MATHEMATICAL MODELLING AND SIMULATION OF POLLUTANT TRANSPORT IN MEANDERING RIVER

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ABSTRACT

The study of pollutant transport has important implications to solve water quality issues which is occurring in most region worldwide. It has been the key focus of river engineering for decades; however, due to the form of the river itself, it remains a challenge for researchers to produce mathematical models that may accurately reflect the advection and diffusion phenomena occurring in the meandering channels. The current study put forward a two-dimensional mathematical model to investigate the distribution of pollutants experiencing the physical process of advection-diffusion process in curved channels. The governing equation is discretized by using explicit finite difference schemes for numerical solutions. Computational results based on MATLAB software revealed that once discharged either continuously or instantaneously, the pollutant is distributed to fulfil the domain. The pollutant also travelled at a much faster rate with the combination of both advection and diffusion process in contrast to when the process is considered independently. Pollutants that are commonly found in river such as ammonium nitrate and crude oil travelled at an extremely lower rates, suggesting that they will remain at the same location for much longer time. The overall results suggested that the proposed mathematical model and numerical solutions are suitable to solve for problems relating to rivers in Malaysia.

ABSTRAK

Kajian mengenai pengangkutan bahan pencemaran mempunyai implikasi penting bagi menyelesaikan masalah kualiti air yang menjadi isu kritikal di kebanyakan wilayah di seluruh dunia. Perkara ini telah menjadi tumpuan utama dalam kajian kejuruteraan sungai selama beberapa dekad; namun, menjadi cabaran bagi para penyelidik untuk menghasilkan model-model matematik yang dapat mencerminkan fenomena alir lintang dan resapan disebabkan oleh bentuk sungai itu yang berlekuk. Oleh itu, kajian ini mengemukakan model matematik dalam dua-dimensi untuk menyiasat taburan bahan pencemaran yang mengalami proses fizikal alir lintang dan serapan dalam alur melengkung. Persamaan ini telah melalui kaedah perbezaan sempit yang eksplisit untuk mendapatkan penyelesaian bagi kajian ini. Hasil komputasi menggunakan perisian MATLAB mendedahkan bahawa setelah bahan pencemaran dilepaskan sama ada secara berterusan atau pada waktu tertentu, bahan pencemaran akan bergerak untuk memenuhi domain. Bahan pecemaran ini juga bergerak dengan kadar yang lebih laju dengan gabungan proses alir lintang dan serapan berbanding ketika proses ini dijalankan secara berasingan. Bahan pencemaran yang biasa dijumpai di sungai seperti amonium nitrat dan minyak mentah pula bergerak pada kadar yang sangat perlahan, menunjukkan bahawa bahan-bahan ini akan berada di lokasi yang sama pada jangka waktu yang lama. Hasil kajian ini secara keseluruhan menunjukkan bahawa model matematik dan kaedah penyelesaian yang dicadangkan adalah bersesuaian untuk digunakan dalam permasalahan berkenaan sungai-sungai di Malaysia.

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LIST OF ABBREVIATIONS

BOD	-	Biochemical oxygen demand
FDM	-	Finite difference method
FEM	-	Finite element method
FVM	-	Finite volume method
GFDM	-	Generalized finite difference method
PDE	-	Partial differential equation
RANS	-	Reynolds Average Navier Stokes

LIST OF SYMBOLS

- concentration of any material dissolved in a medium
- coefficient of diffusion
- flux
- maximum length of the river in x-direction
- maximum width of the river in y-direction
- number of complete sine cycles in the river
- Peclet number
- pollutant travel time
- advection velocity
- horizontal distance
- vertical distance
- del operator
- mesh dimension

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter provides a general overview of global environmental problems, especially water pollution, which is the central investigation of this study. It consists of the problem background, problem statement, objectives of the study, scope of the study and significance of the study.

1.2 Problem Background

Each day, all living things on this planet are becoming more vulnerable to disasters and tragedies owing to a lot of environmental issues. Since the emergence of revolution in 1960s, the rising level of human activity in manufacturing, transport and agriculture around the world has resulted in a series of severe environmental pollution accidents in different regions around the world. Increased concentration level of greenhouse gases as a result of burning a great amount of fossil fuels to fulfil industrial demand for large-scale power generation has led to global warming problem. Coal mining, ferrous minerals, non-ferrous metals and other mineral resources have led to the deforestation and degradation of significant land expenditures. Untreated chemicals, waste and other toxins are accumulating in rivers, reservoirs, lakes and oceans, degrading the quality of water and leading to a freshwater crisis. All this has contributed to the global destruction of the ecological structures of the planet (Marchuk, 2015; Singh, 2017).

The widespread water crisis in the global climate is a threat to humanity and other living organisms that depend on freshwater for drinking and other vital needs to sustain life on Earth. Water pollution is the release into streams, lakes, oceans or other bodies of water of any potentially unwanted physical, chemical or biological substances (Denchak, 2018). The most distinct characteristic of a river compared to lakes and estuaries is its natural downstream flow. Rivers have much higher flow of velocities compared to lakes, while estuaries may have comparable flow velocities with rivers, but they are affected by tides and they can be either downstream or upstream. Due to this feature, contaminants in rivers can travel thousands of kilometres away from lakes or estuaries and therefore, polluting much wider areas (Ji, 2012). Thus, to sustain life on Earth, it is important to look for viable solutions to control river pollution.

The Department of Environment is responsible for monitoring the quality of the rivers, seas, islands and groundwater in this country. The Water Quality Index is utilized on the basis of six main parameters to determine the level of river pollution: dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, ammoniacal nitrogen, total suspended solids and pH. The quality of river water was assessed in 2017 as a result of a total of 5879 samples taken from a total of 477 rivers. Of the 477 monitored rivers, 219 (46%) were found clean, 207 (43%) were mildly polluted and 34 (7%) were polluted. Figure 1.1 shows the river water quality trend for 2008 – 2017 (Ying, 2019).

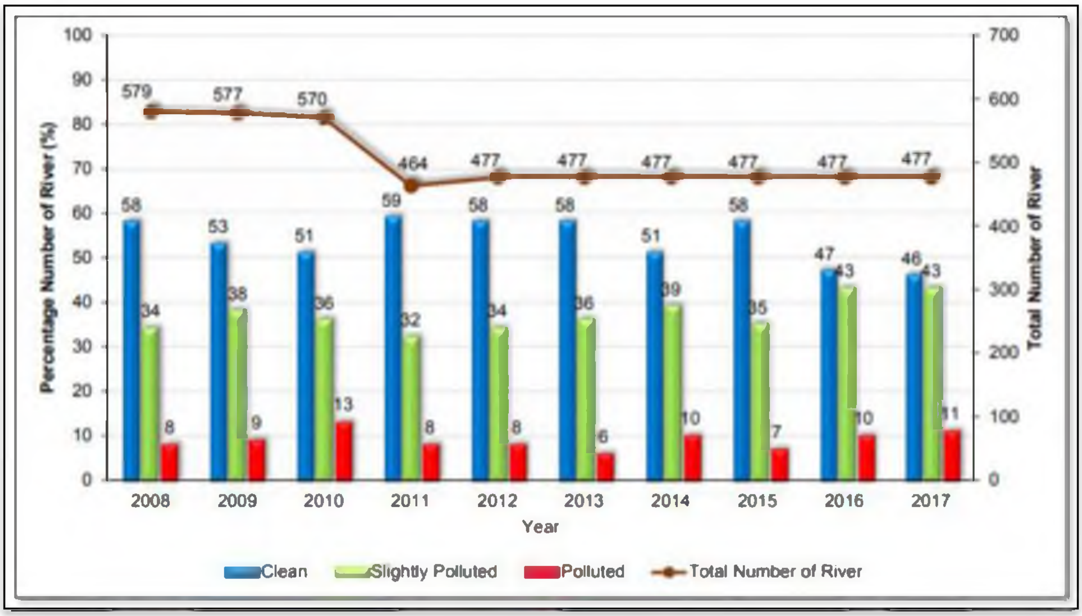

Figure 1.1 The quality trend of Malaysian rivers from 2008 – 2012 (Ying, 2019).

The Department of Environment has five river classifications, with the cleanest being Class 1 and the most polluted being Class 5, that is unsuitable for the application either as a water source or irrigation. Data from recent investigations has revealed that Sungai Tukang Batu in Johor Bahru is the only Class 5 river out of 477 rivers monitored. According to a water quality expert, the sources of pollution at Sungai Tukang Batu were from industrial sources, poorly managed sewage plant and oxidation ponds, waste water from restaurants and shops, as well as direct discharge from households (Leoi, Ahmad and Nordin, 2020). Figure 1.2 illustrates 16 heavily polluted rivers in Johor Bahru and Pasir Gudang, Johor reported as of 22nd July 2019. A number of contaminants have been identified from industrial waste, sewage, domestic waste and littering. The Johor Straits water sample analysis also found that these rivers have been polluted with toxic heavy metals, including lead, chromium, cadmium, arsenic and nickel, which are known to be toxic to aquatic species (Noh and Mohd Yusof, 2019).

Figure 1.2 Map and list of polluted rivers in Johor Bahru and Pasir Gudang, Johor (Noh and Mohd Yusof, 2019).

Rivers erode dirt and rocks, transport the sediment to new locations and redeposit it. The structure of the surface of the earth is eventually shaped by this. There are several kinds of river geomorphology classifications: straight rivers, meandering rivers and braided rivers. Straight river is described by being constrained, rare and unstable. A single-thread channel, sinuous plan shape with a moderate width-to-depth ratio characterises the meandering river. Meandering rivers are primarily formed by fluvial systems in flood plain zones. The braided river consists of multi-threaded, large width-to-depth ratio channels (Dawes and Dawes, 2013). Most rivers in Malaysia follow a meandering course, which is a channel stream with a significant bend, also known as a meander. In this study, this is further shown by the sinusoidal pattern of the Johor Strait and its surrounding small rivers, as shown in the map in Figure 1.2. Thus, this study will focus on the transport of pollutants into meandering rivers.

1.3 Problem Statement

In terms of pollution, the Malaysian rivers are overloaded as a result of public apathy, limited regulation and, in some instances, weak laws and regulations. For the general public and corporations, drains, streams and rivers have been known as convenient waste disposal networks. The inadequate management of solid waste and drainage systems has led to high levels of organic contaminants in our rivers. Rivers are further destroyed by the addition of toxic waste disposal to rivers, rendering it difficult for the natural ecosystem to restore them. Therefore, to establish effective river management strategies and to assess risks from accidental releases of hazardous pollutants, a dynamic pollutant transport model is needed.

This study looks into several key questions based on the problems that have been discussed above:

(a) How to mathematically model the pollutant transport in meandering river?
(b) What is the most appropriate numerical method to solve the model in (a)?
(c) What analysis that can be made based on the results obtained?

The current study will therefore investigate the answers to the following questions based on the above matters.

1.4 Objectives of the Study

This study embarks on the following goals:

(a) To formulate a mathematical model for pollutant transport in meandering river.
(b) To develop numerical algorithms for the governing equations using finite difference method.
(c) To analyse the pollutant concentration profiles based on the parameters which influenced its transportation such as flow velocity and diffusion constant.

1.5 Scope of the Study

Advection-diffusion equation can be solved either analytically or numerically. The pollutants are assumed to move in both x-direction and y-direction as the diffusion term is employed in the governing equation. Additional terms such as the decay, regeneration and enlargement terms will not be considered in the advection-diffusion equation to reduce complexity in this work. The water body is assumed to be an open channel for the modelling of the meandering channel. This study considered the numerical approach, particularly explicit finite difference method to solve the partial differential equation of pollutant transport. MATLAB programming software is used to solve the finite difference schemes and to analyse the results obtained based on the calculations. The results are then compared with findings from existing works.

1.6 Significance of the Study

The significance of the study is stated as follows:

(a) Gain better understanding and mathematical descriptions of the physical, chemical and biological processes in meandering rivers.

(b) Help to improve control of the river pollutions in order to maintain the sustainability of the environment, social and economic development.

(c) Provide alternative options for computationally fast and efficient numerical schemes.

1.7 Thesis Organisation

This thesis comprises of five chapters. Chapter 1 presents the research background which consists of all definitions and geomorphological classifications of rivers. It is followed by the problem statement, objectives of the study, scope of the study, significance of the study and the thesis organisation. Chapter 2 discusses theories and mathematical models surrounding the problem, and reviews some of previously published articles related to the problems to find gaps for the study.

Chapter 3 demonstrates the formulation and improvements made to determine a mathematical model that works on the structure of the rivers in Malaysia. The mathematical model is constructed based on the advection-diffusion equation in two-dimensional space to determine the concentration of water pollutant. This chapter also presents the numerical solution employed to solve for the governing equation, that is by applying finite difference method to both advection and diffusion terms. The solutions are shown graphically using MATLAB software to compare for different conditions of pollutant transport.

Chapter 4 discusses the results obtained from MATLAB software. Five different cases of pollutant transport are investigated which includes the case when both advection and diffusion phenomenon occurred, the case when only each phenomenon existed and the case when different kind of pollutants are transported in the rivers. Each case displays different results on the concentration of the pollutant in the river. Chapter 5 concludes the outcome of the study. This chapter also highlights the contributions made in this study and proposes a few suggestions to be undertaken in future works related to this study.

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