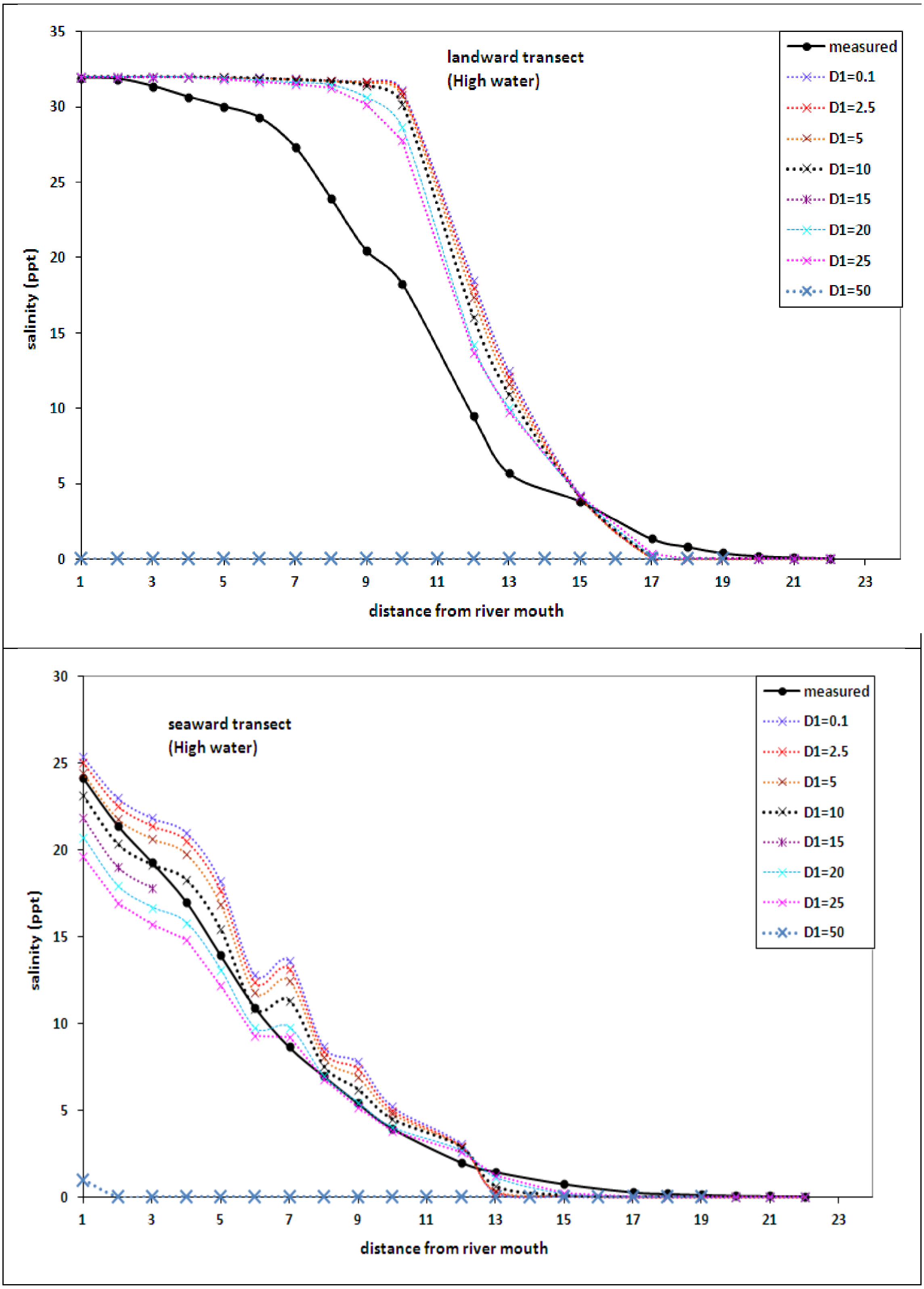


Figure 5-5: Measured and predicted salinity at high water during spring tide on 11 June 2009 (landward transect – upper panel; seaward transect – lower panel) with default D0 (10 m^2s^{-1}) but different value of D1.

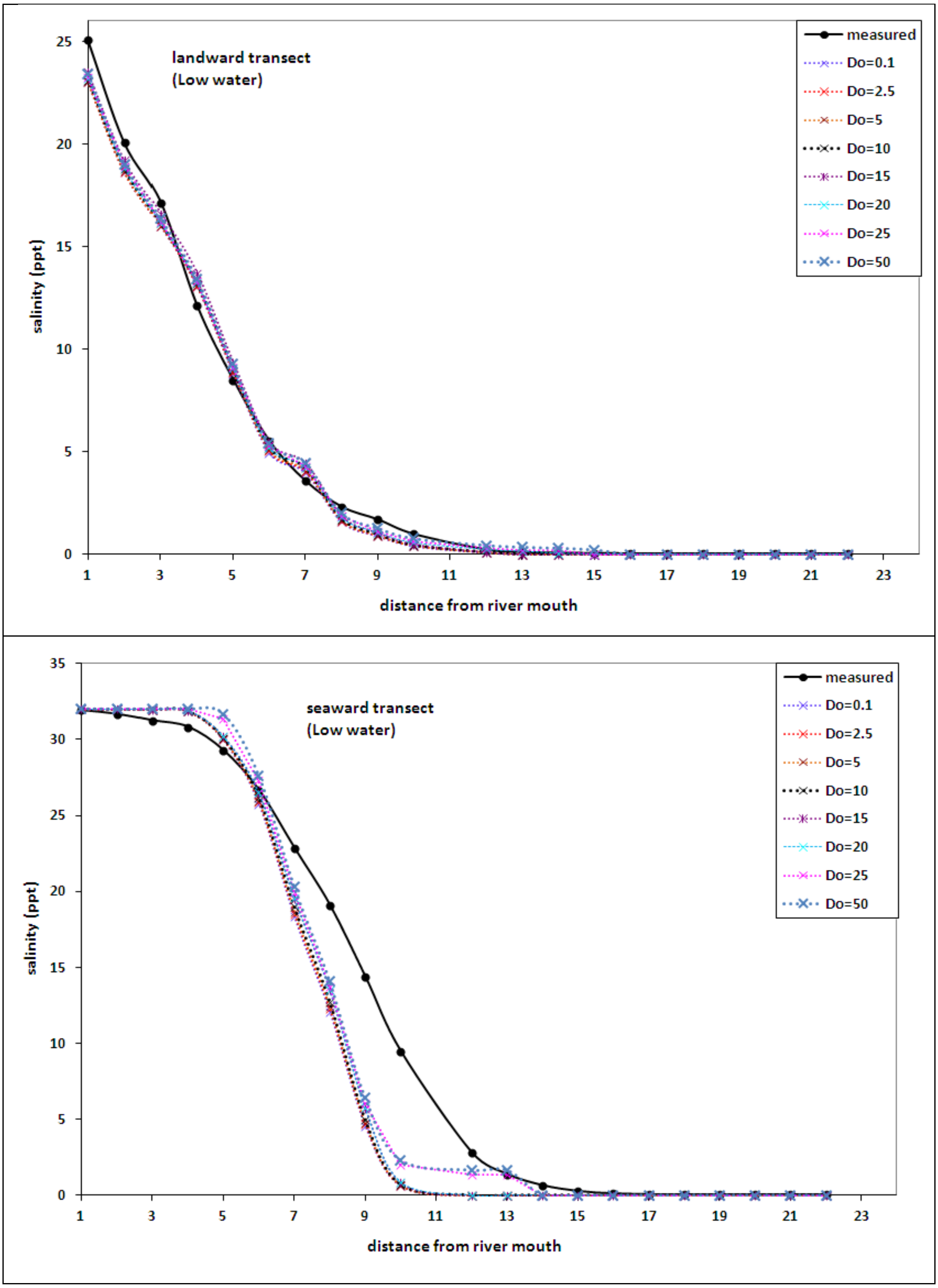


Figure 5-6: Measured and predicted salinity at low water during spring tide on 11 June 2009 (landward transect – upper panel; seaward transect – lower panel) with default D1 (10 m^2s^{-1}) but different values of D0.

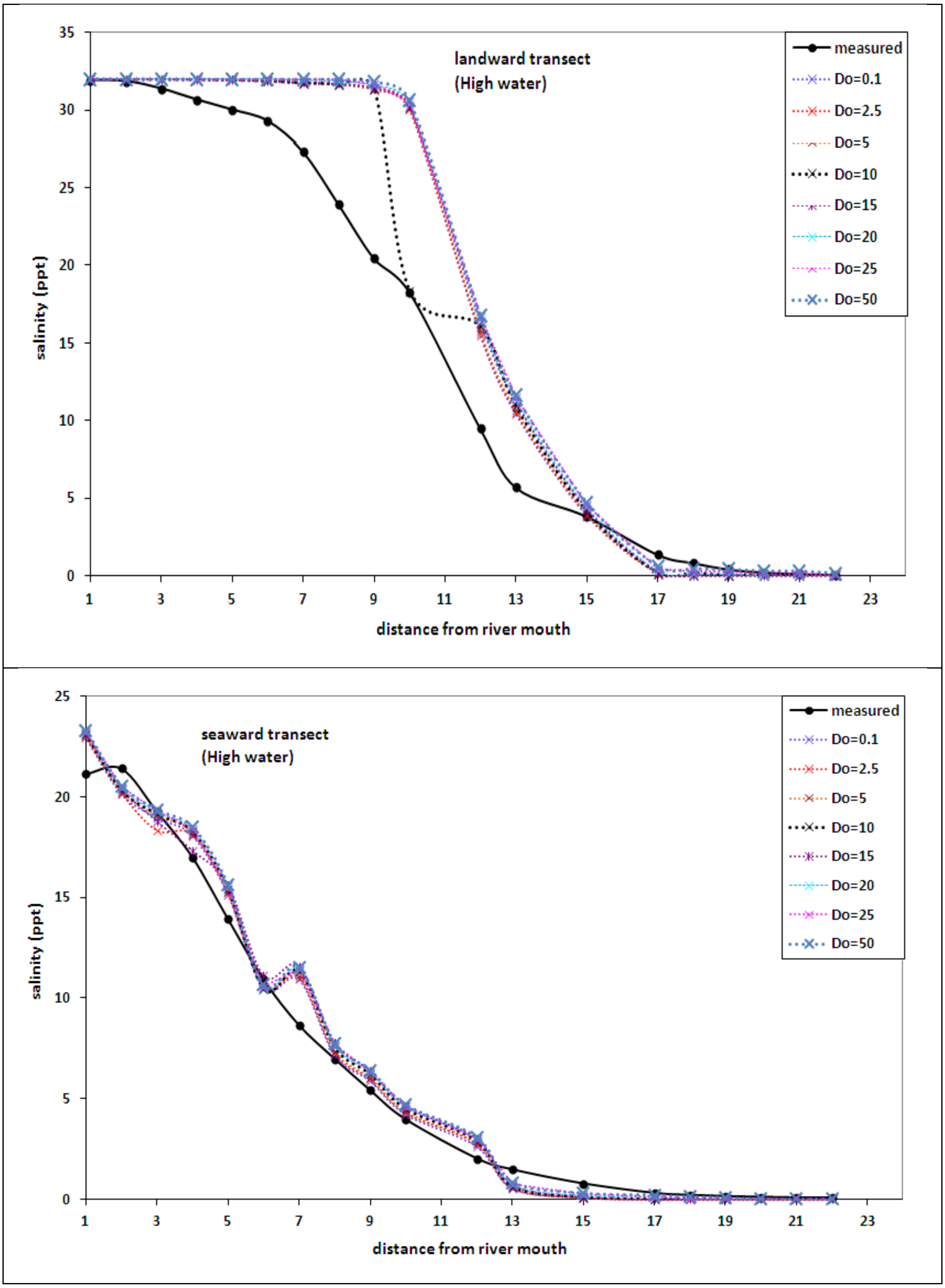


Figure 5-7: Measured and predicted salinity at low water during spring tide on 11 June 2009 (landward transect – upper panel; seaward transect – lower panel) with default D1 (10 m^2s^{-1}) but different values of D0.

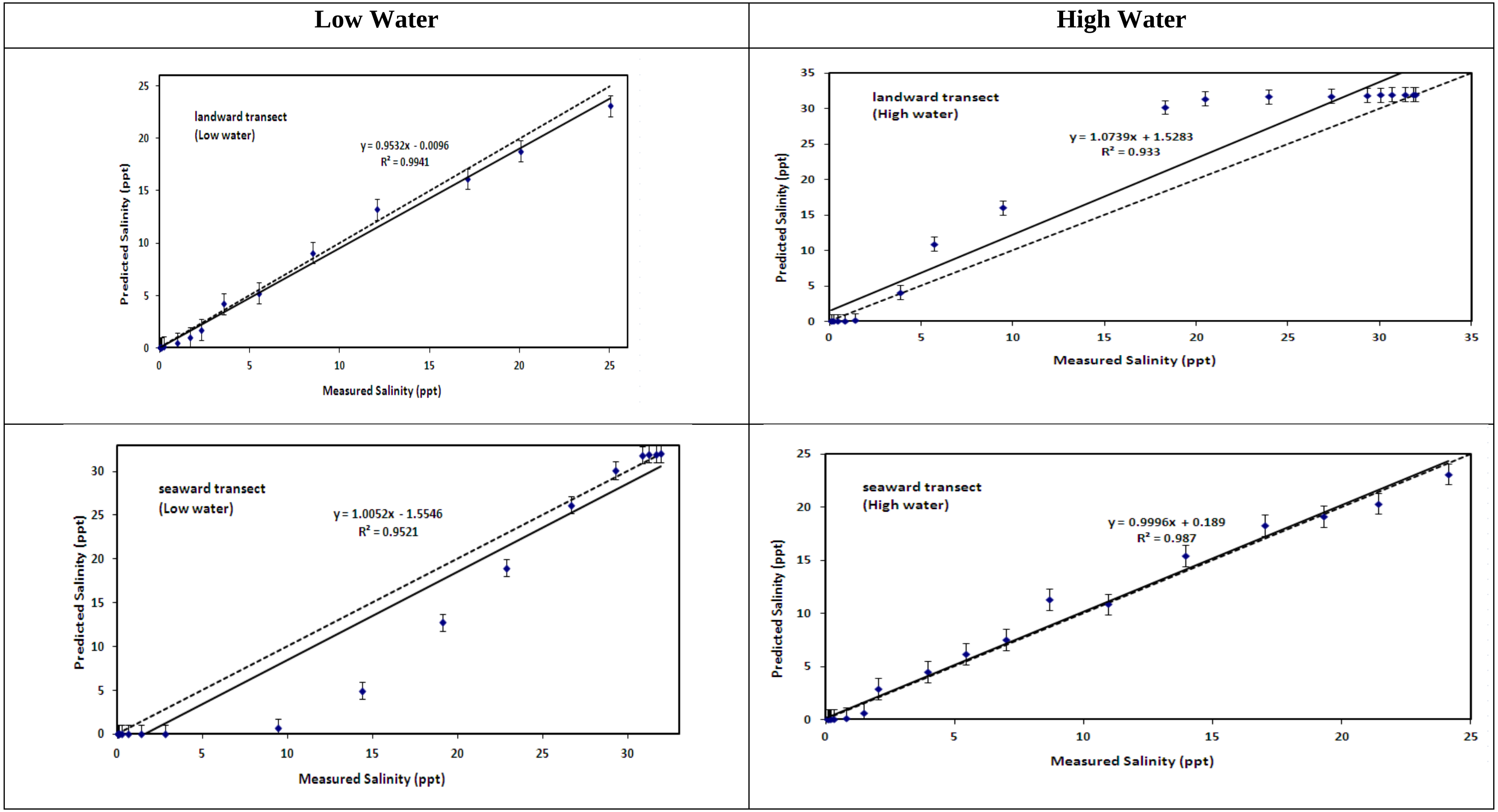


Figure 5-8: Correlation of measured and predicted salinity at low and high water during spring tide on 11 June 2009 (landward transect - upper panel; seaward transect – lower panel) with D0 = 10 m^2s^{-1} and D1= 10 m^2s^{-1}.

5.5 Wet and dry seasons

The major climatic changes that are likely to be important for the water quality of Selangor River basin are the rainfall differences between wet and dry seasons. The bi-monthly DOE water quality data were analysed to see if there were significant differences between the WQI for the two seasons. Table 5-5 shows the mean and standard deviations for the complete data set and for the data divided into wet season (measurements made during the months of October-March) and dry season (April-Sept) for Rantau Panjang.

A null hypothesis "that there is no significant difference between the mean of the WQI of the wet season and of the dry season" was set up. A t-test was performed which showed that the null hypothesis could be rejected at the 5% confidence level (P-value of 0.041 < 0.05). It was therefore decided to run the model for both wet and dry season scenarios but nothing that there was considerable overlap between the WQI in wet and dry seasons. The considerable variability in the WQI during both wet and dry seasons will influence the uncertainty in the models presented later and the confidence that can be placed on the results.

Table 5-5: Mean, Standard Deviation and Number of Observations of the WQI at Rantau Panjang for 1997-2008, for wet and dry seasons, together with the t and P-value to test the difference between the means of the wet and dry seasons.

Rantau Panjang Station					
	Mean WQI	Standard Deviation	Number. of Observations	t-value	P value
All data	75.6	6.6	55		
Wet Season	77.4	5.8	28	2.11	0.041
Dry Season	73.8	7.0	27		

5.6 Summary

The model set-up in terms of the boundary conditions and the selection of mixing parameters has been described. The tidal forcing at the estuary mouth using the seven tidal constituents from the tide gauge was shown to produce an ‘excellent’ match (Sutherland et al. 2004) to the water levels measured at the tide gauge station at km5 after the phases were adjusted by 20 minutes. The value for the channel roughness (Manning’s *n*) was determined by varying it between 0.02 and 0.035 and comparing the modelled water level data against 2 weeks of level data measured in the river near the Kempsey TCG (km34). A value of 0.03 was found to give the highest correlation (R^2 = 0.94).

The two mixing parameters in the InfoWorks model, D0 and D1, were varied across a range of values (0.1 – 50) and the model results compared to the salinities measured by the NAHRIM boat transects. Varying D0 had very little impact on the results (so the InfoWorks default value of 10 was use), while a D1 of 10 produced the best correspondence between model results and the salinity measurements. The model has been shown to perform well during the ebb tides, just before low water and after high water. It performed less-well on a flooding tide when (a) the salinity in the model was several kilometres further downstream than measured from the boat and (b) high salinity water in the model penetrated too rapidly into the river. It was noted that the ‘ramp function’ in the model, designed to allow some brackish water to be drawn back into the estuary when the tide turns, had not been implemented and that this will significantly influence the modelled salinities at the start of the flood tide.

A statistical analysis of the water quality data from Rantau Panjang showed that there was a significant difference (at the 5% level) between the wet season WQI (77.4 ± 5.8) and the dry season WQI (73.8 ± 7.0) and that it was therefore necessary to run the model for both wet and dry season conditions. The uncertainties in the WQI in both wet and dry seasons will affect the modelling results presented in the following Chapters.

CHAPTER 6

PRESENT WATER QUALITY: ANALYSIS AND DISCUSSION

6 Introduction

In this Chapter the current water quality of the Selangor River is modelled and the results discussed. The water quality is assessed using the Malaysian Water Quality Index (WQI) (see Chapter 3), which is based on the levels of just six parameters in the river water – dissolved oxygen (DO), the biological oxygen demand (BOD), the chemical oxygen demand (COD), ammoniacal nitrogen (AN), pH and total suspended solids (TSS), although it is recognised that these parameters depend on all the biological and chemical reactions taking place in the river. The Malaysian Government has a target of achieving Class II for the water quality of the Selangor River, equivalent to a WQI > 79. The biological and chemical reactions in the river are computed within the Infoworks Water Quality model using equations explained in the Manual but over which users have no control. In this study we are also limited by which water quality parameters have been measured e.g. by the DOE at their station near Rantau Panjang, and therefore available to be input to the model.

The WQI in the Selangor River will depend on a) the boundary conditions (flow and water quality) at Rantau Panjang and at the estuary mouth, b) the water flowing into the river through the tidal control gates and c) the chemical and biological processes occurring in the river. The WQI will vary both along the river and with time, due to changes in run-off (wet and dry season) and estuary forcing (spring and neap tidal cycle).

The InfoWorks Water Quality model is first tested against some of the water quality measurements made by NAHRIM along the Selangor River during the wet and dry seasons in 2008. The model is then used to predict the temporal and spatial variations in the above six parameters (and the Water Quality Index calculated from their weighted sum) under a number of necessarily simplified conditions to assess the overall quality of the water in the Selangor River. The importance of run-off from the mainly oil-palm plantations surrounding the lower catchment on the water quality index is also examined by repeating the model computations with the TCGs all closed.

6.1 Calibrating and validating re-aeration in the InfoWorks Water Quality model against measurements.

Beside the photosynthesis from plants, the re-aeration process is the most important route for introducing oxygen into surface waters. Compared to algal photosynthesis, which can only add DO to water in daylight, re-aeration brings DO to water day and night. The oxygen gas from the atmosphere dissolves into the water and replenishes the DO up to a maximum of the saturation level.

Dissolved oxygen concentrations can fluctuate under natural conditions, but can be lowered severely as a result of human activities such as the introduction of large quantities of oxygen-demanding wastes. When the DO levels are low (2 mg/l or less) or when hypoxia occurs (USEPA, 2000) due to oxidation and decomposition of organic matter, aquatic life may be impaired and large mortalities may occur. Typically, oxygen is transferred from atmosphere into the water when DO levels in natural waters are below saturation. The rate of re-aeration is proportional to the DO deficit, which is the difference between the DO concentration and the oxygen saturation value DOS and is usually expressed as

$$\frac{dDO}{dt} = K_{air}(DOS - DO)$$

where K_{air} is the re-aeration rate constant (hour^{-1}). Ji (2008) reported that the larger the DO deficit, the higher the rate of re-aeration. Figure 6-1 (from Ji, 2008) shows what happens to DO levels in a typical river; water has an initial DO concentration, C_0 and the following processes then occur as the water flows downstream.

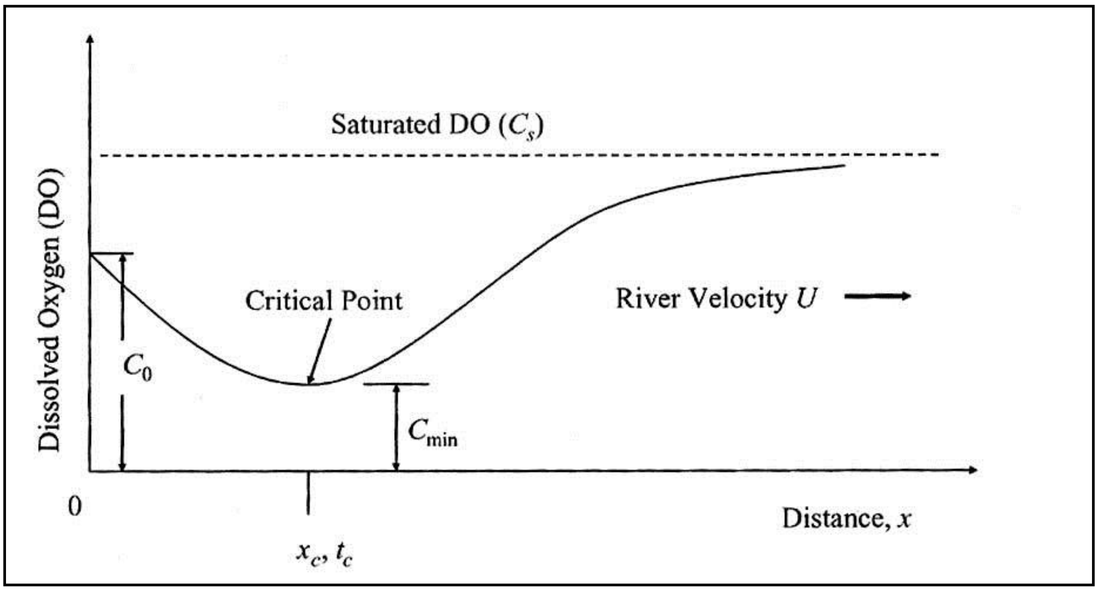


Figure 6-1 : The oxygen-sag curve in a river showing the initial decay of dissolved oxygen under pollutant loading and subsequent recovery by re-aeration. (Figure adapted from Ji, 2008).

Oxygen in the river is used up faster than it is resupplied when pollutants start flowing into the river where the decomposition process occurs actively, reaching a critical minimum level of DO, $C_{\min}$ at distance x_c down the river (after a critical time t_c). Atmospheric oxygen enters through the surface to compensate for the oxygen deficit, resulting in a recovery of the DO concentration up to a maximum of the saturated DO (C_s). Based on a derived regression equation for saturated DO by Chapra and Canale (1998), saturation DO in Selangor River is calculated to be about 7.6 mg/l at a temperature of 29°C at salinity 0.0 ppt (freshwater) and 6.5 mg/l at salinity 32 ppt.

Typical values for the re-aeration rate constant, R_{20} (day^{-1}) for water bodies in temperate regions at 20°C are shown in Table 6-1 (Peavy et al., 1985).

InfoWorks expresses the re-aeration rate coefficient, K_{air}, as

$$K_{air} = f_{air}\frac{b}{A}$$

where f_{air} is the transfer velocity (m/hour) which represents the speed at which a front of oxygen penetrates the water, b is the water surface width (m) and A is the cross-sectional area (m^2). f_{air} is a strong function of temperature and it expressed in InfoWorks by

$$f_{air} = f_{air}(20)\beta^{(T-20)}$$

where $f_{air}(20)$ is the transfer velocity at 20°C and β is the temperature adjustment constant. InfoWorks WQ uses a default value for $f_{air}(20)$ of 0.04 m h^{-1} but when this was used on the Selangor River DO levels in the middle reaches (between 10-30 km) dropped to very low levels (~0.4 mg l^{-1}), too low for organisms to survive.

It was therefore necessary to change the transfer velocity to allow more oxygen into the water through the surface. Previous work done by Mohamed (2001) on the Selangor river, using a different water quality model (Qual2E – a steady-state flow model), had found that a value of 0.04 m h^{-1}, similar to the InfoWorks default value, fitted his data best. However Streeter and Phelps (1925) suggested that a higher value of 0.37 m h^{-1} at 20°C was needed, although this was not for a tropical river.

Table 6-1: Typical values of the re-aeration rate constant, at 20°C, for temperate water bodies (Peavy et al., 1985, p.87)

Receiving water type	**K_{20}(hour^{-1}) at 20°C**
Small ponds and back water	0.004 – 0.01
Sluggish streams and large lakes	0.01 – 0.015
Large streams with low velocity	0.015 – 0.02
Large streams at normal velocity	0.02 – 0.025
Swift streams	0.025 – 0.045
Rapids and waterfalls	> 0.045

The DO in the InfoWorks WQ model was calibrated against measurements made during a 24h period between 0900 25 Nov and 0900 26 Nov 2007, during the wet season, made at three locations along the river, km 10, km 25 and km 50, using a range of values for the re-aeration transfer velocity $f_{air}(20)$ between 0.04 m h^{-1} and 0.8 m h^{-1} (spanning the values used by Mohamed (2001); and Streeter and Phelps (1925)). The input water quality parameters had also been measured at Rantau Panjang during this period and these were used as the boundary input for Rantau Panjang. The water quality at this time was significantly different from the 10-year DOE-average for the wet season. Ideally water quality measurements would have been made at Rantau Panjang for the two weeks prior to 25 November 2007, during which the InfoWorks WQ model was spun-up, but these were not available; the average measured water quality parameters at Rantau Panjang was used for the whole model run. The results are shown in Figure 6.2.

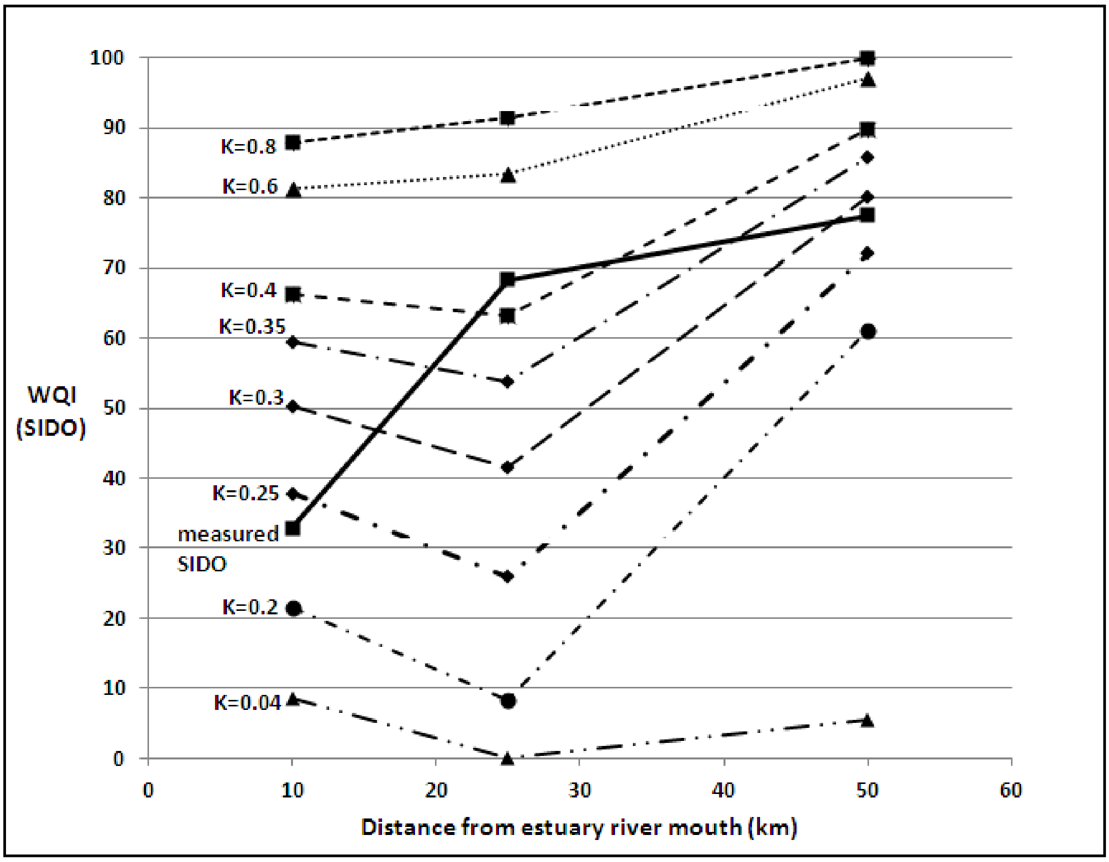


Figure 6-2: Comparison between modelled Sub-Index for DO (SIDO, dashed-type lines) with different values of the rate constant (where K in this diagram is $f_{air}(20)$ and the measured data (solid line) at km 10, km 25 and km 50 on 25 – 26 November 2007.

The $f_{air}(20)$ values that gave the best correspondence between the measured and modelled DO were between $f_{air}(20) = 0.2$ and 0.4 m h^{-1}. The measured and modelled DO values for 0.2, 0.3 and 0.4 m h^{-1} are shown in Table 6-2, averaged over the 8 3-h values (mean and standard deviation shown). Overall the value of $f_{air}(20) = 0.3$ m h^{-1} gave the best match between modelled and measured data, when measured by the sum of the errors squared (Table 6-2). This value for the re-aeration transfer velocity was used in all the subsequent model runs.

This value was then used with the dry season measurements taken on 5 June 2008 at km 25 to assess the validity of this re-aeration transfer velocity against an independent data set; again the average water quality measurements at Rantau Panjang were used as the boundary condition. At km 25 (Figure 6-3) the model over-estimated the DO compared to measurements (4.92 ± 0.25 compared to 4.16 ± 0.41). In view of the assumptions that were made concerning the water quality at the boundaries, the results were considered acceptable.

Table 6-2: The average and standard deviation (in brackets) measured and modelled DO for every 3 hours on 25 – 26 Nov 2007 (wet season) at three sampling stations.

Stations	Measured DO (mg l^{-1})	Modelled DO (mg l^{-1})		
	Average (SD)	$f_{air}(20)=0.20$	$f_{air}(20)=0.30$	$f_{air}(20)=0.4$
km 10	2.98 (1.34)	2.35 (1.47)	3.85 (0.62)	4.65 (0.19)
km 25	4.76 (0.19)	1.47 (0.48)	3.42 (0.28)	4.49 (0.19)
km 50	5.26 (0.25)	4.39 (0.06)	5.42 (0.05)	6.07 (0.05)
	Sum of errors squared	12.0	2.6	3.5

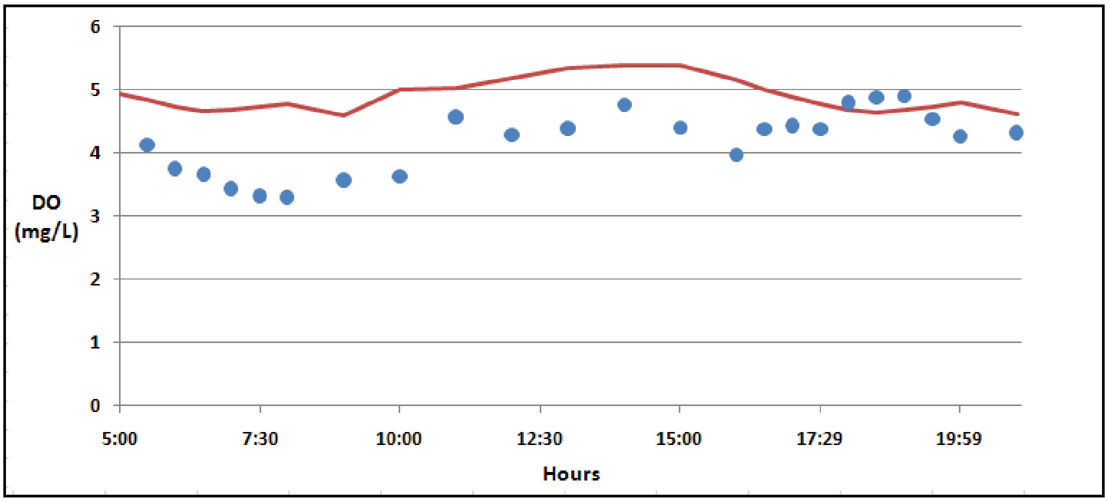


Figure 6-3 : Comparison of model results at km 25 in June 2008. The blue circles represented the measured data; the red solid line gave the model results.

6.2 Variation in WQI along the Selangor River

In this section the InfoWorks hydraulic and water quality models are used to compute the likely variation in the WQI (and its six components) with season and under different tidal forcing along the Selangor River, and therefore to assess the overall water quality of the river in comparison with the Malaysian Water Quality requirements and objectives, i.e. to attain Class II status. Although the model is fast to run runs the processing of the data for display was very time-consuming so the number of runs made with the model was limited.

The WQI (and its six components) have been computed for one wet and one dry season, each spanning one month (two spring-neap cycles) during one recent year for which there were complete data available (2009); the one month period 14 May-14 June has been taken to represent the dry season and 14 October-14 November to represent the wet season. 2010 was not used because the river flow in the dry season was anomalously high (rainfall in the dry season was greater than in the wet season). In both cases the appropriate tidal forcing was included, together with the measured flow at Rantau Panjang, and measured rainfall in each sub-catchment (Table 4-12); the Figure 4-17 show the rainfall at one representative rainfall station RF1 (km 45.5 Jalan Kelang).

To examine how representative these two periods were in relation to other recent wet and dry periods, the average flow at Rantau Panjang and the average daily rainfall at RF1 have been calculated for the 11 years 2000-10. Averages were calculated for the dry season months (May-July), and the wet season months (Oct-Dec), for months with > 90% data, and a mean and standard deviation calculated from these monthly means (Table 6-3); the number of months N used is also shown.

Table 6-3: The average daily flow for the wet and dry months at Rantau Panjang, and rainfall at RF1 (see text for full explanation), compared with the average flow and rainfall for the wet and dry season periods used in the model. Note the anomalously high flow and rainfall in the 2010 dry season.

	Dry Season (May-July)		Wet Season (October-December)	
	Flow at RP (m^3s^{-1})	Rainfall at RF1 (mm day^{-1})	Flow at RP (m^3s^{-1})	Rainfall at RF1 (mm day^{-1})
Mean (N)	38.11 (27)	2.99 (30)	77.72 (27)	6.63 (30)
Standard Deviation	28.55	2.07	42.20	2.64
2009	30.06	2.43	76.37	5.49
2010	66.84	4.48	75.69	3.48

6.2.1 Dry season (May-July) water quality

The data used in the InfoWorks flow and water quality models for the dry season period are shown in Figures 6-4 and 6-5. Figure 6-4 shows the daily flow at Rantau Panjang and the rainfall at one of the stations, Ladang Bukit Belimbing, used in the model to calculate the run-off from the plantation catchments into the river, controlled by the TCGs; the rainfall varies from catchment to catchment depending on the precipitation at the nearest rainfall station. Figure 6-5 shows the tidal stage curve used to drive water levels at the mouth of the model; for clarity the first 14 days only are shown, together with the average water quality of the local coastal waters, a WQI of 85.2 ± 2.6 (Class II, designated as 'clean').

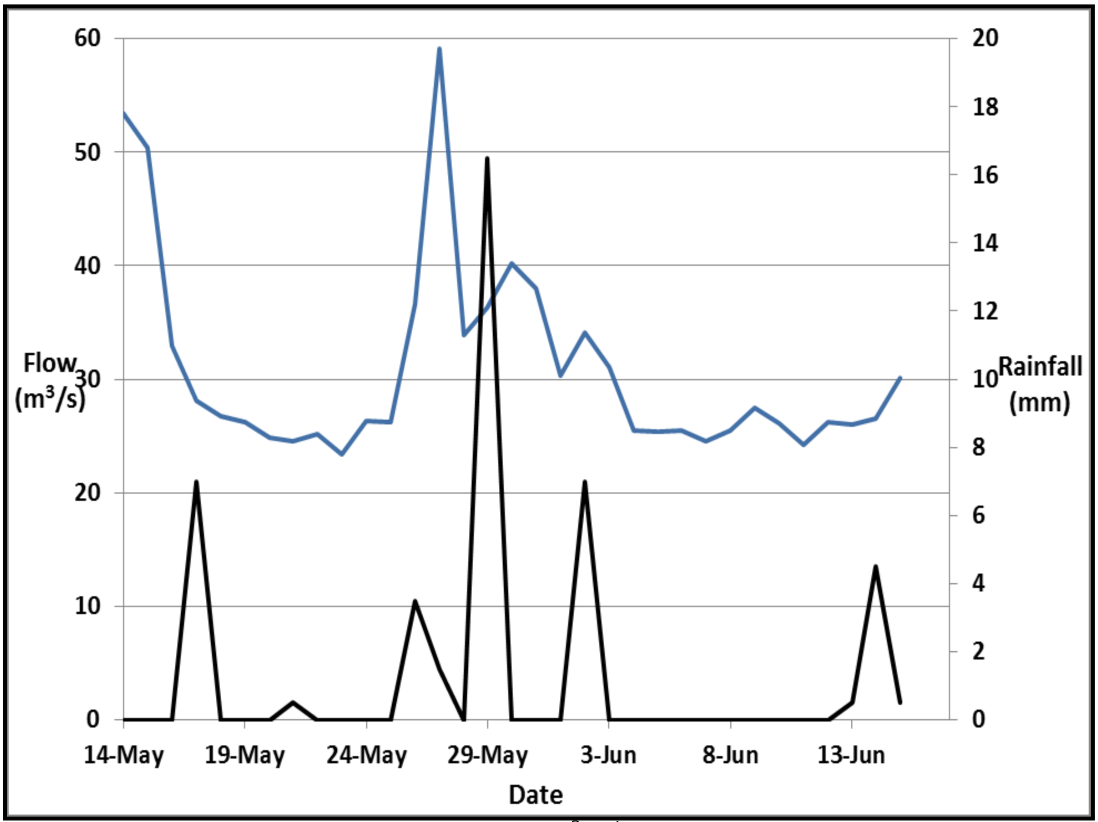


Figure 6-4: Dry Season daily river flow (m^3 s^{-1}) at Rantau Panjang (blue) and daily rainfall (mm) at one of rainfall stations Ladang Bukit Belimbing (black).

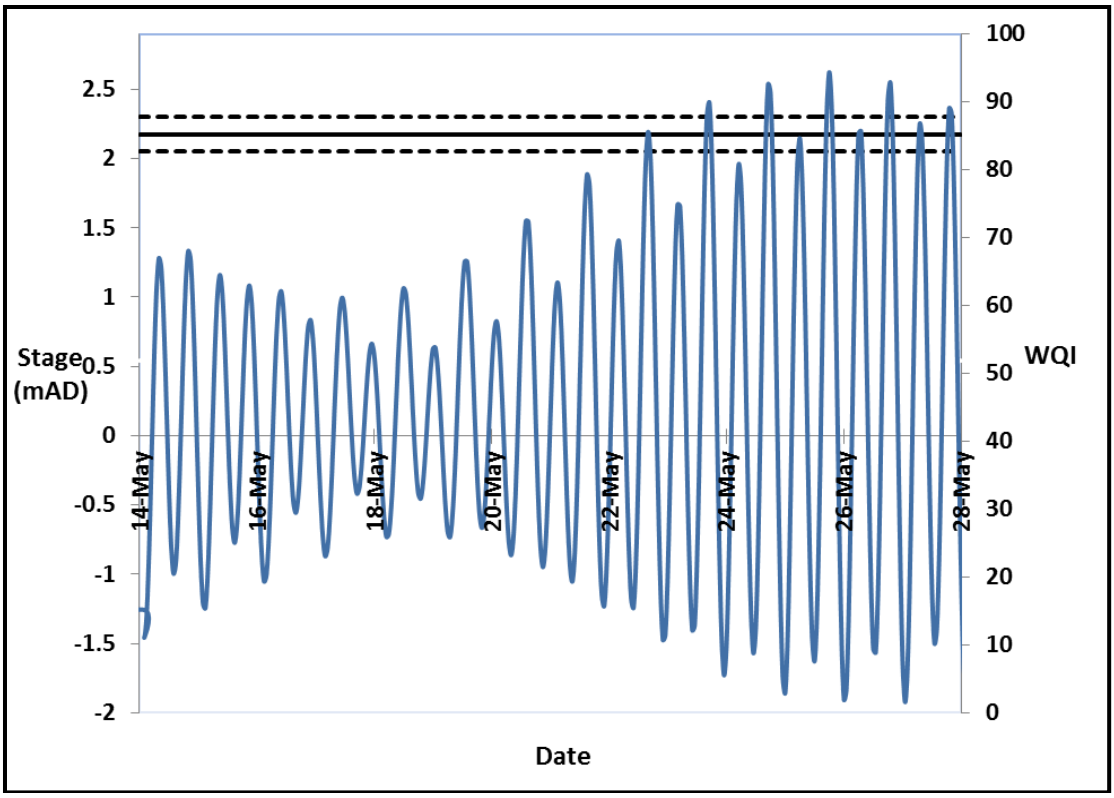


Figure 6-5: The tidal stage at the estuary mouth used to force the model (blue line) and the WQI (black line) used for the estuary water. The black dashed lines show one standard deviation WQI from the measured data.

The dry season WQI along the Selangor River predicted by the InfoWorks Water Quality model is summarised in Figure 6-6. The data are shown for the spring tides and for neap tides; in each case the WQI values have been averaged over ~3 days (six tidal cycles of 12.4h). The 3 days chosen are based on the 3 days around the highest spring tide or lowest neap tide in the day that occurred during the month-long dry or wet season. The variability resulting from the flood and ebb tidal currents and the opening and closing of the TCG, is also shown. The dry season WQI lies between 73.3 to 77.4 (Class II/III) above km 38, and is within the range 60 to 80 (Class III) along the rest of the river, other than within 5 km of the estuary mouth where the river is flushed with ‘cleaner’ sea water and is more than 81 or Class II.

WQI improves slightly between Rantau Panjang and km 38 and there is no difference between spring and neap tidal periods. Below km 38, in the section of the river where there are pollutant loadings entering through the TCGs, WQI drops (by ~10 WQI Units) during neap tides, a minimum of 65±2 (Class III) around km 25, but much less (~2) during spring tides to a minimum of 73±2, because of the higher tidal flushing during spring tides but it is also influenced by the timing of rainfall events. This will affect the hydrodynamic transport and may modify the pollutant concentration. The advection acts to move the pollutant patches away from the pollutant releasing point (TCGs) while turbulent mixing (dispersion) spreads out and dilutes the pollutant concentration. As the advection process is due to river flow, the velocity of flow also controls the pollutants' travel time, dilution and determines how long it takes for pollutants to be completely mixed across the river: however, in this 1D model, pollutants are assumed to be uniformly mixed across the river and through the water column. Only close to the estuary mouth (within 5 km) is the water quality consistently in the Class II category.

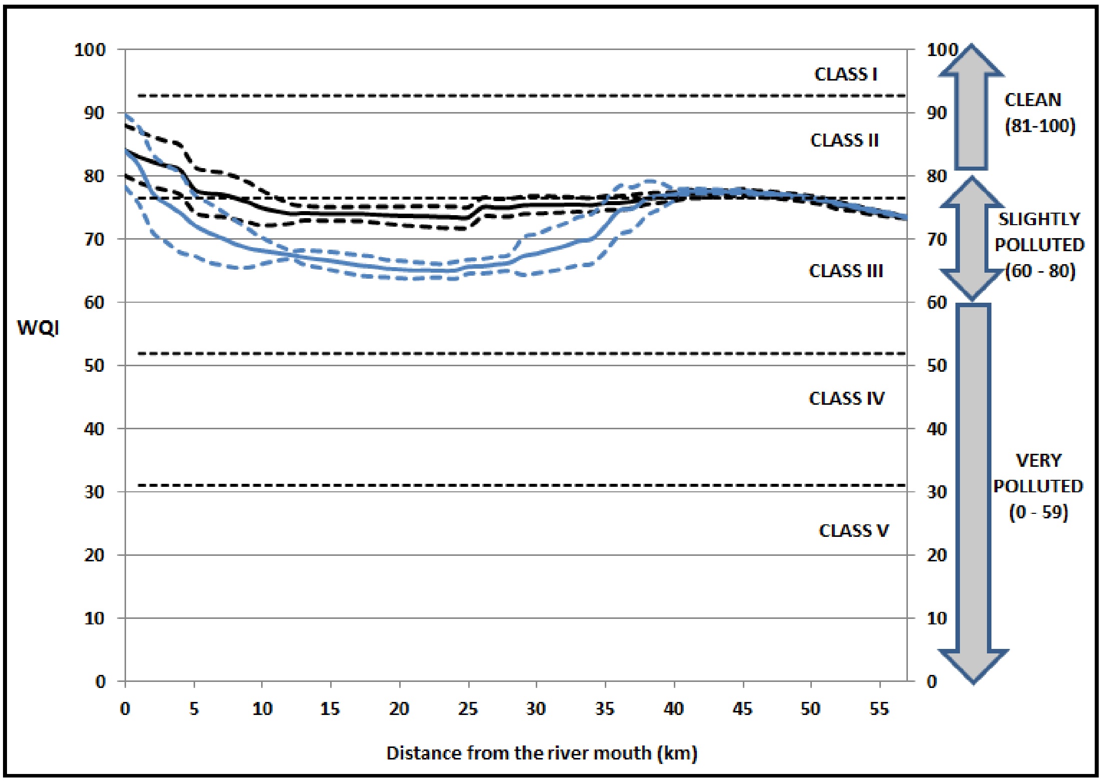


Figure 6-6: Dry Season water quality index as a function of distance down the river. The black lines (mean – solid, dashed +/- 1 standard deviation) are the average values over 3 days of spring tides. The blue lines (mean – solid, dashed +/- 1 standard deviation) are the average values over 3 days of neap tides.

The variations along the river of the six sub-indices that make up the WQI during spring tides are shown in Figure 6-7. Note that these are sub-indices and do not directly translate into concentrations, but that an increase in a sub-index implies better overall water quality (in terms of the WQI). In the lower reaches where pollutants come from the plantations the pH sub-index (SIpH) and the ammoniacal nitrogen sub-index (SIAN) drop. It is assumed that the high level of nitrogen from fertilizers used in the plantations contributes to the nitrification of the river resulting in a decrease in pH. The nitrification process consumes oxygen and thus will deplete the oxygen levels: nitrogen can cause a dissolved oxygen sag in the river (Chapra 1997) although the SIDO does not show any marked decrease in the Selangor river around the TCGs. Unexpectedly the SIBOD and SICOD are both elevated at the point where the pollutants enter the river indicating that the water entering the river from the TCG has a lower BOD and COD than the river water. The highest levels of DO (and SIDO) occur in the upper section of the river (around km 45) as the waters flowing down from Rantau Panjang are re-aerated from the surface, and before mixing of water entering from the TCGs becomes important.

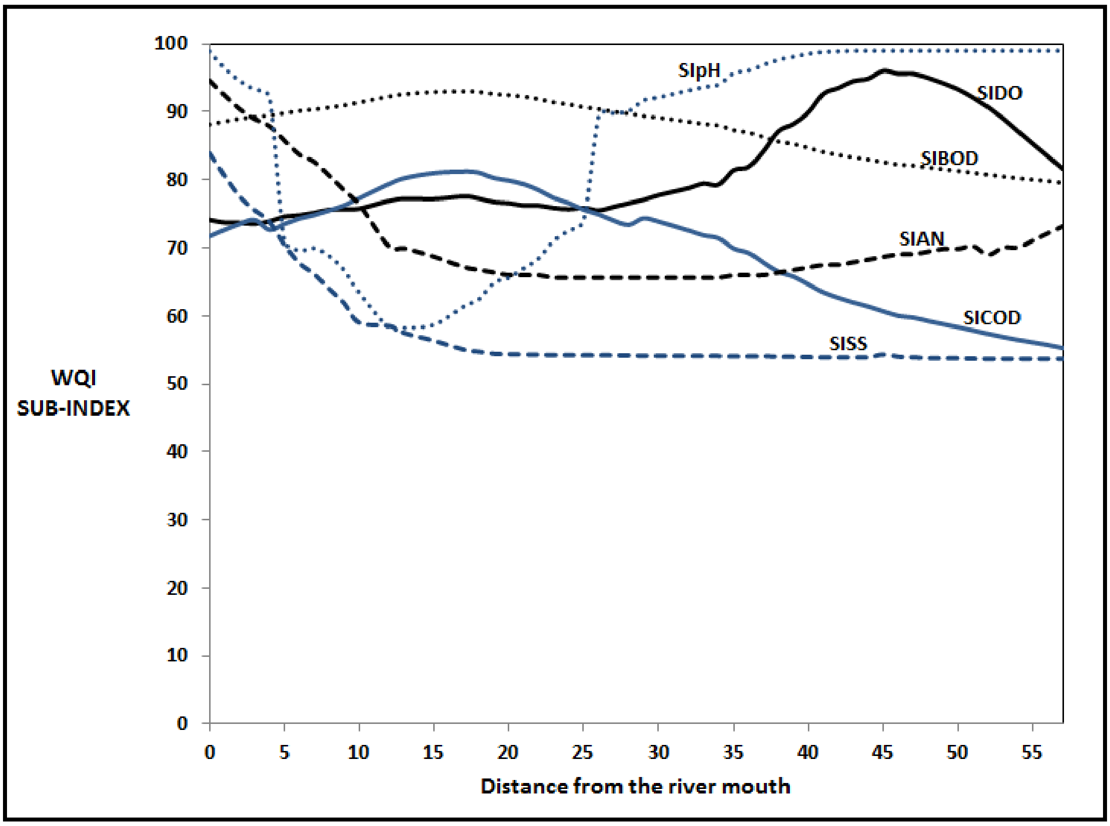


Figure 6-7: Water quality sub-indices along the river averaged over 3 days of Spring tides. A high value of the sub-index contributes to an improvement in the overall WQI.

6.2.2 Wet season (Oct – Dec) water quality

The data used in the InfoWorks water quality model for the wet season period are shown in Figure 6-8. The water quality varies over the month and with distance along the river. To summarise the results two tidal-cycle-averages have been calculated, one for spring tides and one for neap tides, each averaged over 3 days. The distributions of the water quality index and six sub-indices, from the mouth to Rantau Panjang in Figure 6-9 and 6-10.

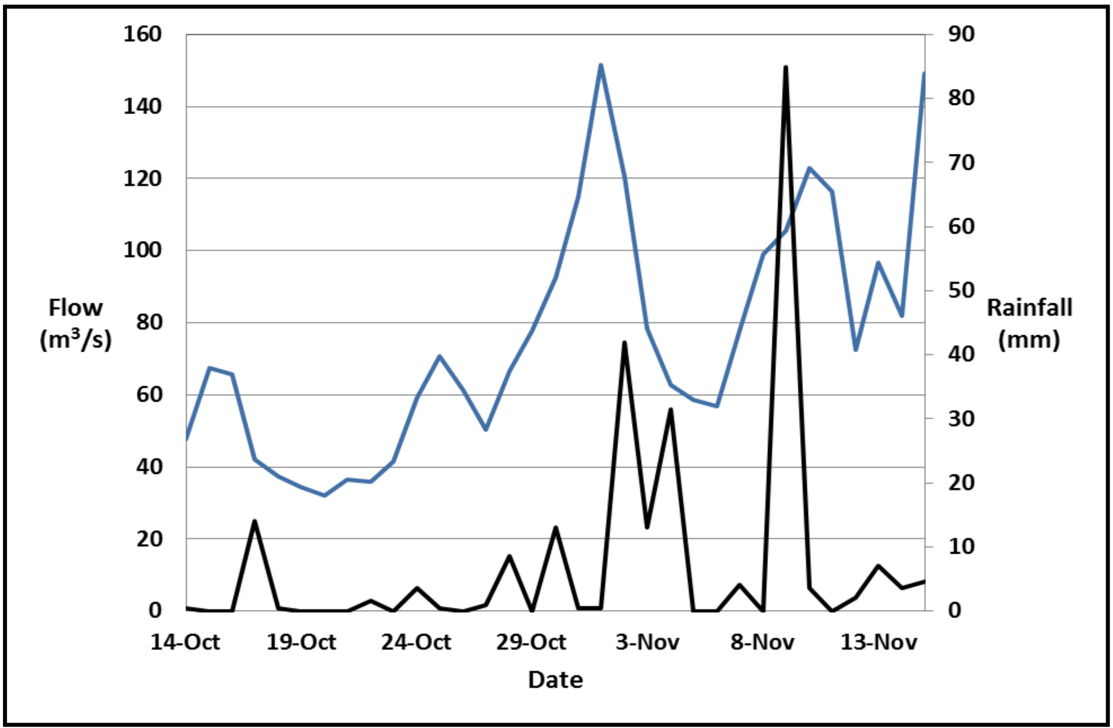


Figure 6-8: Wet Season daily river flow (m^3s^{-1}) at Rantau Panjang (blue line) and daily rainfall (mm) at one of rainfall stations, Ladang Bukit Belimbing (black line).

During the wet season the WQI is almost the same along the whole river and falls into Class II category (Figure 6-9). The water quality during the wet season as measured by the WQI is better than in the dry season by about 10 units on the WQI scale. The water quality at the Rantau Panjang inflow is 77.4 ± 5.8 in the wet season compared to 73.8 ± 7.0 in the dry season (Table 5-5), and the increase in discharge flow due to higher rainfall might also be diluting the pollutants in the river. It should be noted that the variability in WQI shown in Figures 6-6 and 6-9 is the variability due to tidal flows and not the variability in the water quality at Rantau Panjang; this has not been directly considered and is discussed later in this dissertation.

In Figure 6-10 it can be seen that the value of SICOD improves in the area of TCGs. However, the ammoniacal nitrogen and suspended sediment concentration values in the river were high due to fertilizer run-off and erosion from plantations during high rainfall events, resulting in low values of SIAN and SISS. Heavy rain falling on exposed soil can cause substantial leaching of nitrate which comes from nitrogen fertilizers, some of which goes directly into rivers.

DID (1999) has reported that the sediment load SS increases in proportion to the increase in the river runoff; SS in the Bertam River, in the Cameron Highlands of Malaysia, gave 120 mg l^{-1} with runoff of 20 m^3s^{-1} and 220 mg l^{-1} at 30 m^3s^{-1}. Novotny (2003) found that general land disturbance by agriculture activities can increase erosion rates by two or more orders of magnitude. A water quality study conducted by Eiskhani et al. (2009), also in the Bertam River, observed a large increase (up to 6500 mg l^{-1}) in SS, followed by raised levels of total nitrogen (17 mg l^{-1}) and COD (39 - 49 mg l^{-1}), during a wet-season, high-flow event. In the estuary, the sediment loading is strongly affected by the tide. During the low tides, it is about 1,100 mg l^{-1} and about 5,000 mg l^{-1} during the high tides (DID, 1999).

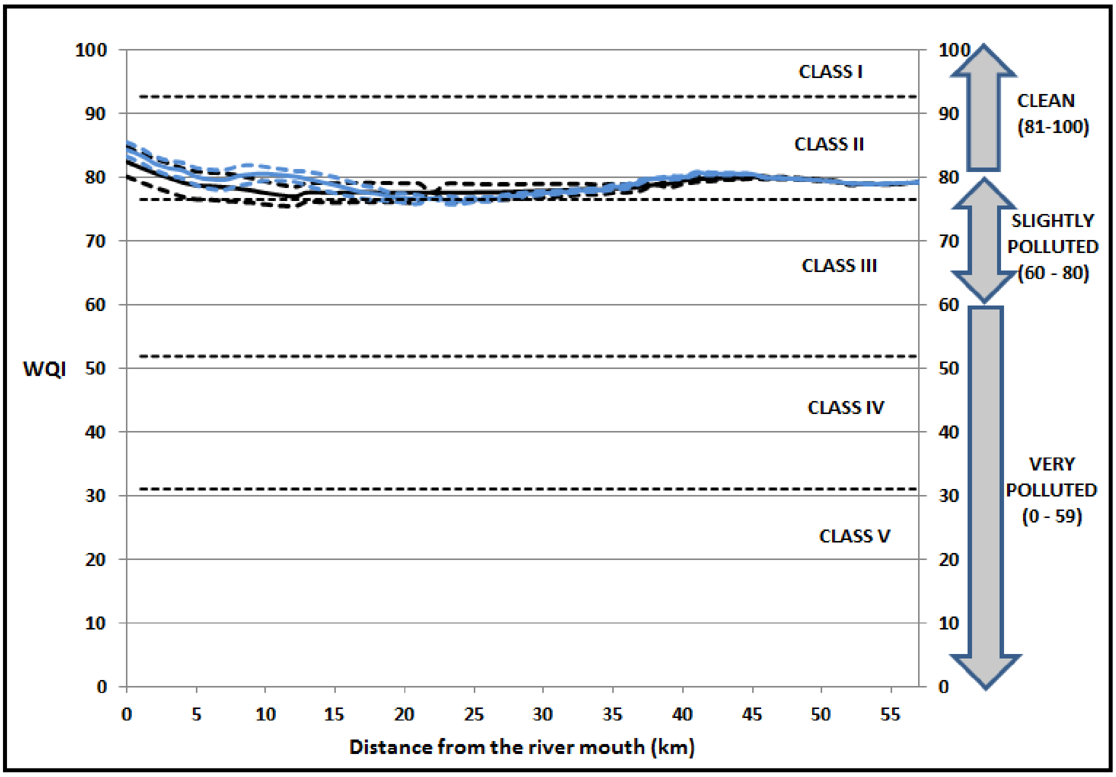


Figure 6-9: Wet Season water quality index as a function of distance up the river. The black lines (mean – solid, dashed ±1 standard deviation) are the average values over 3 days of spring tides. The blue lines (mean – solid, dashed ±1 standard deviation) are the average values over 3 days of neap tides.

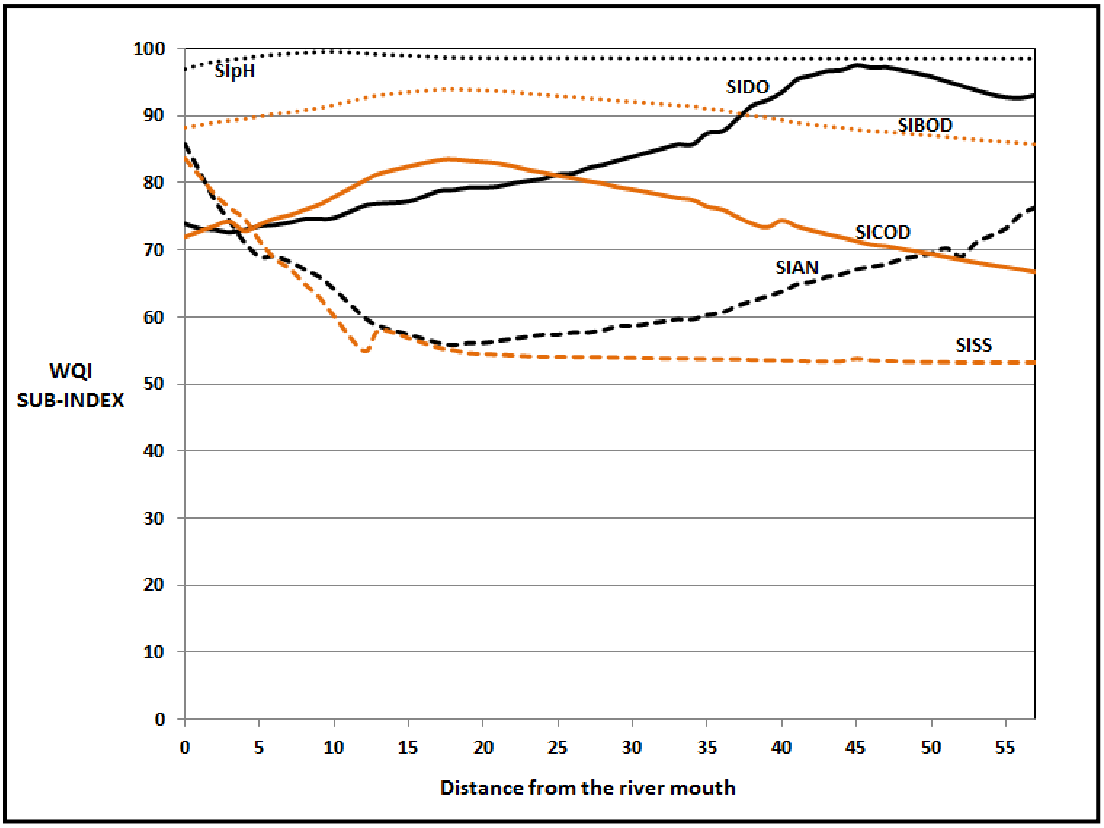


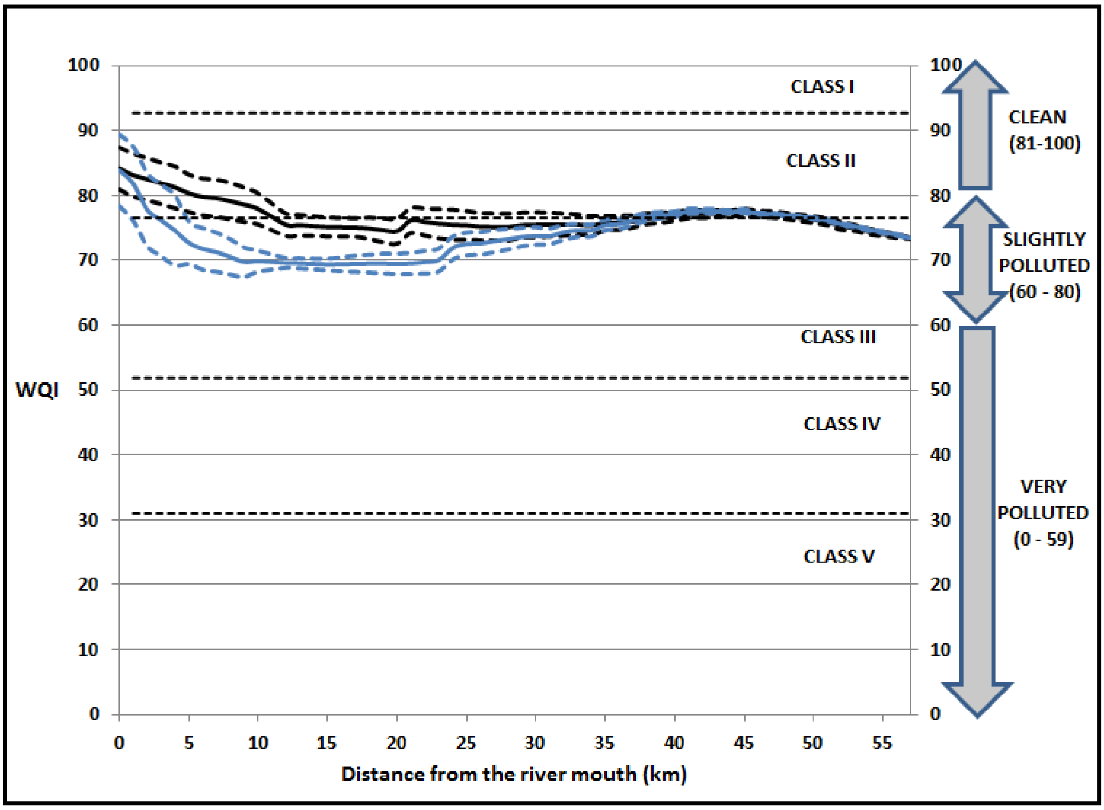
Figure 6-10 : wet season water quality sub-indices along the river, averaged over 3 days of spring tides

6.3 Impact of run-off from TCGs on the Selangor River water quality

It was expected that rain water runoff from the plantations through the TCGs would play an important role in the water quality of the lower reaches of the river, making a direct contribution. They were expected to be significant, perhaps major, sources of pollutants entering the river; the water quality index of the waters in the plantations used in the model were 62 (Class III) during the wet season and 52 (Class IV) during the dry season (see 5.1.2 in Chapter 5). Daniel and Kulasingam (1974) estimated that, during storms, runoff from catchments with plantation crops (oil palm and rubber) over a period of 13 months was twice that of a similar area under jungle, while the low flows were halved.

To look at the effects of runoff through the TCGs the models for spring and neap tides were re-run with the TCGs closed at all times; this involved taking out the rainfall to the catchments as, without this additional modifications, the water in the catchment overflowed the top of the gates. Figure 6-11 (top) shows the wet season WQI for spring and neap tides; Figure 6-6, the equivalent WQI with gates operating, has been repeated in Figure 6-11 (bottom) to allow the differences to be seen more easily.

Above km 40, where there are no tidal effects and therefore no up-river advection of contaminants from the TCGs, no differences can be seen. During spring tides, when tidal flushing is greatest there is very little difference between the gates operating or permanently closed. The main difference is on neap tides between km 12 and km 35 where water quality index improves by around 5 units, from ~65 to ~70. Close to the estuary there is surprisingly little change in the WQI although there at TCGs at km 3, km 5 and km 7.



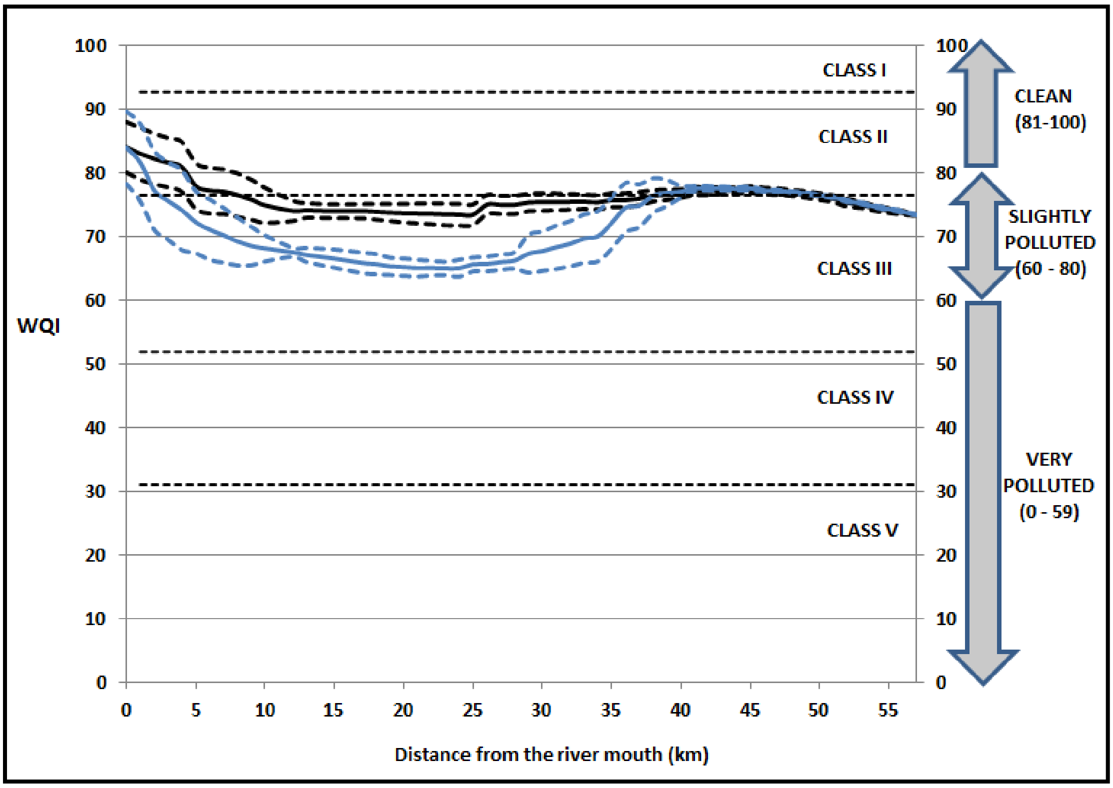


Figure 6-11: Dry season WQI, spring tide (black), neap tide (blue) with standard deviations (dotted line) when the TCGs are kept CLOSED (top), together with TCGs operating normally (bottom) (repeat of Figure 6-6).

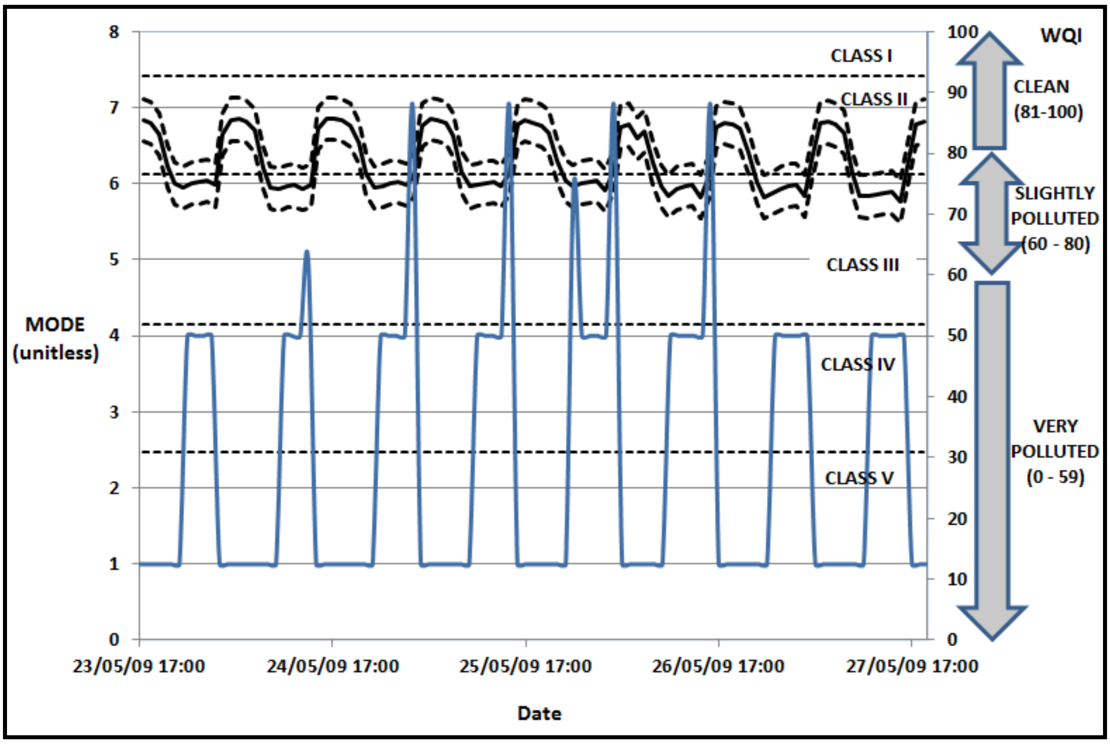


Figure 6-12. The water quality index (black) of the river water close to the TCG at km 7 during the dry season over a 4-day spring tide period. The state of the TCG (its mode of operation) is also shown (blue). Mode 1-3 – Gate closed; Modes 4-7 Gate open with various flow characteristics (see Table 3-7 in Section 3.4.3)

Figure 6-12 shows the water quality predicted by the model in the river at Teluk Penyamun (km 7) at the model node where the TCG inflow joins the river. Four days over spring tide are shown together with the state of the TCG at Teluk Penyamun. Without the TCGs operating the WQI would be expected to show a simple sinusoidal variation at a fixed node (e.g. Teluk Penyamun) in the tidal reaches of the model; on the flood tide, as ‘cleaner’ sea water flows up the river, the WQI increases while, on the ebb tide, in decreases. The operation of the TCGs however, complicates this simple picture. The time-series in Figure 6-12 starts at high water with the TCG at Teluk Penyamun closed (mode 1).

1. As the ebb flow occurs, the WQI decreases and water levels fall until a point is reached where the level in the river is below the level behind the TCG and the TCG opens (modes 4-7 describe the different types of flow through the open gate)
2. The water from the plantations now mixes with the waters ebbing down the river and, unexpectedly, the WQI stops falling, and actually increases

slightly, indicating that the water from the plantation flowing into the river has a higher WQI than the river water.

3. The WQI remains almost constant until, on the flood tide, the TCG closes as river level rises above the water level behind the TCG after which the WQI increases as cleaner sea water flows up the river.

This result was unexpected as the WQI of the water in the plantations input into the model was considerably *lower* than in the river (62) and we had expected to see the WQI in the river *drop sharply* as the TCG opened. The reasons for this result, and how the InfoWorks might be modified to correctly model the water quality are discussed in Chapter 8.

6.4 7Q10 – Low flow analysis

The highest concentration of pollutants in a river, and the worst water quality, might be expected to occur when low flow conditions persist for a number of days. Usually Minimum Average 7 Consecutive Days (MA7CD) that would be expected to occur every ten years, also known as 7Q10, is used for water quality modelling and management (Karamouz et al., 2003, Chapra 1997). The 7Q10 can be estimated by calculating the cumulative probability occurrence of all the years (Chapra 1997, Thomann & Mueller 1987) as;

$$p = \frac{m}{N+1}$$

(Eq. 6-1)

where *m* is the rank number for each flow reading arranged in ascending order, and the recurrence interval, T is given by

$$T = \frac{1}{p}$$

(Eq. 6-2)

For the Selangor River, the lowest flow rate for seven consecutive days in dry period (May – July) was determined for each year at the Rantau Panjang gauging station and assigned a rank, *m* after tabulating the *N* flows in ascending order (Table 6-4).

Table 6-4 : Mean annual flow rate (m^3s^{-1}) of lowest flow in seven consecutive Days for the period of 15 years (1995 to 2009) at Rantau Panjang on the Selangor River, Malaysia.

Rank	**Year**	**Flow (m^3s^{-1})**	**Probability of occurrence; % of time flow**	**Recurrence interval (years)**
1	2000	3.00 ± 0.00	6.25	16.00
2	1999	4.00 ± 0.00	12.50	8.00
3	1998	7.57 ± 1.72	18.75	5.33
4	2002	11.12± 1.85	25.00	4.00
5	2001	14.27 ± 1.18	31.25	3.20
6	2003	14.67 ± 1.08	37.50	2.67
7	2005	24.49 ± 1.79	43.75	2.28
8	2008	24.70 ± 1.15	50.00	2.00
9	1997	25.57 ± 2.88	56.25	1.78
10	2004	25.59 ± 0.93	62.50	1.60
11	2009	26.14 ± 1.91	68.75	1.45
12	2007	26.90 ± 1.05	75.00	1.33
13	2006	28.99 ± 1.37	81.25	1.23
14	1996	32.86 ± 1.57	87.50	1.14
15	1995	43.71 ± 2.29	93.75	1.07

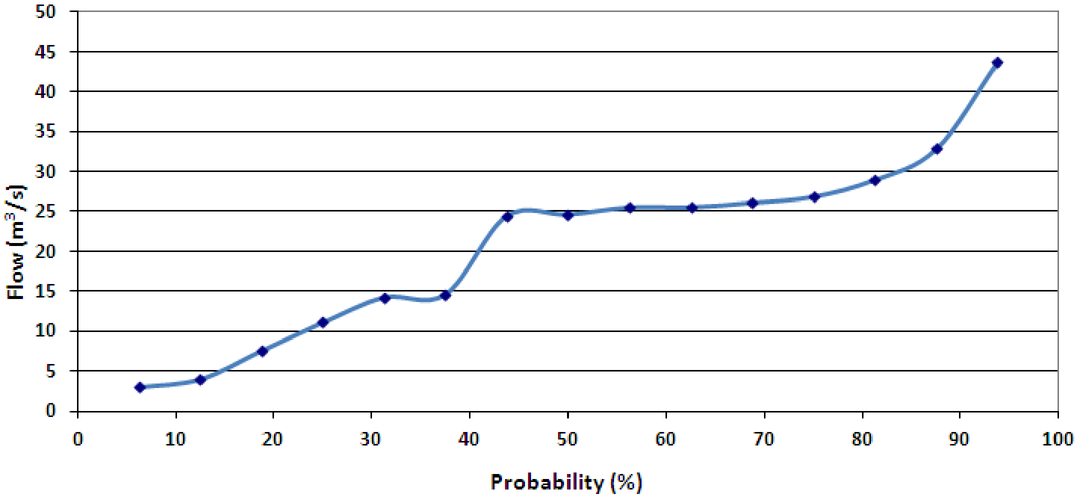


Figure 6-13: Low flow frequency 7Q10 at Rantau Panjang (km 57), for the period of 15 years (1995 to 2009)

Flow at Rantau Panjang is now managed to ensure sufficient water for extraction (up to 35 m^3s^{-1}) at the barrage at km 50. Water is released from the reservoirs behind the Tinggi and Selangor dams to maintain sufficient flow reaching the barrage. The lowest flows shown in Table 6-4 are prior to completion of the Selangor dam in 2005. Under the current river management plans, a minimum base flow down the Selangor River of 3.5 m^3s^{-1} is maintained. Using this low flow value for the Rantau Panjang river flow (extraction ± 3.5 m^3s^{-1}) in the model, together with typical tidal forcing at the mouth, it was found that the water quality of most of the river dramatically improved so that the majority of the river achieved clear Class II status. It was suspected that the oxygen replacement process under these low flow conditions achieved saturated levels (Figure 6-14 and Figure 6-15) and that flow into the river through the TCG gates was negligible due to the very low rainfall which coincides with the periods of 7Q10. What is uncertain in this modelling is whether the re-aeration transfer velocity of 0.3 m h^{-1} is appropriate when the river is flowing so slowly.

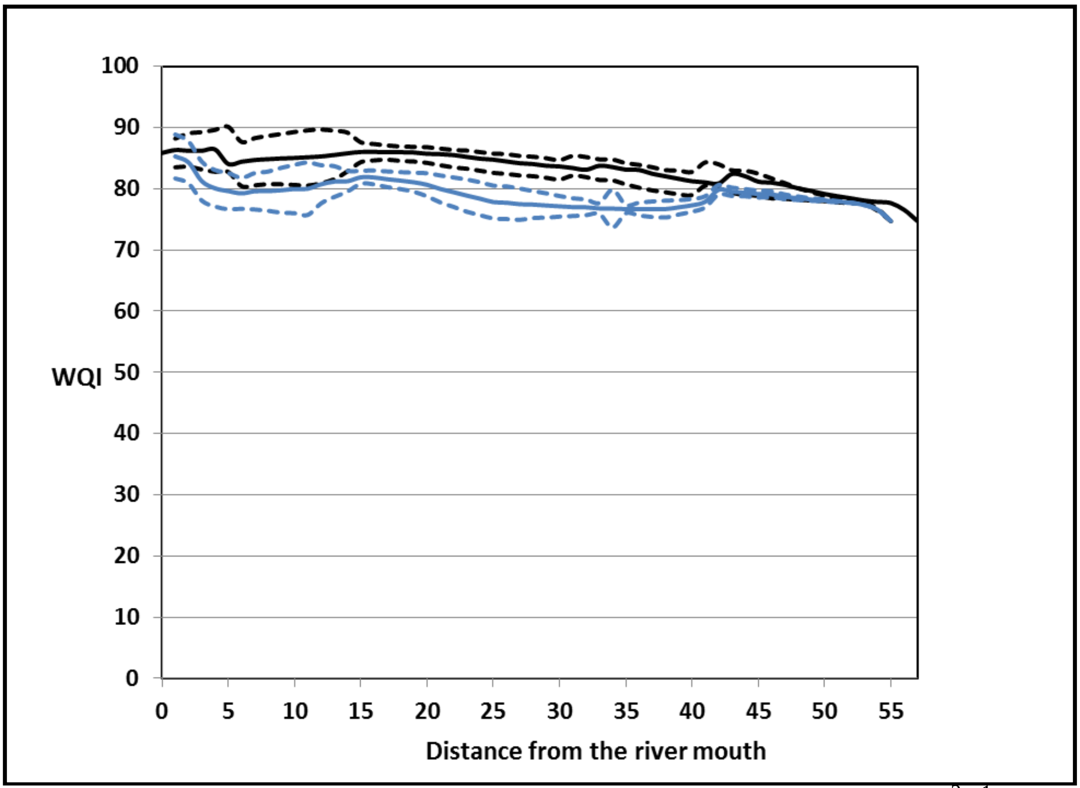


Figure 6-14. WQI and class in the river stretch at very low flow (3.5 m^3s^{-1}). The black line is the WQI during spring tide with its standard deviation (dotted line); the blue line is the WQI during neap tide with its standard deviation (dotted line).

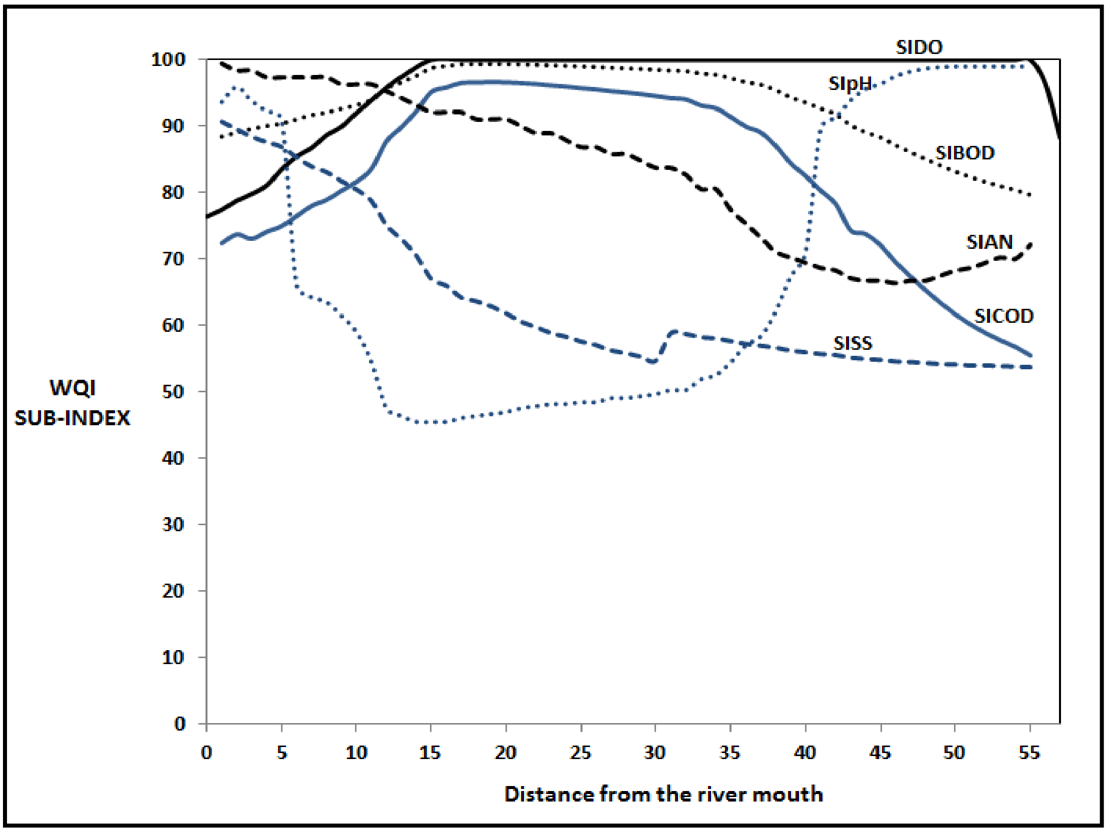


Figure 6-15: Water quality sub-indices along the river averaged over 3 days of Spring tides. A high value of the sub-index contributes to an improvement in the overall WQI.

6.5 Summary

The default value for the re-aeration transfer velocity (f_{air}) of 0.04 m h^{-1} produced DO levels in the river that were too low to support life so f_{air} was varied and the modelled DO compared to measured DO values at three stations in the river (at km 10, km 25 and km 50). A value of 0.3 m h^{-1} gave the lowest deviations between the model and measurements. The new transfer velocity was validated using another set of measured DO at km 25 which, in view of the assumptions that were made concerning the water quality at the model boundaries, were considered acceptable.

The variation in WQI along the Selangor River was then computed for two month-long periods, one in the dry season (14 May to 13 June 2009) the other in the wet season (14 Oct to 14 Nov 2009), using actual tidal forcing, river flow at Rantau Panjang and rainfall data in each sub-catchment where the TCGs were located. 2009 data were chosen rather than 2010, the most recent year available, because of the unusually high dry season flow and rainfall in 2010 (compared to the 2000-2010 average). The water quality at Rantau Panjang was set to the long-term (11 years) mean (for wet and for dry season). The mean water quality along the estuary was calculated for the three days around peak spring tide and three days around neap tide. The standard deviations of the WQI for each of these periods were also calculated.

For the dry season the water quality index at Rantau Panjang was set to 72.5 (Class III: slightly polluted), 85.2 (Class II: clean) at the coastal boundary input and all sub-catchments to 52.4 (Class IV: highly polluted). The water quality is lowest during neap tides reaching a minimum WQI of 65±2 (Class III) around km 25; during spring tides the minimum is 73 ± 2, similar to that at the Rantau Panjang boundary. Only close to the estuary mouth is the WQI consistently in Class II.

In the wet season water quality index at Rantau Panjang was set to 76.8 (Class II: clean), 85.2 (Class II: clean) at the coastal boundary input and all sub-catchments to 62.2 (Class III: slightly polluted). Water quality varies very little along the river and remains in the Class II category (although close to the Class II/Class III boundary) during both spring and neap tides.

The impact of run-off from TCGs to the river water quality was examined by re-running the model with the TCGs closed all the times. Unexpectedly there was very little difference with the gates operating and allowing contaminated water into the river, and with the gates closed. The main difference was observed during neap tides where the WQI improved by up to 5 units (~65 to ~70) between km 12 and km 35. A time series showing the WQI in the river close to a TCG showed some interesting features which are investigated and discussed in Chapter 8.

The effect of very low flow rate was investigated. The flow at Rantau Panjang is now maintained by releasing water from the Tinggi and Selangor dams to ensure a minimum of 3.5 m^3s^{-1} after extraction of up to 35 m^3s^{-1}) at the barrage at km 50. Under these conditions it was found the WQI dramatically improved along the whole river to Class II; it was suspected that this was due to little Class III water from Rantau Panjang passing the barrage, cleaner coastal water penetrating up the river and high DO levels along most of the river.

CHAPTER 7

PREDICTION OF FUTURE WATER QUALITY: 2015, 2020 and 2030

7 Introduction

This Chapter is concerned with the prediction of future values of the parameters that make up the WQI along the Selangor River - dissolved oxygen (DO), the biological oxygen demand (BOD), the chemical oxygen demand (COD), ammoniacal nitrogen (AN), pH and total suspended solids (SS), over the next 20 years as a result of the changes in land-use in the upper catchment of Selangor River. Development of the lower reaches, below Rantau Panjang, is assumed to be minor.

Changes in land-use in the upper catchment were determined using the ArcGIS application for the three years when data were available, 1997, 2005 and 2008. The water quality data from the DOE station just below Rantau Panjang were used to estimate the levels of the six components which made up the WQI, appropriate for the years 1997, 2005 and 2008. The three main land-use categories (forest, urban and agriculture) were then used to generate three sets of equations for each of the WQI component listed above, and to solve for the contribution made by each land-use category (per km^2). Using the GIS land-use areas plus the predicted land-use for 2015, a simple regression analysis was used to extrapolate the land-use areas to the years 2020 and 2030: these land-use areas (and those for 2015) were then combined with the results of the water-quality/land-use from 1997-2008 to predict the future water quality at Rantau Panjang and used as input to the InfoWorks Water Quality model. This analysis was conducted for both the wet and dry seasons.

The uncertainty associated with each of these estimates of future water quality was derived from uncertainties in the measurements of water quality and from uncertainties in the land-use (both historical and future) and, because of the complex nature of the equations used to derive future water quality, were combined using a Monte Carlo approach.

This study is limited because 1) the predicted pattern of land-use changes for Selangor State is only available for 2015 (Kuala Selangor Local Planning Report, 2006), 2) the changes in water quality only apply at the upper boundary condition, not at river mouth where water quality is assumed to remain unchanged, 3) all the input water quality parameters at TCGs are assumed to remain the same, and 4) the rate of water extraction at the Batang Berjuntai barrage is assumed to remain constant over this period. Details on how the values of water quality parameters were estimated are explained in the next Section.

The InfoWorks models were then run using the mean water quality predictions for 2015, 2020 and 2030, for the wet and dry seasons, to determine the effects of the deteriorating water quality at Rantau Panjang on the water quality in the lower reaches of the Selangor river; the extraction of water at Batang Berjuntai was included in all these model runs and was found to have a large effect on water quality particularly in the dry season.

7.1 Land-use and land-use changes

The relationship between land-use and water quality were established from historical land-use and water quality data. Table 7-1 shows the changes in the areas of forest, urban, agriculture, and water over the period 1966-1997 (Department of Agriculture, 2001, unpublished data) for the Selangor basin but, as there were no equivalent data for water quality, these data were not used but they show the general trend of deforestation of land for agriculture and urbanisation. Land-use in the upper catchment was better known for the years 1997, 2005, 2008 and there was also a prediction of land-use in 2015 for the whole of the Selangor River basin; the predicted land-use for 2015 is taken from the Kuala Selangor Local Planning Report (2006) document. The land-use data were provided by DOA and the Malaysian Remote Sensing Agency (MRSA).

The land-use was reclassified from the original land-use components (shown in Table 7-2) into four new categories: urban or built-up land, agricultural land, forest and water, according USGS specification (Milazzo, 1983; Anderson et al., 1976) for uniformity of analysis and to suit the types of land-use in the Selangor River basin (Table 7-2). The reclassified land-use maps are shown in Figures 7-1a to 7-1d. The areas of the four land-use categories for 1997, 2005, 2008 and 2015 are shown in Table 7-3; an estimate of ±2% has been made of the uncertainty associated with each area which will be used later, but it must be noted that the uncertainty is only an estimate based on GIS experience.

Table 7-1: Rates of change of land-use changes over 32 years period (1966 – 1997). Data source: Dept. of Agriculture, 2001 (unpublished data).

Land-use type	**Rate of change (km^2/year)**
Forest	5.11 (deforestation)
Urban build-up	2.87
Agriculture	7.58
Water	0.787

Table 7-2: Land-use reclassification and its components.

	Land use reclassification	**Land use components**
1.	Urban or built-up land	Residential
		commercial and services
		industrial
		transportation
		communications and utilities
2.	Agricultural land	Oil palms
		Rubber trees
		Paddy fields
		Other agricultural land
3.	Forest	Forested area
		Wetland
		Swamps
		Mangroves
4.	Water	Streams and canals
		Lakes and reservoirs

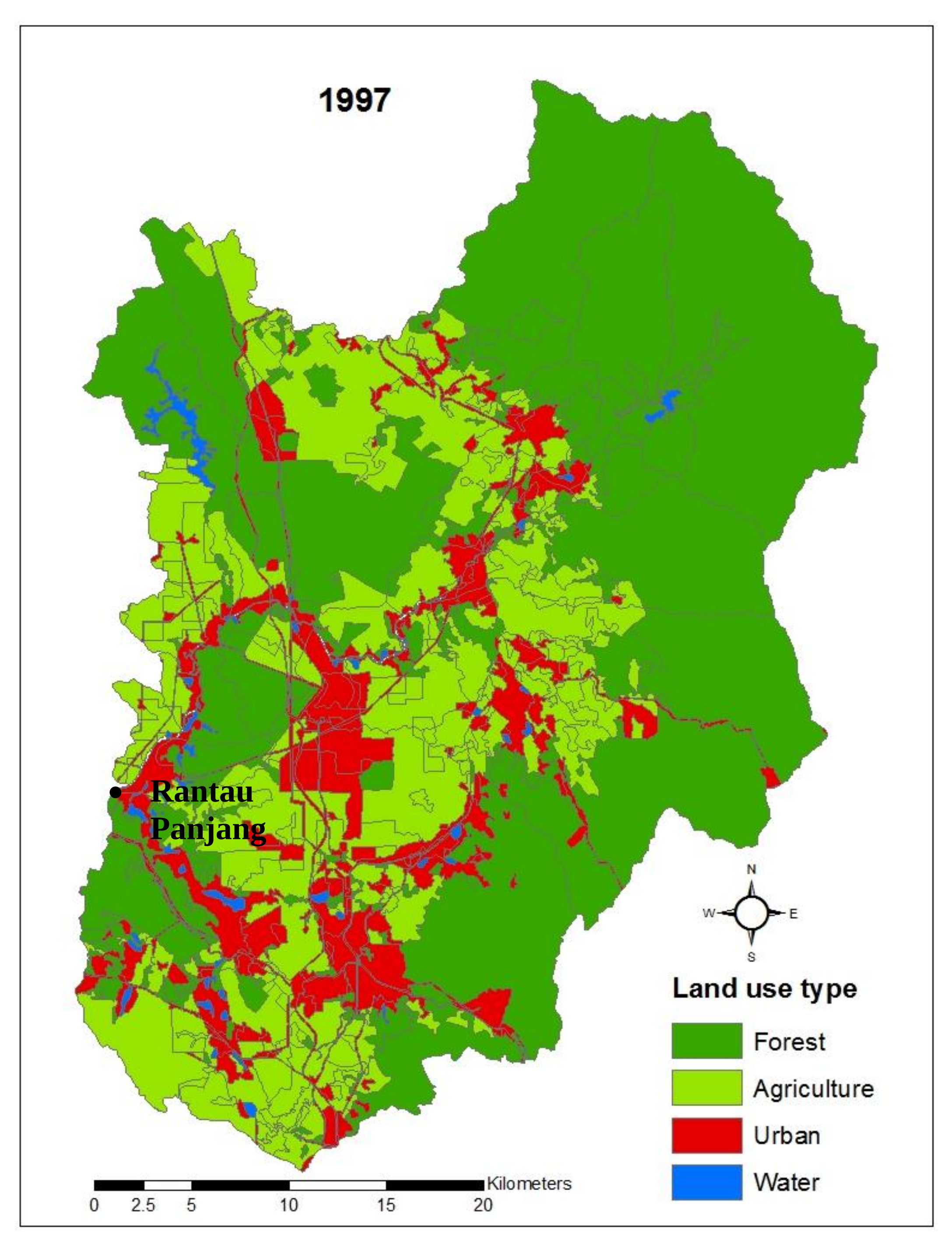


Figure 7-1a: Land-use map for 1997 for the upper catchment (the area that drains into the Selangor River above Rantau Panjang) reclassified into the four land-use types shown in Table 7-2. The location of Rantau Panjang is shown.

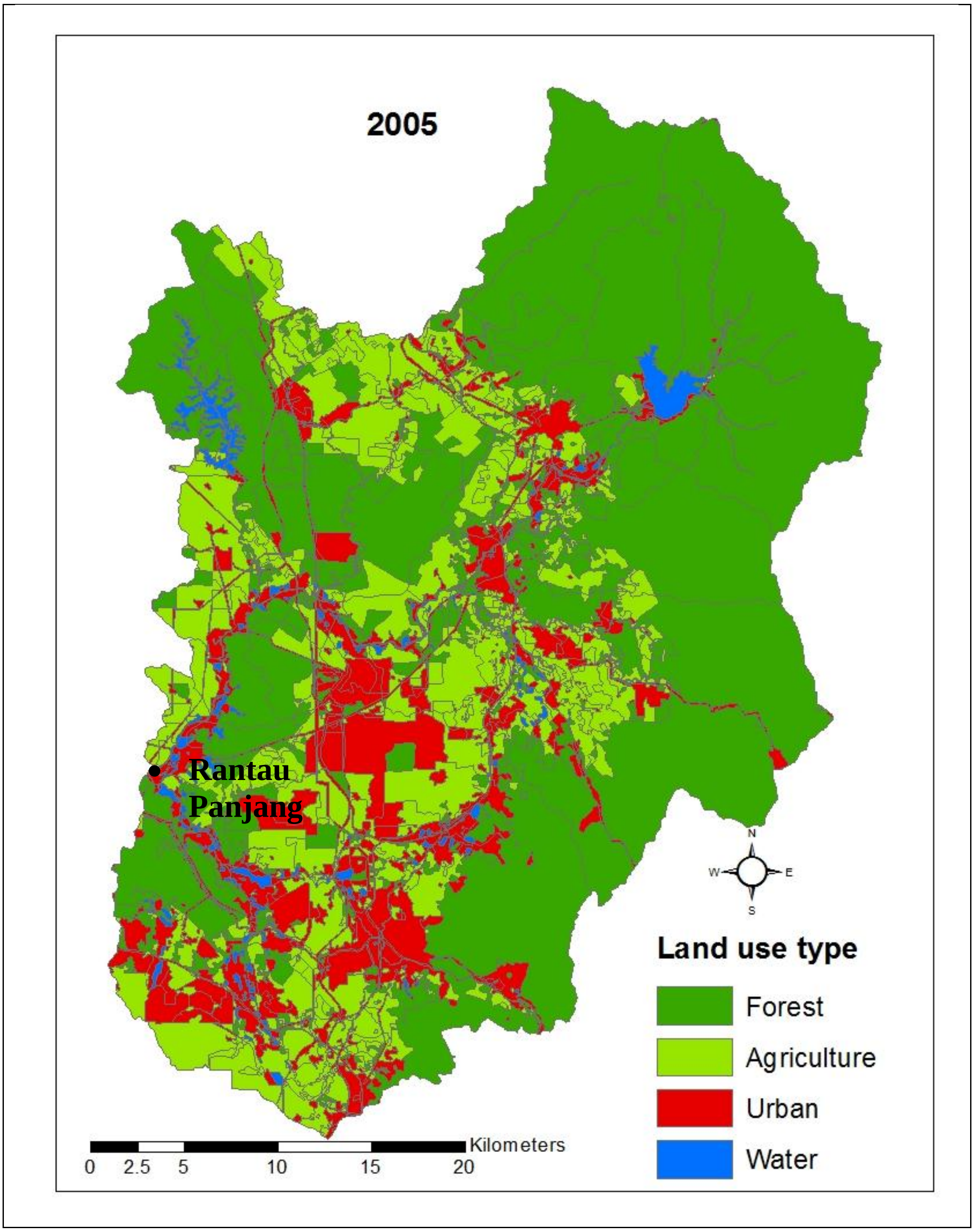


Figure 7-1b: Land-use map for 2005 for the upper catchment (the area that drains into the Selangor River above Rantau Panjang) reclassified into the four land-use types shown in Table 7-2. The location of Rantau Panjang is shown.

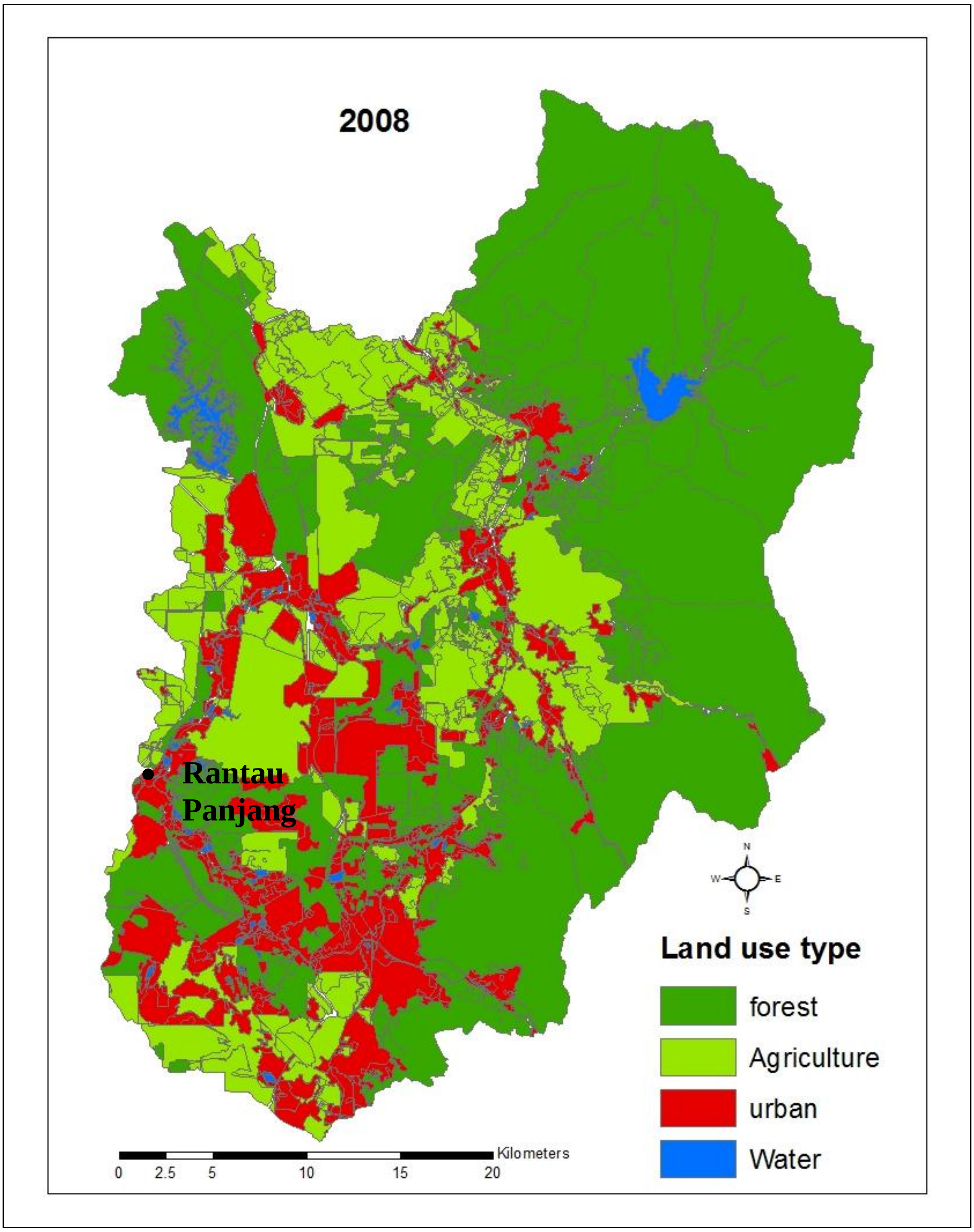


Figure 7-1c: Land-use map for 2008 for the upper catchment (the area that drains into the Selangor River above Rantau Panjang) reclassified into the four land-use types shown in Table 7-2. The location of Rantau Panjang is shown.

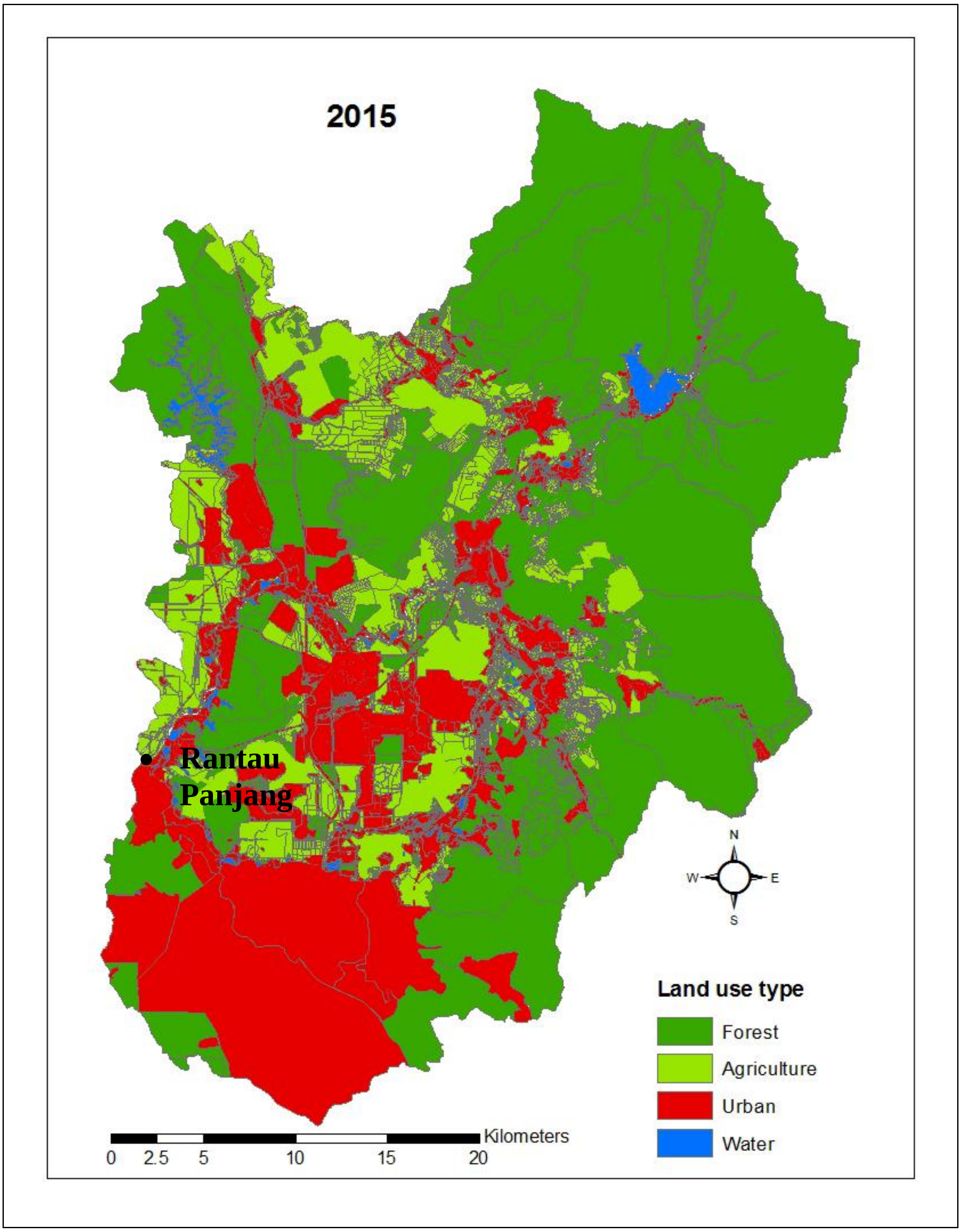


Figure 7-1d: Map of projected land-use for 2015 for the upper catchment (the area that drains into the Selangor River above Rantau Panjang) reclassified into the four land-use types shown in Table 7-2, taken from the Kuala Selangor Local Planning Report (2006). The location of Rantau Panjang is shown.

Table 7-3: Land-use areas from Figures 7-1a to 7-1d for 1997, 2005, 2008 and 2015. 2% errors assumed.

Year	**Land-use type**			
	Forest	Urban	Agriculture	Water
1997	829 ± 16	189 ± 3.8	411 ± 8.2	18.8
2005	840 ± 16	217 ± 4.3	349 ± 7.0	37.8
2008	832 ± 16	255 ± 5.1	341 ± 6.8	29.1
2015	822 ± 16	354 ± 7.7	259 ± 5.2	26.7

The rates of change in land-use were estimated by fitting regression lines through the data in Table 7-3. Only the regression lines for agricultural land-use and urban land-use were statistically significant at 95% (Figures 7-2 to 7-4); however as these were the only data available all three trend lines values were used to estimate the areas of forest, urban and agricultural land-use in 2015, 2020 and 2030. The uncertainties in these values are likely to be large and, for the uncertainty calculations described below have been assumed to be twice those in Table 7-3 (±4%).

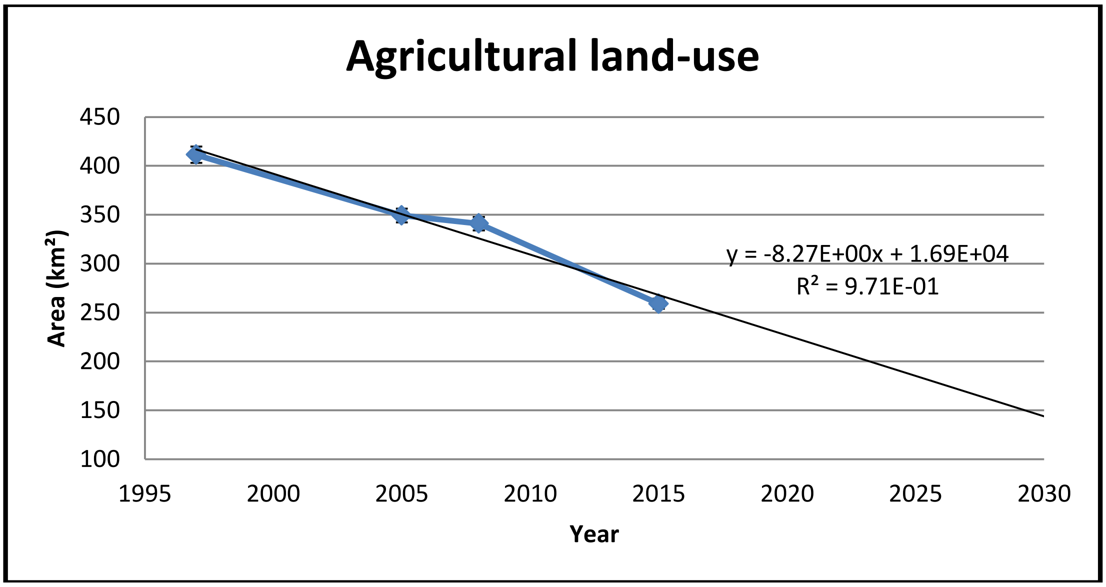


Figure 7-2: Agricultural land-use from 1997 to 2015 from GIS and trend line to 2030

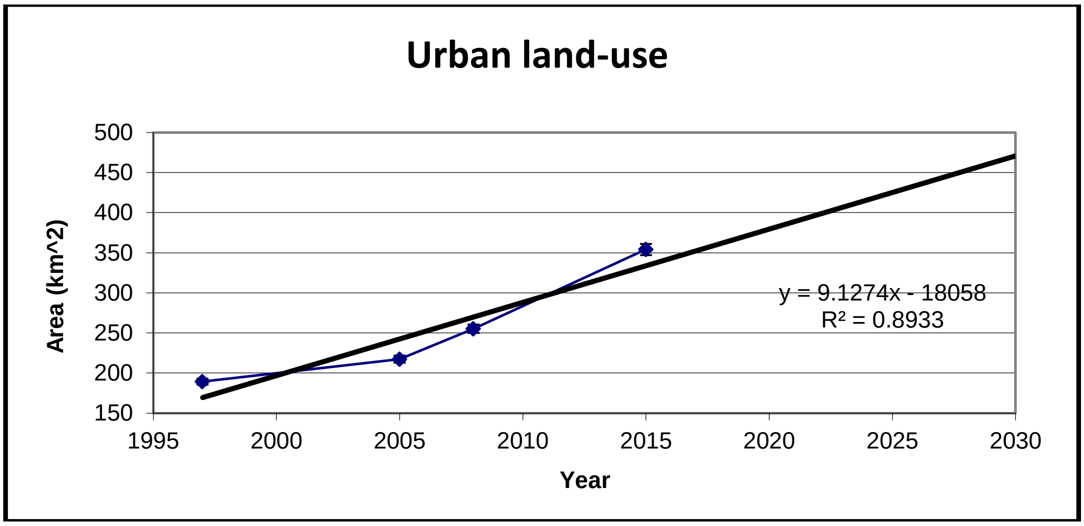


Figure 7-3 Urban land-use between 1997 and 2015 from the GIS analysis with the trend line to 2030

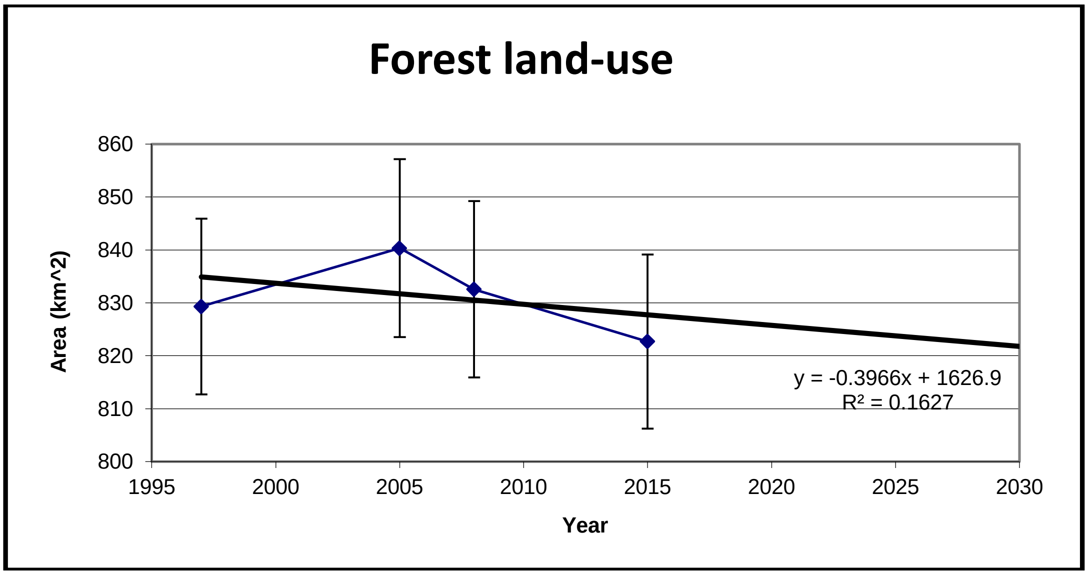


Figure 7-4: Forested area between 1997 and 2015 from GIS and trend line to 2030

Table 7-4: Land-use areas for calculated for 2015, 2020 and 2030 from the trend lines shown in Figures 7-2 - 7-4. Uncertainties of ±4% are assumed.

Year	**Land-use type**		
	Forest	Urban	Agriculture
2015	824 ± 33	333 ± 8.2	267 ± 10.4
2020	822 ± 33	379 ± 7.0	226 ± 8.9
2030	820 ± 33	470 ± 6.8	143 ± 5.6

7.2 Estimation of water quality parameters

The two-monthly water quality measurements from the DOE measurement station near Rantau Panjang were used to estimate the water quality parameters at Rantau Panjang appropriate to each of the three land-use maps, 1997, 2005 and 2008, for the wet season and the dry season. The measurements in the years 1997-1998 were used for 1997 (6 measurements for wet season, 6 measurements for dry season), 2004-2006 for 2005 (9 measurements for each season) and 2007-2009 for 2008 (9 measurements for each season). Mean and standard deviation of each parameter are shown in Table 7-5 and used in the model for the calculation of water quality for 2015, 2020 and 2030.

Table 7-5: Water Quality parameters for 1997, 2005, 2008 from Rantau Panjang

Parameters (mg l^{-1}) (except pH, WQI)	**1997**		**2005**		**2008**	
	Wet	Dry	Wet	Dry	Wet	Dry
DO	5.58±0.39	5.86±0.64	6.38±0.52	5.92±0.81	5.11±0.54	5.31±0.77
COD	21.1±11.6	35.0±11.8	25.3±6.6	34.3±18.8	38.3±9.00	34.2±9.06
BOD =0.13*COD	2.75±1.51	4.55±1.54	3.29±0.85	6.84±0.36	4.98±1.17	4.44±1.18
Suspended Solids (SS)	257±153	174±100	111±53	106±104	63.5±53.1	53.2±17.6
Ammoniacal Nitrogen (AN)	0.15±0.10	0.14±0.10	0.27±0.18	0.26±0.23	0.16±0.13	0.22±0.09
pH	6.27±0.32	6.28±0.15	6.89±0.61	6.84±0.36	5.88±0.44	6.10±0.41
WQI	76.7±13.4	75.3±13.1	79.0±9.7	77.4±15.6	79.0±9.7	77.9±10.7

7.2.1 Estimating water quality at Rantau Panjang in 2015, 2020 and 2030

A simple model was used to establish the impact of the changes in land-use in the upper catchment of the Selangor River on the water quality at Rantau Panjang. It was assumed that each square kilometre of each land-use type made a time-invariant contribution to the water quality, but that the contribution was different for each component of the water quality, e.g. the DO in year X is given by

$$DO_X = K_{DO,LU1}A_{LU1,X} + K_{DO,LU2}A_{LU2,X} + K_{DO,LU3}A_{LU3,X} + \cdots \qquad \text{(Eq. 7-1)}$$

where $K_{DO,LU1}$ is the contribution made to the DO_x component of the water quality per square kilometre of Land-Use 1 ($LU1$), and $A_{LU1,\,X}$ is the area of Land-Use 1 in year X etc. The land-use areas of forest, urban, agriculture and water for 1998, 2005 and 2007 are known (Table 7-3), as are the water qualities at Rantau Panjang for approximately the same periods (Table 7-5). Hence three equations can be written of the form of Equation 7-1 above, one for each year 1998, 2005 and 2008. This limits the number of land-use categories to three if the equations are to be solved for the K values; as the area of water was the smallest of the four land-use categories, and the water bodies are mainly a reflection run-off from the other three land-use types, the water category was omitted.

The three equations with three unknowns can be solved simultaneously but much more easily by expressing each component of the water quality Y in a matrix form and solved for $K_{Y,F}$, $K_{Y,U}$, $K_{Y,Ag}$, by matrix inversion using MATLAB (where F is Forest, U is urban and Ag is agricultural land use).

$$[Y_{1998} \quad Y_{2005} \quad Y_{2008}] = \begin{bmatrix} A_{F,1998} & A_{U,1998} & A_{Ag,1998} \\ A_{F,2005} & A_{U,2005} & A_{Ag,2005} \\ A_{F,2008} & A_{U,2008} & A_{Ag,2008} \end{bmatrix} * \begin{bmatrix} K_{Y,F} \\ K_{Y,U} \\ K_{Y,Ag} \end{bmatrix} \qquad \text{(Eq. 7-2)}$$

The values for each water quality component for 2015 were then calculated using the predicted areas of land-use (forest, urban, agriculture) using the K_Y values. Table 7-6 shows the rates of change and also the rates of change for the period 1967-1997 from the Department of Agriculture (2001). Table 7-7 shows the *K* values for each WQI parameter from the solution of the equations above. The water quality values and the overall WQI for 2020 and 2030 were estimated from the rates of land-use change for urban and agriculture taken from the linear regression lines fitted through the 1998-2015 values and tabulated in Table 7-8. To maintain comparability between the InfoWorks model runs in this Chapter and those in Chapter 6, the BOD values were always set to 0.13*COD.

Table 7-6: Land-use changes over 1998-2015 (this study). Also shown are changes over the previous 32 year-period 1966–1997 (Department of Agriculture, 2001).

Land use category	**Rate of change (km^2/year) 1998-2015**	**Rate of change (km^2/year) 1966-1997**
Forest	-0.40 (R^2 = 0.16) Assumed constant in this study	-5.11 (deforestation)
Urban	9.13 (R^2= 0.89)	2.87
Agriculture	-8.27 (R^2= 0.97)	7.58

Table 7-7: *K* values for the Urban, Agriculture and Forest land-use types for each of the six water quality parameters of the WQI

Parameters	***K* values (per km^2)**					
	Forest		**Urban**		**Agriculture**	
	Wet	Dry	Wet	Dry	Wet	Dry
DO (mg/l)	0.026 ± 0.078	0.013 ± 0.051	-0.034 ± 0.132	-0.016 ± 0.066	-0.0237 ± 0.100	-0.005 ± 0.076
BOD (mg/l)	-0.0091 ± 0.0356	-0.0060 ± 0.087	0.043 ± 0.057	0.0116 ± 0.14	0.0044 ± 0.050	0.0186 ± 0.11
COD (mg/l)	-0.070 ± 0.27	-0.046 ± 0.66	0.33 ± 0.44	0.089 ± 0.14	0.034 ± 0.38	0.14 ± 0.87
pH	0.023 ± 0.089	0.019 ± 0.053	-0.026 ± 0.10	-0.018 ± 0.090	-0.017 ± 0.13	-0.014 ± 0.068
SS (mg/l)	-0.37 ± 2.9	-0.075 ± 2.7	-0.96 ± 3.9	-0.64 ± 3.7	1.801 ± 4.40	0.81 ± 3.8
AN (mg/l)	0.0029 ± 0.011	0.0037 ± 0.018	-0.0033± 0.017	-0.0048 ± 0.027	-0.0040 ± 0.014	-0.0049 ± 0.024

Table 7-8: Concentration of water quality parameters projected to enter the Selangor River at Rantau Panjang for 2015, 2020 and 2030. See text for explanation of red values.

Parameters	**Concentration values**					
	2015		**2020**		**2030**	
	Wet	Dry	Wet	Dry	Wet	Dry
DO (mg/l)	4.08 ± 1.02	4.33 ± 0.45	3.54 ± 0.96	3.80 ± 0.44	2.93 ± 0.69	2.78 ± 0.39
BOD (mg/l)	7.97 ± 3.07	3.88 ± 3.18	10.0 ± 3.46	3.66 ± 3.69	13.4 ± 3.79	3.21 ± 4.03
COD (mg/l)	61.3 ± 23.8	29.8 ± 24.5	75.3 ± 26.6	28.1 ± 28.4	102.8 ± 29.2	24.6 ± 31.0
pH	5.02 ± 1.37	5.53 ± 1.27	4.53 ± 1.57	5.21 ± 1.46	3.61 ± 1.80	4.61 ± 1.73
SS (mg/l)**	-150± 191 171 ± 146	-77.2± 133 169 ± 119	-252 ± 245 171 ± 146	-153 ± 180 169 ± 119	-397 ± 297 171 ± 146	-287 ± 258 169 ± 119
AN (mg/l)	0.199 ± 1.04	0.162 ± 0.160	0.207 ± 1.355	0.130 ± 0.168	0.070 ± 1.43	0.084 ± 0.167
WQI value	**60.0 ± 8.9** **53.4 ± 9.0**	**67.6 ± 9.3** **61.3 ± 8.9**	**55.5 ±9.1** **48.5 ± 9.5**	**62.9± 10.0** **56.2± 10.2**	**50.4 ± 9.3** **43.3 ± 9.7**	**56.2 ± 9.8** **48.8± 10.2**
WQI Class	**III/III**	**III/III**	**III/IV**	**III/III**	**IV/IV**	**III/IV**

Leaving discussion of the uncertainties until the next section, it can be seen that four of the six water quality parameters show a decrease in water quality at Rantau Panjang through the period 2015 to 2030. Dissolved oxygen levels drop, biological and chemical oxygen demand increases and pH drops, becoming much more acidic. Two parameters are predicted to improve, ammoniacal nitrogen (AN) levels decrease, presumably due to decreased areas under agriculture, and suspended solids (SS) levels become negative. These unrealistic values of SS are shown in red in Table 7-8. The red values of the WQI values, using the negative values for SS which result in the SS sub-index value being set to its maximum (highest water quality) value of 100 (see Section 3.3), drop from 60 to 50 (class III to class IV) in the wet season and from 67 to 56 (both Class III) in the dry season. If the average values of SS for the period 1997-2009 (black values) are used, the WQI values drop from 54 to 43 (Class III to Class IV) in the wet season and from 61 to 49 (Class III to Class IV) in the dry season.

7.3 Uncertainties in the water quality calculations

The results shown in Section 7-3 include estimates of uncertainties. The uncertainties in each water quality parameter taken from the DOE measurement station near Rantau Panjang are shown in Table 7-5 (mean and standard deviation of the measurements). The uncertainties in the land-use areas are shown in Table 7-3. The uncertainties in the *K* values derived from the matrix inversion were obtained using a Monte Carlo method. Monte Carlo methods cover a broad range of techniques (Fishman, 1995) which rely on the repeated random sampling of the input parameters to obtain the distribution of the output parameter(s). 1000 values for each *K* were generated using the MATLAB function ‘randn’ to generate random values of the input parameters based on their mean and standard deviation. Again, for model comparability BOD was set to 0.13*COD. COD (and BOD) Suspended sediments, pH and Ammoniacal Nitrogen were assumed to be log-normally distributed. Strictly, this assumes the input values are normally distributed or log-normally distributed and independent. This analysis resulted in some unrealistic values for most parameters (negative values and, for DO, for example, values higher than saturation). Traps were specified to account for unrealistic values of DO. All values were restricted to the range of their mean (or mean of log) ± 2 standard deviations.

Each 1000 sets of *K* values were then used to generate the 1000 values of each water quality parameter for 2015, 2020 and 2030, which were then combined, using the sub-indices, to produce 1000 values of the WQI, for each of the wet and dry seasons. Mean and standard deviations were calculated from each series of 1000 values.

7.4 WQI of the Selangor River in 2015, 2020 and 2030

7.4.1 Water abstraction

The water abstraction at the Batang Berjuntai barrage (km 50), described in Chapter 2, is included in the Hydrodynamic and Water Quality InfoWorks models for 2015, 2020 and 2030; it is assumed that the abstraction rate will remain constant at 35 m^3/s, although in reality this extraction is likely to increase in the future as water demands increase. In the dry season it is assumed that sufficient water will be released from the Selangor and Tinggi reservoirs to provide sufficient water for this extraction, and for a base-flow of 3.5 $m^3 s^{-1}$.

7.4.2 Water quality along the Selangor River

The predicted values of water quality parameters from Table 7-8 were used as pollutant input for the Water Quality model at Rantau Panjang. Following the methodology used in Chapter 6 the WQI (and its six components) have been computed for one wet and one dry season, each spanning one month (two spring-neap cycles) in each of the years 2015, 2020 and 2030; the one month period of 17 May to 17 June 2015, 14 May to 14 June 2020 and 16 May to 16 June 2030 have been taken to represent the dry season; and 27 October to 27 November 2015, 24 October to 24 November 2020 and 19 October to 19 November 2030 to represent the wet season. The tidal forcing is correct for these dates but, of course, rainfall and river flow have to be estimated. The river flow at Rantau Panjang and rainfall data necessary for the model are taken to be the same as those used in Chapter 6 for the wet and dry seasons (i.e. the actual river flow measured at Rantau Panjang and rainfall that occurred during the one month periods 14 May to 14 June 2009 and 14 October to 14 November 2009). Ideally multiple model runs should be undertaken, using a variety of rainfall and river flow conditions, but there was insufficient time available for this work.

The dry and wet season WQI profiles along the Selangor River predicted by the InfoWorks Water Quality model are shown in Figure 7-5 and 7-6. The data are shown for the spring tides and for neap tides; in each case the WQI values have been averaged over 3 days and the range of the WQI (maximum and minimum WQI at each location) resulting from the flood and ebb tidal currents is also shown. The impact of the extraction of water at the Batang Berjuntai barrage, resulting less flowing down the river, can be clearly seen on all the water quality profiles in Figures 7-5 and 7-6. The average water quality between km 40 and km 10 for each model run are summarised in Table 7-9 together with the equivalent values for 2009/10. It must be noted that the WQI of the Selangor River appears to *improve* between 2009/10 and 2015 (Table 7-9) but this is because the runs of the model in Chapter 6 do not include the extraction of water at Batang Berjuntai barrage, which later runs clearly show as having an impact on the WQI. It is known that some extraction was occurring from the Batang Berjuntai barrage in 2009/10 but no information is available on how much this was.

Table 7-9: Average value of WQI (and WQI Class) for the stretch of the Selangor River between km 15 and km 40. [Note that 2009/10 data are <u>not</u> directly comparable due to omission water extraction]

15 – 40 km	**2009/10***	**2015**	**2020**	**2030**
Dry season Springs	75.2 ± 3.0 (Class II/III)	79.7± 1.4 (Class II)	79.1± 1.6 (Class II)	77.6± 2.6 (Class II/III)
Dry season Neaps	69.3 ± 7.5 (Class III)	79.1± 1.4 (Class II)	79.0± 1.6 (Class II)	76.7 ± 2.2 (Class II/III)
Wet Season Springs	79.5 ± 1.7 (Class II)	70.5± 3.6 (Class III)	65.7± 3.9 (Class III)	57.1± 4.7 (Class III)
Wet Season Neaps	78.4 ± 2.2 (Class II)	68.3± 1.6 (Class III)	62.9± 1.8 (Class III)	54.7± 2.0 (Class III)

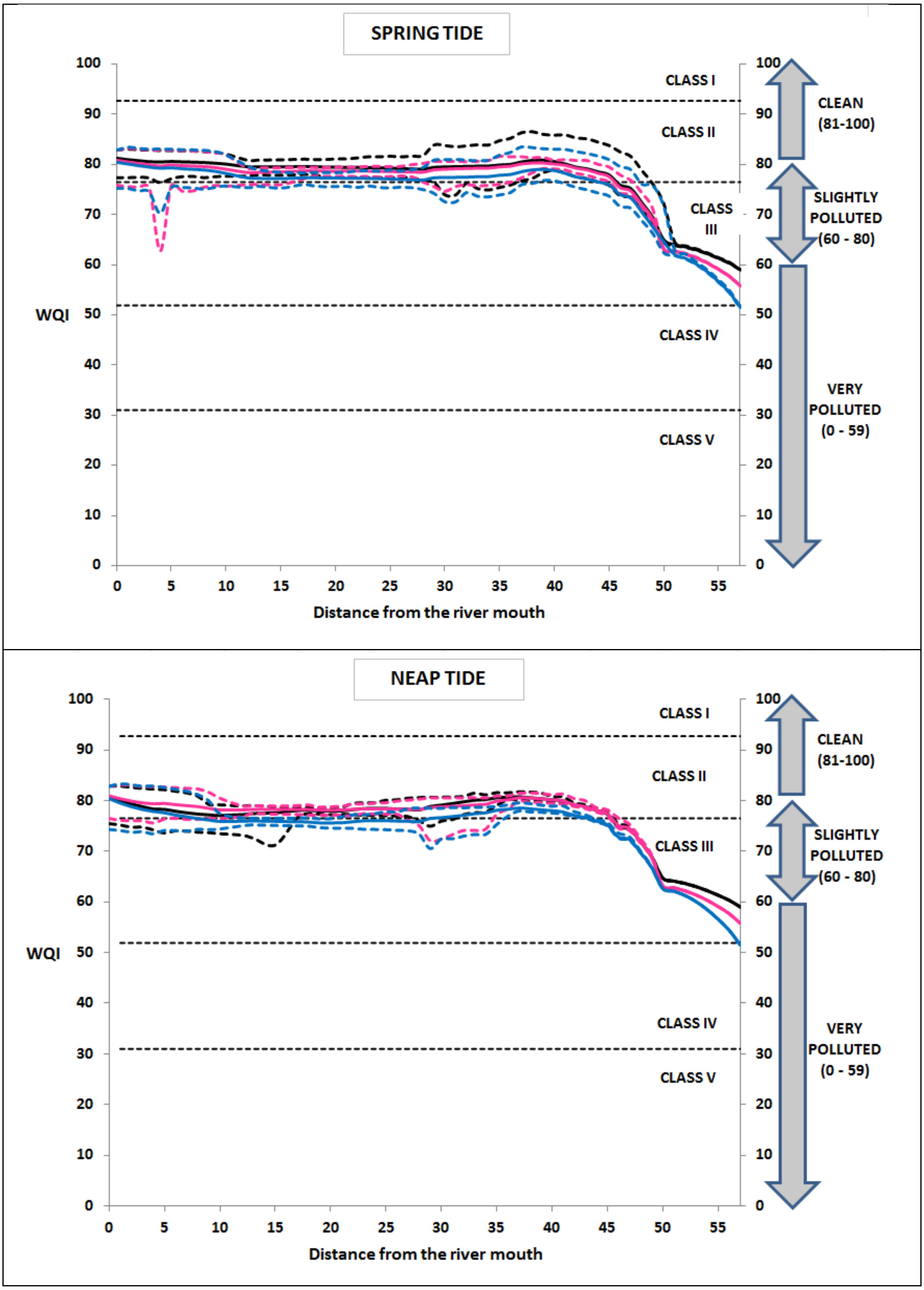


Figure 7-5 : WQI for 2015 (black line), 2020 (pink line) and 2030 (blue line) with each standard deviations (dotted lines) during DRY season for spring tide (upper panel) and neap tide (lower panel).

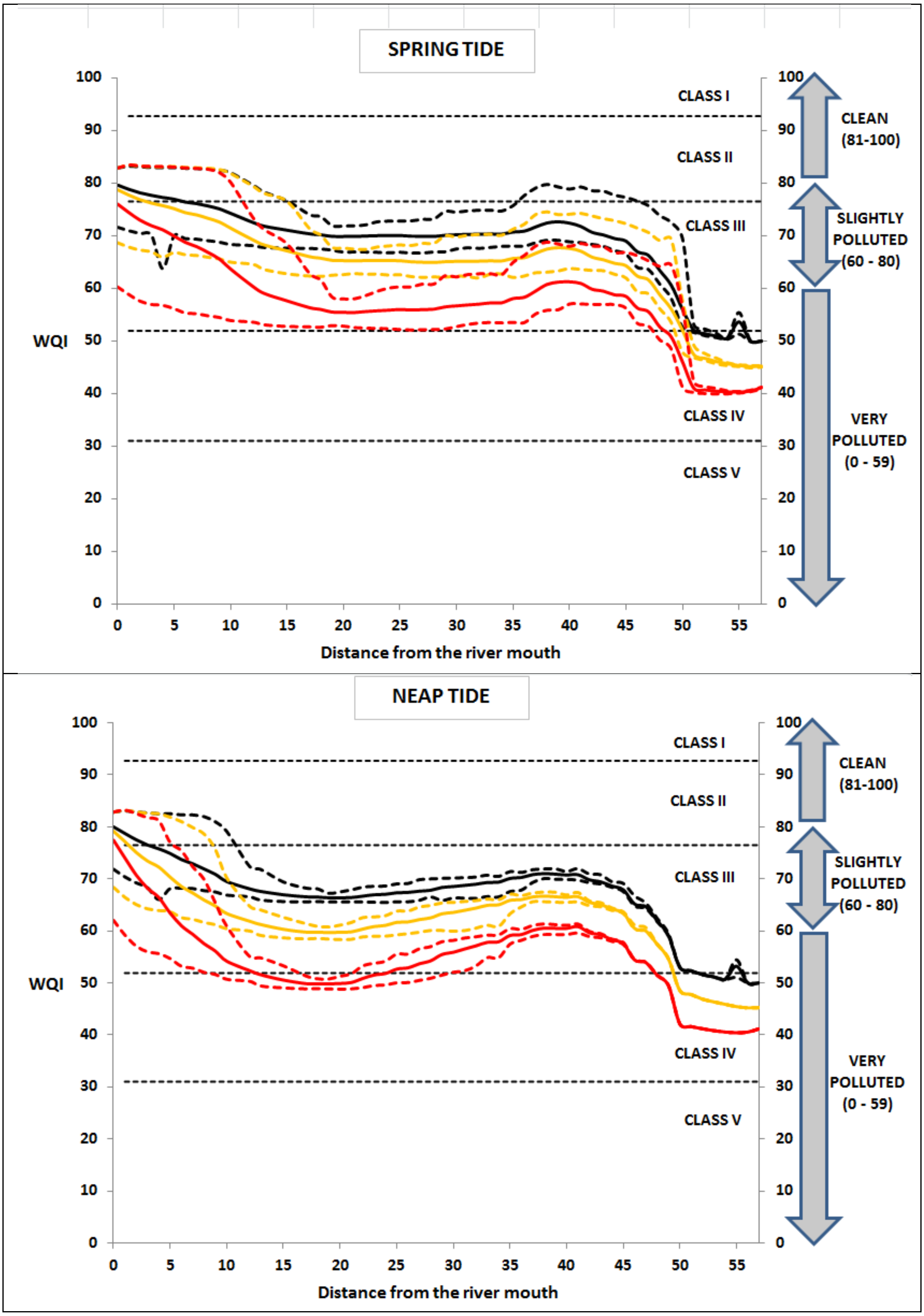


Figure 7-6 : WQI for 2015 (black line), 2020 (yellow line) and 2030 (red line) with each standard deviations (dotted lines) during WET season for spring tide (upper panel) and neap tide (lower panel).

7.4.2.1 Predicted WQI for 2015

The water quality during the wet season along most of the river responds to the dropping WQI at Rantau Panjang, during both spring and neap tides. WQI increases rapidly from around 50 (Class IV) between Rantau Panjang and Batang Berjuntai barrage, to around 70 between km 15 – km 40 as a result of the extraction of Class IV water at Batang Berjuntai barrage; there is little difference between spring and neap tidal periods. Between km 15 and the estuary mouth water quality improves to Class II.

During the dry season the WQI improves to almost 80 (Class II) along most of the river (below km45). During the dry season the water quality entering the river at Rantau Panjang is 59, better than the value of 50 during the wet season.

7.4.2.2 Predicted WQI for 2020

During wet season the water quality along the whole river with the exception on the 10 km closest to the estuary mouth is ~5-7 WQI units less than in 2015, reflecting the lower WQI (~45) at Rantau Panjang. Once again the strongest feature is the rapid increase of WQI just below Batang Berjuntai barrage. On neap tides the worst WQI occurs around km 20 (60 ± 2) (Class III) perhaps due to the influx of water from the plantations through the TCGs.

During the dry season the WQI is similar to that in 2015. The WQI is generally in Class II, but near the Class II/III boundary.

7.4.2.3 Predicted WQI for 2030

In the wet season water quality along the whole river deteriorates and drops to an average WQI of 57 ± 5 during spring tides and 55 ± 2 during neaps for the stretch between km 15 and km 40 (Class III); however there is a decrease in WQ towards km 20 where in drops to 57 ± 3 on springs tides (poor Class III) and 49 ± 2 (Class IV) on neap tides.

The WQ during the dry season is a little less than in 2015 and 2020 and is 77 ± 2, just on the border line between Class II and Class III but the deterioration is very small.

The water quality at Rantau Panjang predicted for 2015, 2020 and 2030, with their uncertainties, and the model values for the WQI averaged between km 40 and km 10, are summarised in Figure 7-7.

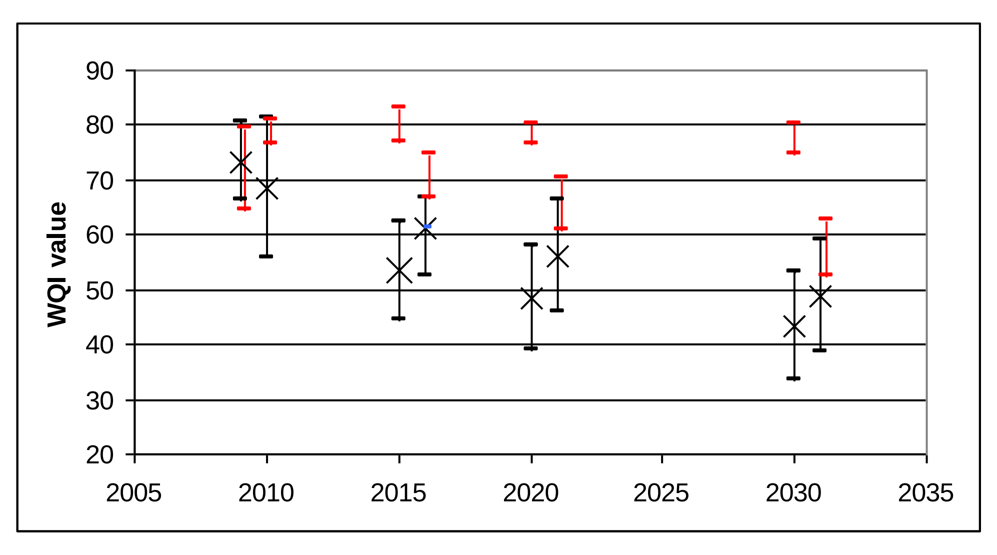


Figure 7-7: WQI values (black) for Rantau Panjang showing uncertainties from Monte Carlo prediction for DRY and WET (offset by +1year) for 2015, 2020 and 2030. Values for 2009 are measured values of WQI at DOE Rantau Panjang station ±1 standard deviation. Model predictions for the average WQI between km 40 and km 15 are shown (red); the range shown for the red values is the maximum RANGE of WQI due to the Spring-Neap tidal changes.

7.5 Summary

Land-use maps for the upper part of Selangor River basin for the years 1997, 2005 and 2008 have been used, together with water quality parameters from the DOE measurement station close to Rantau Panjang, to calculate the contribution made to each water quality parameter of each square kilometre of forest, urbanisation and agricultural land (*K*-values) for the dry and wet seasons. Trends in land-use between 1997 and 2008, plus projected land-use for 2015, were used to estimate the land areas being used for forest, urbanisation and agriculture for 2020 and 2030. These areas were then combined with the *K*-values to provide estimates for the six water quality parameters, DO, COD, BOD (set to 0.13*COD), AN, pH and SS, and also the values of the WQI.

Levels of four parameters, DO, COD, BOD and pH showed marked deterioration with time while ammoniacal nitrogen levels improved due to the reduced areas under agricultural cultivation. Total suspended solids were also predicted to decrease and becomes negative, a physically unrealistic scenario, so for the modelling of river using InfoWorks total suspended solids were assumed to remain at their average 1997-2009 levels. The overall water quality at Rantau Panjang between 2015 and 2030 drops from 54 to 43 (Class III to Class IV) in the wet season and from 61 to 49 (Class III to Class IV) in the dry season.

Estimates of the uncertainty of the *K*-values and of the water quality parameters for the years 2015, 2020 and 2030 were made using a Monte Carlo method of 1000 randomly-generated land-use and water quality estimates. The uncertainties in the water quality values for 2015, 2020 and 2030 were considerable, resulting in uncertainties in the final WQI vales of ±10 WQI units.

The InfoWorks model of the Selangor River was run in a similar way to Chapter 6 to provide estimates of the water quality of the river between the Rantau Panjang and the sea. In general in the wet season the water quality of the whole of the river dropped as the water quality at Rantau Panjang decreased although there was a marked improvement in water quality between Rantau Panjang and km 40 attributed to the extraction of water at the barrage at km 50. The WQI typically improves by 20 WQI units (equivalent to one WQI Class) over this section but the water quality of the Selangor River between km 40 and km 15 still drops with time (Table 7-9) from upper Class III to close to the Class III/IV category in 2030. During the dry season the WQI downstream of km 40 is predicted to decrease a little from Class II to Class II/III borderline.

CHAPTER 8

DISCUSSION OF RESULTS

8 Introduction

This Chapter discusses the use and limitations of the InfoWorks RS and InfoWorks WQ models, the results of the use of these models to obtain WQI profiles along the Selangor River and the limitations identified. The WQI for wet and dry seasons, using flow and water quality data for Rantau Panjang for the most recent period are discussed. The limitations on the water quality of the water entering the river through the TGC are described and ways of improving the representation in the model of the water from the plantations in future runs of the models are considered. The results of the WQI for 2015, 2020 and 2030, and their uncertainties are critically discussed.

8.1 Limitations of the InfoWorks hydrodynamic model for the Selangor River.

The InfoWorks hydrodynamic model was driven at the estuary mouth by the tidal constituents (derived from a 30-day tide gauge record) and by the measured river flow from the gauging station at Rantau Panjang. Unfortunately there were no additional water level measurements along the river that could be used to validate the model. Neither were there any measurements of the tidal currents at any point along the river that could be used for validation. Hence the model was tested against the measurements of salinity made during the four NAHRIM field campaigns (Figures 5-4 and 5-5). The model showed reasonable skill at reproducing the measured along-river profiles of salinity; changing the two diffusion parameters D0 and D1 made very little difference to the output of the model.

The model was weak at describing the salinity close to the estuary mouth as the flood-tide started. This was attributed to the failure of the model to allow for any of the brackish water swept out of the estuary at the end of the ebb-tide to be brought back into the estuary. The ‘ramp function’ (Section 5.4) described in the InfoWorks RS Manual clearly had not been correctly implemented. Consequently, immediately the tide begins to flood the water quality becomes that of the Straits of Malacca (the lower boundary condition) and has a WQI of 85 (Class II); this will result in the water quality in the estuary being better than it should.

The water extraction at the Batang Berjuntai barrage at km 55 was not included in the models of the river in 2009/10 as the data on the exact amount of water being extracted while the barrage, extraction station and reservoirs were being constructed were not available (DID, 2007). The 2009/10 models could usefully be run again using a number of different extraction rates (up to the maximum 35 $m^3 s^{-1}$) to examine the possible range of influence of the extraction on water quality. Within the limitations of the validation data available the hydrodynamic model appeared to perform well. There is clearly a need for systematic measurements of stage and current, preferable over a complete spring-neap tidal (14-day) cycle, to be made to properly assess the performance of the InfoWorks RS model.

The ease of set-up and speed of running on a standard PC of the InfoWorks modelling suite is a great advantage over more complex 2D or 3D models, such as the Delft 3D model used by Van Breeman (2008) to model the salt intrusion into the Selangor estuary, especially as many of the river systems in Malaysia which will be studied in the future have limited physical, hydrographic and chemical records. The InfoWorks RS and WQ models are sufficiently versatile, with links between a variety of riverine and estuarine systems, such as hydrodynamic, chemical and biological processes, pre-programmed into the models. They have a limited number of tuneable parameters (such as Manning’s *n*, diffusion D0 and D1, re-aeration coefficient) which can be adjusted for any particular river.

They have the disadvantage of being simplistic. The 1D structure of the hydrodynamic model prevents correct representation of the thermo-haline structure often found in estuaries which can result in suppressed vertical mixing and result in the underestimate of the range of the WQI in these regions. The lack of a ramp function to allow more realistic mixed river and coastal water back into estuary at start of flood tide needs to be implemented to improve the representation of the water quality in the estuary.

8.2 Prediction of present water quality

There is very little water quality data available for the Selangor River against which the InfoWorks Water Quality model can be validated. Most of the water quality data (such as those from the DOE monitoring station close to Rantau Panjang, see Section 4.5.1) have been used in deriving the boundary conditions for the water entering down the river. Water quality data were therefore collected during NAHRIM field campaigns (Section 4.5.2) and were used for the conservative salinity tracer for the hydrodynamic validation but could not be used for to validate the water quality along the Selangor river as there were no concurrent (ideally daily) measurements of water quality available either from Rantau Panjang or from the catchment canals at the time of the field campaign.

Acknowledging these limitations, the model predicts that the present WQI of the Selangor River to be typically around Class III throughout its lower reaches (Section 6.2). Water quality is generally a little better during the wet season than the dry season due to the increased volume of rainfall and the consequent dilution of the pollutants entering at Rantau Panjang and through the TCGs. The river shows some ability to assimilate the chemical pollutants in its middle reaches (between Rantau Panjang and km 35 where water quality improves slightly) but there is no evidence that the river is able to assimilate chemical pollutants lower down the river although this is complicated by the presence of the TCGs. Unexpectedly, closing the TCGs in the model did not have a large effect on water quality in the model. Water quality measurements by NAHRIM scientists in the canals close to the TCGs (Table 5-1) indicated very low WQI in both the wet season (62 Class III/IV) and the dry season (52 Class IV). These values were used, together with the daily rainfall rates, to define the water run-off through the catchment and were expected to have a significant impact on the water quality of the Selangor River; reasons for this are discussed in the next Section.

There is clearly a pressing need for more water quality data against which to validate the InfoWorks WQ model; without this there can be only limited confidence in the WQI predictions along the river.

8.3 Effects of run-off through the TCGs

As shown in Section 6.3 keeping the TCGs closed in the model, preventing any water from the plantations from entering the river, improves the WQI a little, particularly in the dry season on neap tides when the overall WQI is at its worst, but nowhere enough to improve the water quality to Class II. Quantitatively, the improvement in WQI as a result of closing the TCGs permanently, in the dry season, on the river as a whole is 0.6 WQI units on spring tides and 1.2 WQI units on neaps. Considering just the section of the river adjacent to the TCGs (km 3 – km 32), the improvements are 1.8 WQI units on spring tides and 3.7 units on neap tides.

In the model the canal system in the plantations behind each TCG is represented by a series of geographically-distributed 'nodes' which define water volume and flow rates via the channel cross-sections and lengths. Rainfall volume for each catchment is introduced at single point (or two points, depending on channel geometry), which then flows through the drainage canals (see Figure 8-1 for an example of one catchment). Water quality in the plantations was defined through the rainfall water quality; in Figure 8-1 this is at the point labelled 'Rainfall Input Data Kg Lubok'.

However it was found that the water quality in the relatively-shallow drainage canals has time to change as it flows towards the TCG, through the rapid uptake of oxygen as the transfer velocity for oxygen for the whole model was set to 0.3 m h^{-1}, the value established through calibration in the main river. Figure 8-2 shows the time series of DO concentration at the node just upstream of the TCG (close to where the water quality measurements were made). This starts at the 'correct' value (the initial start-up DO value at the TCG of 6.0 mg l^{-1}) but rises rapidly to 7.1 mg/l during model spin-up before falling to around 6.5 mg l^{-1} as 'polluted water' flows throughout the catchment and reaches the TCG. As a result of the changes to DO and the other water quality parameters, this has the effect of altering the WQI from 52 at the 'rainfall node' to 62 at the TCG in the wet season, and 42 to 52 in the dry season, and significantly moderates the impact of the water from the TCGs.

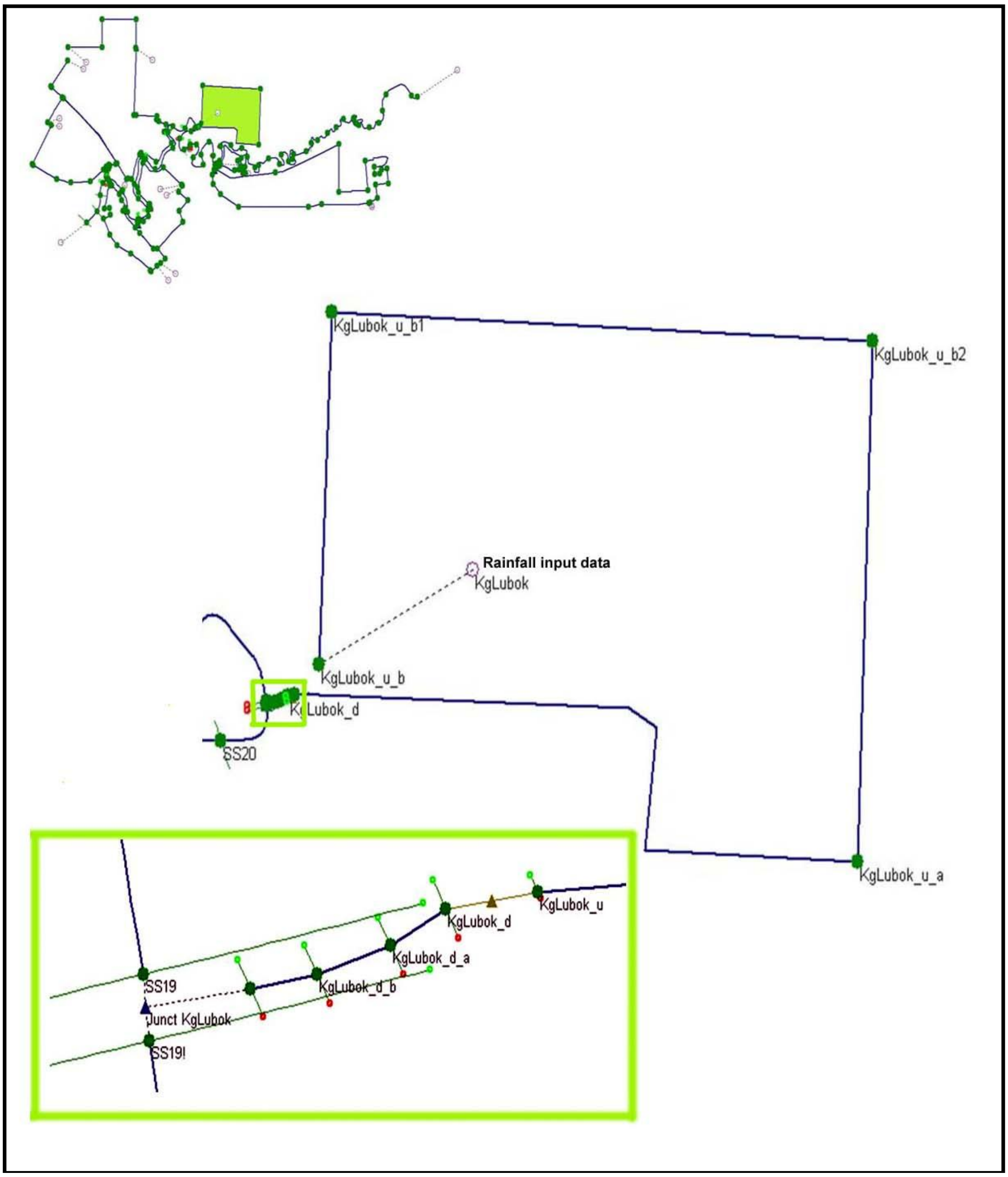


Figure 8-1: Nodes for one of the sub-catchment, at Kampong Lubok. The primary canals extend from node KgLubok_u just upstream of the TCG (see brown triangle in green inset) through to KgLubok_u_b where the rainfall is input into the catchment. When the TCG is open water flows down the channel from KgLubok_d to the junction with the river between nodes SS19! and SS19.

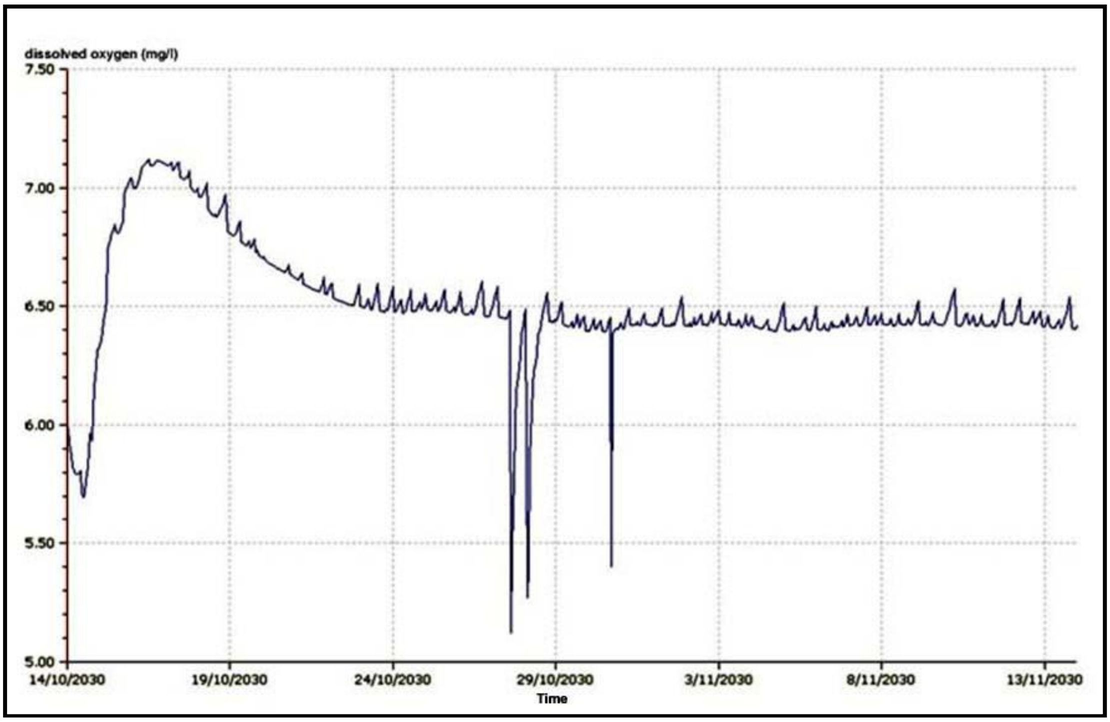


Figure 8-2: The DO concentration evolution behind one of the TCGs during model run. The DO is set to 6.0 mg l^{-1} throughout the catchment at time-zero. The first 14 days are used to ‘spin-up’ the model.

The next step in solving this problem is to investigate the use of a lower transfer velocity for oxygen for catchment nodes compared to that used in the river to see if this produces a more realistic value for the WQI at the TCGs; the model allows either single transfer velocity throughout the model or for each node to have its transfer velocity defined individually at each node. The reason for not implementing the variable transfer velocity initially was lack of sufficient calibration data but it is now clear that the WQI of the water entering the river through the TCGs is too ‘good’ when 0.4 m h^{-1} is used in the canals. Further runs of the model are now needed to investigate the effects of reducing the transfer velocity on all the sub-indices that contribute to the WQI as the water in the canals flows towards the TCGs. Alternatively, the water quality modelling could be ‘switched off’ in the canals behind the TCGs to ensure the water flowing through canals remained at the desired WQI when it reached the TCGs while retaining the hydrodynamic effects of flow through the canals.

8.4 Prediction of water quality in 2015, 2020 and 2030

The ‘model’ to predict the water quality used three GIS maps of actual land-use (1997, 2005 and 2008) from which areas of land being used for forests, urbanisation and agriculture in the upper catchment (i.e. feeding into the Selangor River above Rantau Panjang) were calculated. Water quality data from the DOE station just below Rantau Panjang were amalgamated to provide estimates of the six water quality parameters for the same years, for the wet and dry seasons. As the DOE data were measured every two-months there were between 6 and 9 measurements for each period from which mean and standard deviation were calculated. It was assumed that the contribution of each km^2 (referred to as *K*-values) of each land-use remains the same over time. The *K*-values were then used with the trends in the land-use over time, including the land-use areas predicted by the Kuala Selangor Local Planning Report (2006) to occur in 2015, to estimate the values of the water quality entering the Selangor River at Rantau Panjang in 2020 and 2030. Only the *K*-values calculated for total suspended solids (TSS) predicted unrealistic (negative) results; the future values of TSS were therefore set to the average TSS value measured at DOE station near Rantau Panjang.

The model predicted that increasing the areas of urbanisation and agriculture decreased DO levels and the pH of the river while increasing COD, BOD and ammoniacal nitrogen. All of these changes mean that increasing urbanisation and agriculture at the expense of the forested areas will reduce the water quality at Rantau Panjang. The land-use trends until 2030 assumes urbanisation to occur mainly at the expense of areas currently under agriculture rather than forest. The result from the model however is that the WQI of the water entering the Selangor River at Rantau Panjang is predicted to drop in the wet season to 53.4 (Class III) in 2015, 48.5 (Class IV) in 2020 and 43.4 (Class IV) in 2030; the equivalent values in the dry season are 61.3, 56.2 and 48.8 to about 77, 73, 65 respectively (Table 7-7).

These WQI values have considerable uncertainty associated with them, about ±10 WQI units, due to the uncertainty associated with the components that were used in the WQI estimation. The model runs for 2015, 2020 and 2030 have to be viewed with this in mind. Additionally, these runs have used a single realisation of the Pantau Panjang river flow time-series and the contemporary rainfall time-series for the one-month periods 14 May-14 June 2009 (dry) and 14 October-14 November 2009 (wet). Ideally multiple runs should be undertaken to assess the impact of a) the range of the WQI values and b) the effect of a variety of flow and rainfall conditions.

The InfoWorks model runs for 2015, 2020 and 2030 include water extraction at the Batang Berjuntai barrage at a rate of 35 m^3s^{-1}. The results of all six runs agree that the presence of the barrage and the extraction of water at this point results in a rapid improvement in water quality below the barrage. This can be seen from Table 7-9 which shows the average water quality between km 15 and km 40 for 2009/10 from the InfoWorks model is worse than that predicted for 2015 despite having a better WQI at Rantau Panjang. The most consistent feature of the models is the difference in the water quality below the barrage between dry and wet seasons in the Selangor River. Dry season changes between 2015 and 2030 are small with WQI remaining around 80, close to the Class II/III border while in the wet season the WQI deteriorates steadily from 71 ± 4 in 2015, 65.5 ± 5 in 2020 to 58 ± 5 (Class III/IV) in 2030.

The extraction of ‘polluted’ water at the barrage improves the water quality of the river by significantly reducing the volume (by 35 m^3s^{-1}) of polluted water flowing downstream and, on some days, leaving just the base flow of 3.5 m^3s^{-1}. The effect is greater in the dry season when river flow is lower (averaging 40 m^3s^{-1} at the Rantau Panjang gauging station between 1997 and 2008) and thus a smaller proportion of polluted water passes the barrage so very little change in WQI is predicted. In the wet season when flow is considerably greater (averaging 80 $m^3 s^{-1}$ at the Rantau Panjang gauging station between 1997 and 2008) than the extraction rate the water quality of the lower Selangor River drops and reaches Class IV in some sections.

The poor water quality predicted at Rantau Panjang resulting from urbanisation of areas in the upper catchment will result in only modest decrease in water quality along the lower reaches in the dry season (see Figure 7-5), but the very sharp decreases predicted in the wet season will make Malaysia’s target of Class II for the lower reaches of the Selangor River more difficult to achieve. The critical term is the river flow at Rantau Panjang minus the extraction at Batang Berjuntai barrage (nominally 35 m^3 s^{-1}); when this is large as it typically is in the wet season the water quality of the Selangor Rive will be poor, when it is small then the water quality will be controlled by the tidal flushing and the flow through the TCGs.

8.5 Impacts on the Selangor River fire fly colonies

The survival of the ecosystems near the river mouth of the Selangor River is a major concern although it can be seen from the model that the tidal flushing and extraction at the Batang Berjuntai barrage are able to mitigate some of the effects of the deteriorating water quality entering at Rantau Panjang in the dry season. The economically-important firefly colonies, a major eco-tourism attraction for this area, that habitat a 10 km-brackish stretch of the Selangor River face considerable threat due to changes in the riverine environment resulting in a decline in the firefly and their prey snail populations (Hamzah and Mohkeri, 2008). Nada et al. (2009) measured the WQI in the region of the fire fly colonies during 2006-7 to be 79.8 ± 2.8; the InfoWorks model for 2009/10 predicts the WQI over the same region as 75.8 ± 5.2. The impact of worsening water quality at Rantau Panjang is predicted to be considerable during the wet season, despite the extraction of water at the Batang Berjuntai barrage; the model predicts the WQI between km 10-km 17 will drop to 67-71 in 2015 (Class III), to 68-61 in 2020 (Class III) and 59-51 in 2030 (Class III/IV).

In the dry season the extraction of water at the barrage reduces freshwater flow downstream so reducing the impact of the pollution at Rantau Panjang but this also has the effect of allowing salt water intrusion further into the estuary (Van Breeman, 2008) thus adversely affecting the fire-fly ecosystem particularly the *berembang* trees (the fire flies host tree) which require brackish water of a particular salinity range to thrive to survive.

8.6 The need for further work

Despite the additional field programmes carried out by NAHRIM (described in Chapter 4) specifically designed to bridge some of the gaps, the data available for this study were limited and meant that many aspects of the model calibration and validation were not as well defined or tested as would have been liked. Priority needs to be given to the collection of further data. In particular:

1) For the hydrodynamic data either a time series of water levels or currents are needed to validate the model, preferably covering a full spring-neap cycle of tides.

2) Further water quality data for the river and estuary are needed, to allow proper validation of the InfoWorks WQ model. Measurements of the water quality just offshore of the estuary mouth in the Straits of Malacca are needed to supplement those already collected by NAHRIM (there is no information on the range of variability in WQ with reference to season or spring-neap cycle)

3) More systematic sampling of the water quality just inside the tidal control gates is needed to define the TCG boundary conditions. It is likely that the WQ inside the canals is quite variable, and a regular sampling campaign is required to investigate the WQI of the waters enter the Selangor River through the TCGs.

4) A proper validation data set is needed for the lower reaches of the river against which the model can be tested; this would ideally consist of daily measurements of water quality at Rantau Panjang for a month together with simultaneous water quality measurements at a) a location in the river close to a TCG, b) in the canals inside one or two TCGS and c) at Kuala Selangor (km 5).

5) The InfoWorks RS and WQ models need to be re-run and validated to include the ramp-function at the estuary mouth, water extraction at Batang Berjuntai barrage and the ‘correct’ WQI for the water entering the river via the TCGs (possibly by using a lower re-aeration coefficient in the catchment canals).

When this has been achieved there will then be opportunities for investigating further the relative importance of the water entering from Rantau Panjang or from the TCGs and investigation of the effects of varying the extraction rates of water at the Batang Berjuntai barrage, and of the processes occurring in the river which could allow the river to assimilate some of the pollutants and to achieve the desired Class II standard. A major assumption of this work is that the processes coded into the InfoWorks Water Quality model are appropriate to a tropical river such as the Selangor; considerable further research will be needed to establish if this assumption is valid.

6) The water quality models for 2015, 2020 and 2030 need to be re-run with a variety of flow and rainfall scenarios to investigate the variability on the WQI along the river during both wet and dry seasons.

CHAPTER 9

CONCLUSIONS

9 Introduction

The research objectives (Section 1.4) of this thesis were

1. to set-up a one-dimensional hydrodynamic model (InfoWorks^{TM} RS) of the Selangor River and its estuary, and calibrate it against measured data,
2. to set-up a one-dimensional water quality model (InfoWorks^{TM} WQ) that integrates with the hydrodynamic model,
3. to evaluate the effects of run-off from oil-palm plantations through the Tidal Control Gates (TCGs) on the water quality of the lower reaches of the Selangor River, and
4. using data and estimates of future land use change, to estimate how severely the water quality of the lower reaches of the Selangor River will be the impacted by urban and industrial developments planned for the upper reaches (above the gauging station at Rantau Panjang) by 2015, 2020 and 2030.

Additionally, setting up the commercial one-dimensional numerical model, InfoWorks^{TM} RS, which includes both the hydrodynamics and water quality components of the river-estuary network, provided an important opportunity to evaluate InfoWorks as a tool for the management of water quality issues of rivers and estuaries in Malaysia.

9.1 The InfoWorks Hydrodynamic Model

It was concluded that, within the limitations imposed by the lack of tidal stage and tidal current data and validation against four along-river salinity transects, the InfoWorks WS hydrodynamic model showed reasonable skill at reproducing the measured profiles of salinity and that the model was doing a reasonable job at describing the hydrodynamics of the river; changing the two diffusion parameters D0 and D1 made very little difference to the output of the model.

The model was weak at describing the salinity close to the estuary mouth as the flood-tide started. This was attributed to the failure of the model to allow for brackish water swept out of the estuary at the end of the ebb-tide to be brought back into the estuary. The ‘ramp function’ (Section 5.4) described in the InfoWorks model clearly had not been correctly implemented and this needs to be remedied as quickly as possible.

9.2 The InfoWorks Water Quality Model

It is concluded that the InfoWorks WQ model could not be properly evaluated for the Selangor River due to the paucity of water quality data. The data that were available were used to provide the boundary conditions at Rantau Panjang and the estuary mouth, and to set the values of tuneable parameters in the model such as the oxygen transfer velocity. The along-river profiles of the water quality parameters and the overall WQI for the ‘present’ conditions (Chapter 6) must be viewed carefully in the knowledge that a proper validation has not been possible with the data available.

9.3 Prediction of present water quality

Acknowledging the limitations discussed above, the model predicts that the present WQI of the Selangor River to be typically around Class III throughout its lower reaches (Section 6.2). Water quality is generally a little better during the wet season than the dry season due to the increased volume of rainfall and the consequent dilution of the pollutants entering at Rantau Panjang and through the TCGs. The river shows some ability to assimilate the chemical pollutants in its middle reaches (between Rantau Panjang and km 35 where water quality improves slightly) but there is no evidence that the river is able to assimilate chemical pollutants lower down the river although this is complicated by the presence of the TCGs.

It is concluded that the effects of flow into the Selangor River from the plantations though the TCGs was not being correctly modelled due to the evolution of water quality as it flowed through the canals. The water quality had been defined at the point it entered the canal system but the water quality had been measured close to the TCGs. Two ways of solving this problem were suggested, a) reducing the transfer velocity for oxygen in the canals or b) switching off all ‘water chemistry’ in the canals so that all water quality parameters remain unchanged in the canals as water flows towards the TCGs. The effects of run-off from through the WCGs cannot be evaluated from the models that have been run so far.

9.4 Prediction of future water quality

From the changes in land-use and water quality at Rantau Panjang it is concluded that the WQI in the Selangor River is predicted to drop in 2015, 2020 and 2030 to about 77, 73, 65 respectively as the quality of the water entering at Rantau Panjang decreases due to the expected developments in the upper reaches of the Selangor river basin (Chapter 7). The model runs for these three scenarios includes water extraction at the Batang Berjuntai barrage at a rate of 35 m^3s^{-1} which improves the water quality predicted in 2015 compared to that predicted in Chapter 6 for the ‘present’ conditions.

It is concluded that the extraction of water at the Batang Berjuntai barrage will play an important role in controlling the water quality in the Selangor River in the future, particularly in the dry season; this could allow the WQI to get close to the Class II target level for the lower reaches specified by Malaysian development plans. In the wet season water quality is predicted to get steadily worse. The evidence from the model so far is that the river does not have sufficient assimilative capacity to cope with increased pollution load delivered at Rantau Panjang. It will therefore be necessary to treat the water released from new urban areas before it is released into the Selangor River if the lower reaches are not to deteriorate due to increased development. As part of the development plans for the region it is strongly recommended that water treatment is made a mandatory requirement, with the objective of at least maintaining the water quality at Rantau Panjang at current levels (as defined by the 2000-2009 average values) but preferably improving the WQI at Rantau Panjang to a level that will ensure that the lower reaches of the Selangor River reach the desired Class II standard during both wet and dry seasons. Some further work with the model will be needed to determine what this level should be, after the problems with the TCGs have been solved.

9.5 Effects on the fire flies

Land use changes in the upper part of Selangor River basin are likely to result in a direct and deleterious impact on water quality of the lower reaches of the Selangor River. The survival of the famous eco-tourism attraction, the firefly colonies near the river mouth is one of the major concerns. Although tidal flushing and the extraction of water at the Batang Berjuntai barrage are able to mitigate some of the worst effects of the worsening water quality it is concluded that the water quality in the wet season is likely to deteriorate to Class IV by 2030 along the 10 km stretch of brackish river they inhabit. This worsening water quality plus the increasing salinity resulting from reduced freshwater flow volume (Van Breeman, 2008) pose a considerable threat which may result in the destruction of their breeding habitats (FRIM, 2006).

9.6 Overall conclusions of this study

It is clear from the model, as currently configured, that it will not be possible to attain Class II (Malaysian Vision for Water 2025) without action to improve the quality of the water entering at Rantau Panjang and (possibly) through the TCGs. The WQI of the coastal water entering the Selangor estuary is in the Class II category but there is little opportunity to improve the quality of the coastal waters in the Straits of Malacca by local action.

The InfoWorks hydrodynamic and water quality models are likely to be very useful modelling tools that can be relatively easily used by scientists and managers to assess the impacts of future developments in the upper reaches of the Selangor river basin over the next twenty years.

Some problems have been identified with the InfoWorks^{TM} model as it is currently configured for assessing the present and future water quality of the lower reaches of the Selangor River. Limitations were also identified in the data available to configure and validate the model. However, the model produced encouraging results where compared to measurements in the river and holds considerable promise as a model that can be run by non-specialist modellers to assist in predicting the water quality of rivers in Malaysia.

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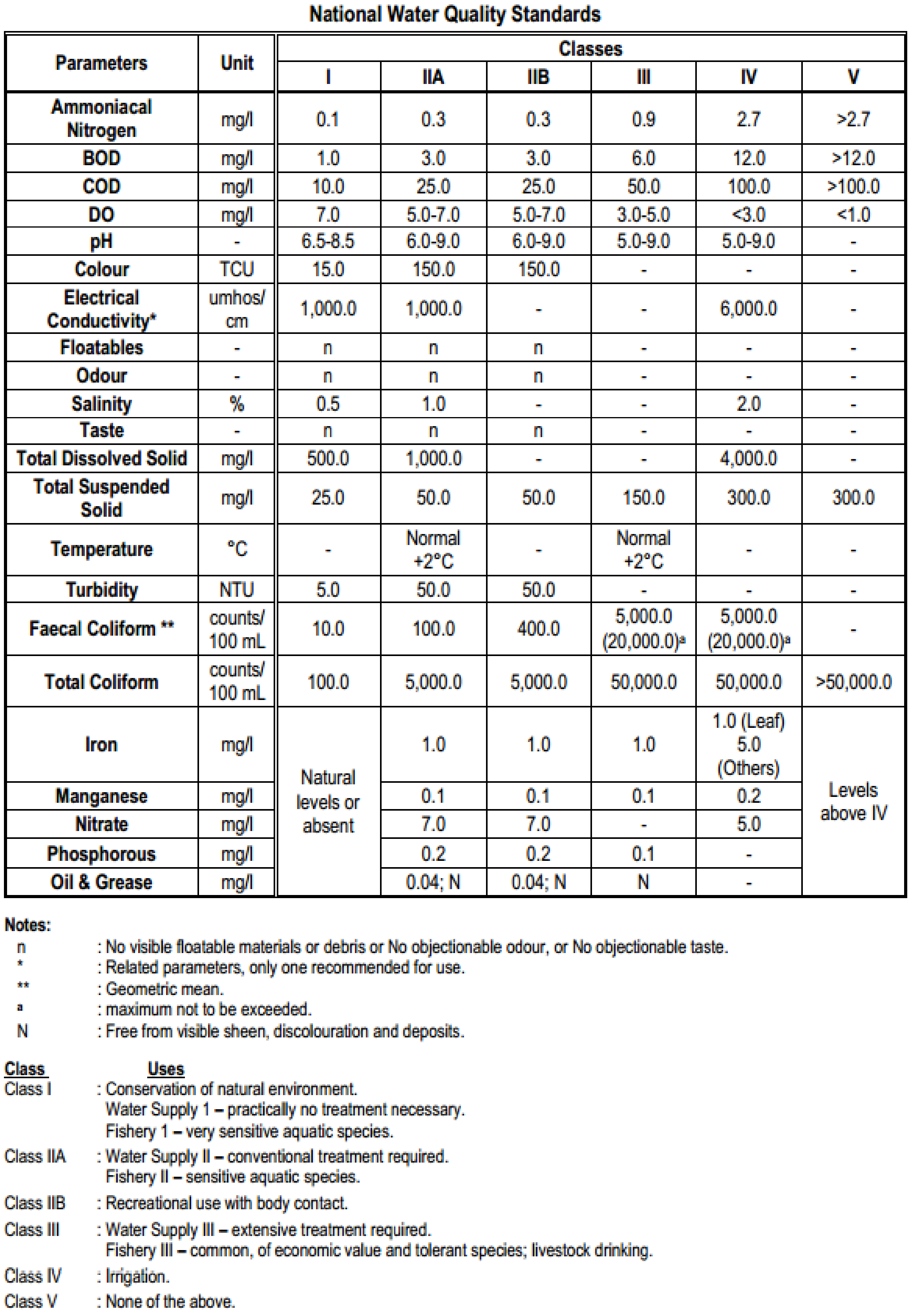
APPENDIX A



National Water Quality Standards

Parameters	Unit	Classes					
		I	IIA	IIB	III	IV	V
Ammoniacal Nitrogen	mg/l	0.1	0.3	0.3	0.9	2.7	>2.7
BOD	mg/l	1.0	3.0	3.0	6.0	12.0	>12.0
COD	mg/l	10.0	25.0	25.0	50.0	100.0	>100.0
DO	mg/l	7.0	5.0-7.0	5.0-7.0	3.0-5.0	<3.0	<1.0
pH	-	6.5-8.5	6.0-9.0	6.0-9.0	5.0-9.0	5.0-9.0	-
Colour	TCU	15.0	150.0	150.0	-	-	-
Electrical Conductivity*	umhos/ cm	1,000.0	1,000.0	-	-	6,000.0	-
Floatables	-	n	n	n	-	-	-
Odour	-	n	n	n	-	-	-
Salinity	%	0.5	1.0	-	-	2.0	-
Taste	-	n	n	n	-	-	-
Total Dissolved Solid	mg/l	500.0	1,000.0	-	-	4,000.0	-
Total Suspended Solid	mg/l	25.0	50.0	50.0	150.0	300.0	300.0
Temperature	°C	-	Normal +2°C	-	Normal +2°C	-	-
Turbidity	NTU	5.0	50.0	50.0	-	-	-
Faecal Coliform **	counts/ 100 mL	10.0	100.0	400.0	5,000.0 (20,000.0)[a]	5,000.0 (20,000.0)[a]	-
Total Coliform	counts/ 100 mL	100.0	5,000.0	5,000.0	50,000.0	50,000.0	>50,000.0
Iron	mg/l	Natural levels or absent	1.0	1.0	1.0	1.0 (Leaf) 5.0 (Others)	Levels above IV
Manganese	mg/l		0.1	0.1	0.1	0.2	
Nitrate	mg/l		7.0	7.0	-	5.0	
Phosphorous	mg/l		0.2	0.2	0.1	-	
Oil & Grease	mg/l		0.04; N	0.04; N	N	-	

Notes:

n : No visible floatable materials or debris or No objectionable odour, or No objectionable taste.
* : Related parameters, only one recommended for use.
** : Geometric mean.
a : maximum not to be exceeded.
N : Free from visible sheen, discolouration and deposits.

Class **Uses**

Class I : Conservation of natural environment.
Water Supply 1 – practically no treatment necessary.
Fishery 1 – very sensitive aquatic species.

Class IIA : Water Supply II – conventional treatment required.
Fishery II – sensitive aquatic species.

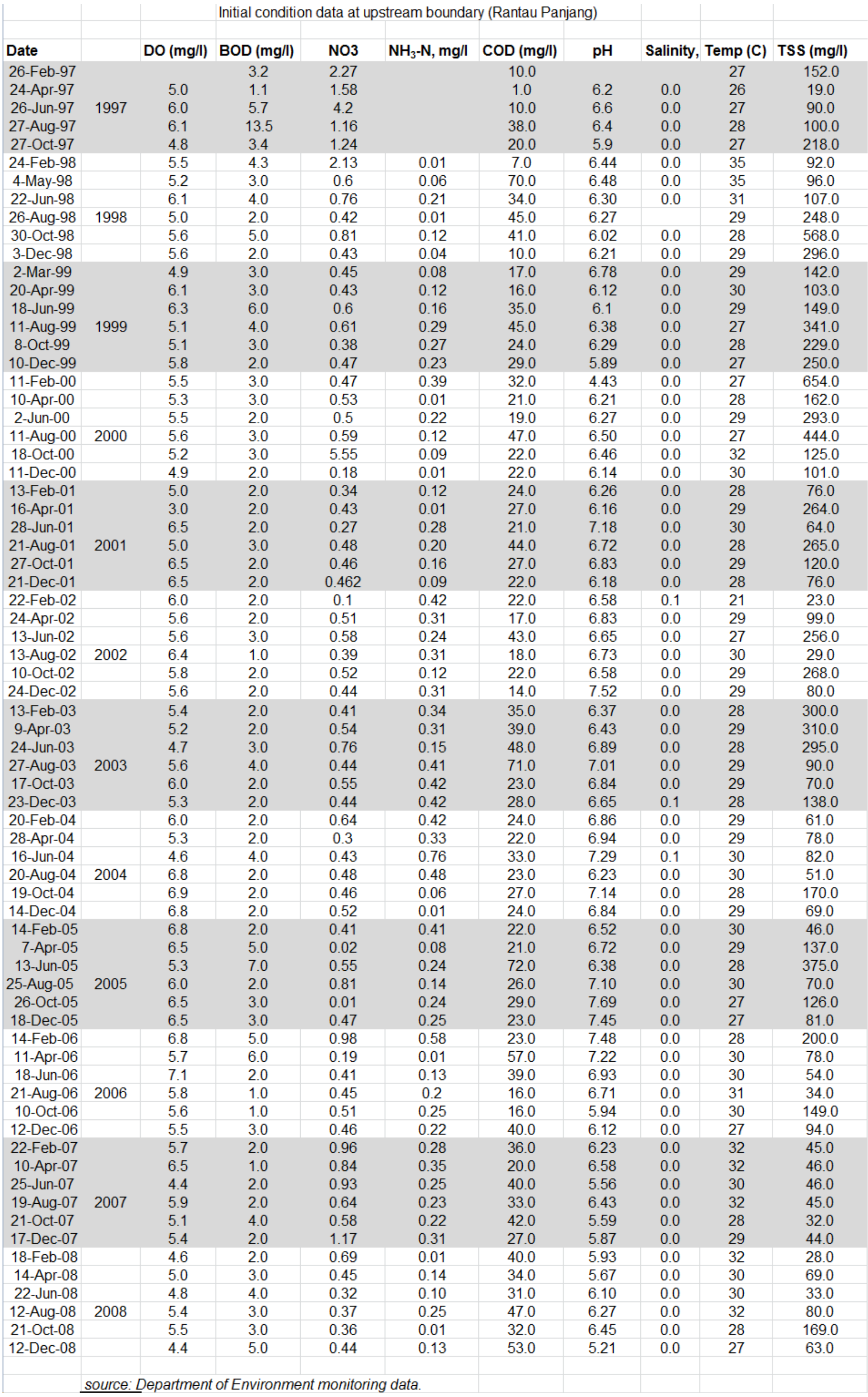
Class IIB : Recreational use with body contact.

Class III : Water Supply III – extensive treatment required.
Fishery III – common, of economic value and tolerant species; livestock drinking.

Class IV : Irrigation.

Class V : None of the above.

APPENDIX B



Initial condition data at upstream boundary (Rantau Panjang)

Date		DO (mg/l)	BOD (mg/l)	NO3	NH_3-N, mg/l	COD (mg/l)	pH	Salinity,	Temp (C)	TSS (mg/l)
26-Feb-97	1997		3.2	2.27		10.0			27	152.0
24-Apr-97		5.0	1.1	1.58		1.0	6.2	0.0	26	19.0
26-Jun-97		6.0	5.7	4.2		10.0	6.6	0.0	27	90.0
27-Aug-97		6.1	13.5	1.16		38.0	6.4	0.0	28	100.0
27-Oct-97		4.8	3.4	1.24		20.0	5.9	0.0	27	218.0
24-Feb-98	1998	5.5	4.3	2.13	0.01	7.0	6.44	0.0	35	92.0
4-May-98		5.2	3.0	0.6	0.06	70.0	6.48	0.0	35	96.0
22-Jun-98		6.1	4.0	0.76	0.21	34.0	6.30	0.0	31	107.0
26-Aug-98		5.0	2.0	0.42	0.01	45.0	6.27		29	248.0
30-Oct-98		5.6	5.0	0.81	0.12	41.0	6.02	0.0	28	568.0
3-Dec-98		5.6	2.0	0.43	0.04	10.0	6.21	0.0	29	296.0
2-Mar-99	1999	4.9	3.0	0.45	0.08	17.0	6.78	0.0	29	142.0
20-Apr-99		6.1	3.0	0.43	0.12	16.0	6.12	0.0	30	103.0
18-Jun-99		6.3	6.0	0.6	0.16	35.0	6.1	0.0	29	149.0
11-Aug-99		5.1	4.0	0.61	0.29	45.0	6.38	0.0	27	341.0
8-Oct-99		5.1	3.0	0.38	0.27	24.0	6.29	0.0	28	229.0
10-Dec-99		5.8	2.0	0.47	0.23	29.0	5.89	0.0	27	250.0
11-Feb-00	2000	5.5	3.0	0.47	0.39	32.0	4.43	0.0	27	654.0
10-Apr-00		5.3	3.0	0.53	0.01	21.0	6.21	0.0	28	162.0
2-Jun-00		5.5	2.0	0.5	0.22	19.0	6.27	0.0	29	293.0
11-Aug-00		5.6	3.0	0.59	0.12	47.0	6.50	0.0	27	444.0
18-Oct-00		5.2	3.0	5.55	0.09	22.0	6.46	0.0	32	125.0
11-Dec-00		4.9	2.0	0.18	0.01	22.0	6.14	0.0	30	101.0
13-Feb-01	2001	5.0	2.0	0.34	0.12	24.0	6.26	0.0	28	76.0
16-Apr-01		3.0	2.0	0.43	0.01	27.0	6.16	0.0	29	264.0
28-Jun-01		6.5	2.0	0.27	0.28	21.0	7.18	0.0	30	64.0
21-Aug-01		5.0	3.0	0.48	0.20	44.0	6.72	0.0	28	265.0
27-Oct-01		6.5	2.0	0.46	0.16	27.0	6.83	0.0	29	120.0
21-Dec-01		6.5	2.0	0.462	0.09	22.0	6.18	0.0	28	76.0
22-Feb-02	2002	6.0	2.0	0.1	0.42	22.0	6.58	0.1	21	23.0
24-Apr-02		5.6	2.0	0.51	0.31	17.0	6.83	0.0	29	99.0
13-Jun-02		5.6	3.0	0.58	0.24	43.0	6.65	0.0	27	256.0
13-Aug-02		6.4	1.0	0.39	0.31	18.0	6.73	0.0	30	29.0
10-Oct-02		5.8	2.0	0.52	0.12	22.0	6.58	0.0	29	268.0
24-Dec-02		5.6	2.0	0.44	0.31	14.0	7.52	0.0	29	80.0
13-Feb-03	2003	5.4	2.0	0.41	0.34	35.0	6.37	0.0	28	300.0
9-Apr-03		5.2	2.0	0.54	0.31	39.0	6.43	0.0	29	310.0
24-Jun-03		4.7	3.0	0.76	0.15	48.0	6.89	0.0	28	295.0
27-Aug-03		5.6	4.0	0.44	0.41	71.0	7.01	0.0	29	90.0
17-Oct-03		6.0	2.0	0.55	0.42	23.0	6.84	0.0	29	70.0
23-Dec-03		5.3	2.0	0.44	0.42	28.0	6.65	0.1	28	138.0
20-Feb-04	2004	6.0	2.0	0.64	0.42	24.0	6.86	0.0	29	61.0
28-Apr-04		5.3	2.0	0.3	0.33	22.0	6.94	0.0	29	78.0
16-Jun-04		4.6	4.0	0.43	0.76	33.0	7.29	0.1	30	82.0
20-Aug-04		6.8	2.0	0.48	0.48	23.0	6.23	0.0	30	51.0
19-Oct-04		6.9	2.0	0.46	0.06	27.0	7.14	0.0	28	170.0
14-Dec-04		6.8	2.0	0.52	0.01	24.0	6.84	0.0	29	69.0
14-Feb-05	2005	6.8	2.0	0.41	0.41	22.0	6.52	0.0	30	46.0
7-Apr-05		6.5	5.0	0.02	0.08	21.0	6.72	0.0	29	137.0
13-Jun-05		5.3	7.0	0.55	0.24	72.0	6.38	0.0	28	375.0
25-Aug-05		6.0	2.0	0.81	0.14	26.0	7.10	0.0	30	70.0
26-Oct-05		6.5	3.0	0.01	0.24	29.0	7.69	0.0	27	126.0
18-Dec-05		6.5	3.0	0.47	0.25	23.0	7.45	0.0	27	81.0
14-Feb-06	2006	6.8	5.0	0.98	0.58	23.0	7.48	0.0	28	200.0
11-Apr-06		5.7	6.0	0.19	0.01	57.0	7.22	0.0	30	78.0
18-Jun-06		7.1	2.0	0.41	0.13	39.0	6.93	0.0	30	54.0
21-Aug-06		5.8	1.0	0.45	0.2	16.0	6.71	0.0	31	34.0
10-Oct-06		5.6	1.0	0.51	0.25	16.0	5.94	0.0	30	149.0
12-Dec-06		5.5	3.0	0.46	0.22	40.0	6.12	0.0	27	94.0
22-Feb-07	2007	5.7	2.0	0.96	0.28	36.0	6.23	0.0	32	45.0
10-Apr-07		6.5	1.0	0.84	0.35	20.0	6.58	0.0	32	46.0
25-Jun-07		4.4	2.0	0.93	0.25	40.0	5.56	0.0	30	46.0
19-Aug-07		5.9	2.0	0.64	0.23	33.0	6.43	0.0	32	45.0
21-Oct-07		5.1	4.0	0.58	0.22	42.0	5.59	0.0	28	32.0
17-Dec-07		5.4	2.0	1.17	0.31	27.0	5.87	0.0	29	44.0
18-Feb-08	2008	4.6	2.0	0.69	0.01	40.0	5.93	0.0	32	28.0
14-Apr-08		5.0	3.0	0.45	0.14	34.0	5.67	0.0	30	69.0
22-Jun-08		4.8	4.0	0.32	0.10	31.0	6.10	0.0	30	33.0
12-Aug-08		5.4	3.0	0.37	0.25	47.0	6.27	0.0	32	80.0
21-Oct-08		5.5	3.0	0.36	0.01	32.0	6.45	0.0	28	169.0
12-Dec-08		4.4	5.0	0.44	0.13	53.0	5.21	0.0	27	63.0

source: Department of Environment monitoring data.