FLOW AND SEDIMENT PATTERN SIMULATION AT IJOK INTAKE, DISTRICT OF LARUT MATANG, PERAK

by

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LIST OF SYMBOLS

b	width of weir opening
C_d	discharge coefficient
C_v	sediment concentration
D	grain size of sediment
d	flow depth
d_{50}, d_{10}	particle size distribution, % finer by weight
Fr	Froude number
g	gravitational acceleration
h	head over the weir
k_s	surface roughness
n	Manning's roughness coefficient
n'	Manning's coefficient corresponding to grain roughness
P_k	bed material gradation
Q	discharge
Q_t	total unit sediment discharge (m^3/s)
R	hydraulic radius
Re	Reynolds number
Re_*	grain Reynolds number
S	bed slope
T_s	total unit sediment discharge (kg/s)
U, V	velocity along a vertical profile
U_*	shear velocity

ρ	mass density of water
μ	dynamic viscosity
ρ_s	mass density of sediment
γ_s	specific weight of sediment
Θ	degree of v-notch weir
$\varphi_{b,k}$	non-dimensional bed load transport capacity
$q_{b,k}$	equilibrium transport rate
$\varphi_{s,k}$	non-dimensional suspended load transport capacity
τ_c	critical shear stress
τ_b	bed shear stress

SIMULASI ALIRAN DAN PEMENDAPAN DI AMBILAN IJOK, DAERAH LARUT MATANG, PERAK

ABSTRAK

Perkembangan pesat di sekitar sistem sungai boleh menyumbang kepada perubahan morfologi akibat kenaikan atau penurunan daya angkutan sedimen, hakisan dan pemendapan di sepanjang saluran. Memahami proses pemendapan di sungai dan struktur hidraulik penting kerana hal ini boleh menjejaskan bekalan air untuk disalurkan ke tanah pertanian. Bagi memahami masalah tersebut, satu rangka pemodelan fizikal dan matematik telah diterapkan untuk menyiasat aliran dan pola pemendapan di ambilan Ijok, Sungai Ijok, Malaysia. Perisian HEC-RAS (1D model) dan CCHE2D (2D model) telah digunakan sebagai model matematik di mana hasil dari HEC-RAS digunakan sebagai masukan untuk CCHE2D. Model fizikal direka dan dibina dengan menggunakan skala 1:15 di makmal fizikal REDAC. Penyelidikan secara bandingan menggunakan kedua-dua model dilakukan dengan menjalankan sepuluh keadaan simulasi yang berbeza iaitu tanpa struktur dan dengan struktur hidraulik. Berdasarkan hasil, simulasi telah membuktikan bahawa berlakunya penggumpulan endapan di hadapan struktur hidraulik yang mengurangkan kapasiti aliran untuk menyalurkan air ke dalam terusan. Namun, untuk simulasi menggunakan struktur hidraulik, model fizikal boleh meramalkan fenomena aliran dan pengangkutan endapan dengan tepat kerana model CCHE2D menggunakan kaedah pengubahsuaian untuk mewakili struktur hidraulik. Dengan demikian, dapat disimpulkan bahawa kombinasi model fizikal dan matematikal dapat memberikan kelebihan dalam menganalisis masalah pemendapan di struktur hidraulik sungai bagi merancang projek merekabentuk tebatan endapan.

FLOW AND SEDIMENT PATTERN SIMULATION AT IJOK INTAKE, DISTRICT OF LARUT MATANG, PERAK

ABSTRACT

Rapid development near the river systems can contribute to morphology changes due to increased or decreased sediment carrying capacity, erosion and deposition along the channel. Understanding the sedimentation processes in the river engineering, and hydraulic structures are of vital importance as this can affect water supply for the agricultural lands in the command area. To understand the problem, frameworks of physical and mathematical modeling were applied to investigate the flow and sediment pattern at Ijok Intake, Ijok River, Malaysia. HEC-RAS (1D modeling) and CCHE2D (2D modeling) software were used as the mathematical model where results from HEC-RAS were used as input for CCHE2D. Physical model was designed and constructed with a 1:15 undistorted scale at REDAC physical model laboratory. The comparative study using both models was performed by running simulation for ten different conditions without and with intake structure. Based on the results, it was proven that sediments were accumulated in front of intake structure and reduce the flow capacity to convey water into the canal downstream. However, for simulation using intake structure, physical model can predict the flow and sediment transport phenomena accurately because CCHE2D model used simplification and modification to represent an intake structure. Thus, it can be concluded that combination of the physical and mathematical model can be analyzing the river sedimentation near an intake structure for further design mitigation works.

CHAPTER 1

INTRODUCTION

1.1 Introduction

River is a natural stream or water flowing towards an ocean, a lake or another stream. River is a component of the hydrological cycle generally collected from the precipitation through surface runoff, groundwater recharge and release of stored water in natural reservoirs. The roles of rivers are very wide to the earth and its mankind. It has played an important role in the economic, social, cultural and religious life of people (FISRWG, 1998; Downs and Gregory, 2004).

Any disturbances either by natural events or human induced activities can bring changes to river morphology. River changes their shape and morphology over time as a result of the hydraulic forces and sediment transport process. These changes could be gradual or rapid (Chang, 1988). In river system, sedimentation embodies the process of erosion, transportation, deposition and the compaction of sediment. Erosion is the detachment of soil particles; transportation is the movement of eroded soil particles in flowing water; and deposition is settling of eroded soil particles to the bottom of a water body or left as water leaves. Each river seeks a state of dynamic equilibrium, which is a balance between flow conditions and sediment transport that allow the water available to carry the sediment to sea at the rate it is supplied (Vanoni, 1975; Graf, 1984; Chang, 1988; Downs and Gregory, 2004; Alekseevskiy et al., 2008).

The problem of sedimentation at water intakes on rivers can largely be minimized by knowing the sediment pattern and appropriate design of the intake structure. Design of the river intake structure must consider issues related to erosion and sedimentation. In particular, the structure should be designed in order to minimize the quantity of bed load sediment that enters the intake structure. This is important to preserve suitable flow characteristics within pump intakes and prevent accumulation of sediment, which can minimize the maintenance cost to remove sediment accumulated within the intake and river bed in front of the intake (Nakato and Ogden, 1998; Guo and Zhen, 2001; Michell et al., 2006).

River sedimentation and morphology problems are among the most complex and least understood phenomena in nature. Many scientists and engineers have been looking for better tools to overcome the sedimentation problems in order to resolve the problem of environment and river engineering, which connected to natural characteristic and human intervention (FISRWG, 1998; Garcia, 2008).

Most of the rivers in Malaysia is facilitated with an intake structures. This intake structure is a method of collecting surface water from the bottom of a waterway. The water is obstructed through a screen over a canal (usually made of concrete and built into the river bed) and deliver to the users. The intake structures are required at many electrical power generation sites, irrigation, municipal water-treatment facilities and other water uses (Nakato and Ogden, 1998).

There are several approaches in studying river hydraulics and sediment transport such as field measurements, mathematical model, physical model studies and combination for both models. Presently, there is still a lack of research on sedimentation near intake structure; one of the main reasons is the complexity to determine the flow and sediment patterns near the structure. In solving these river engineering problems, the combination all of these techniques can bring about to solve the complex process of sedimentation in river water intake.

1.2 Research Background

The study area is Ijok Intake and located at the northern part of the Perak State in the western corner of Peninsular Malaysia (Figure 1.1). Ijok Intake was constructed to divert some flow for Kerian Irrigation Scheme (KRS). Water from Ijok River is diverted through Ijok Intake and flow through Ijok Canal and joining the Merah River before entering the Bukit Merah Reservoir (BMR).

KRS is the oldest and the first using pond water reservoirs for irrigation purposes to farmers, and it was built in 1902 and completed in 1906 at a cost of RM1.6 million at the time. KRS covering an area of approximately 23,560 ha. Main water supply for KRS is from the BMR which receives the most of its water from the Kurau River, Merah River and Ijok River. From BMR water is conveyed through two primary canals, namely the Main Canal and Selinsing Canal as shown in Figure 1.2.

Figure 1.1: Perak State, Peninsular Malaysia

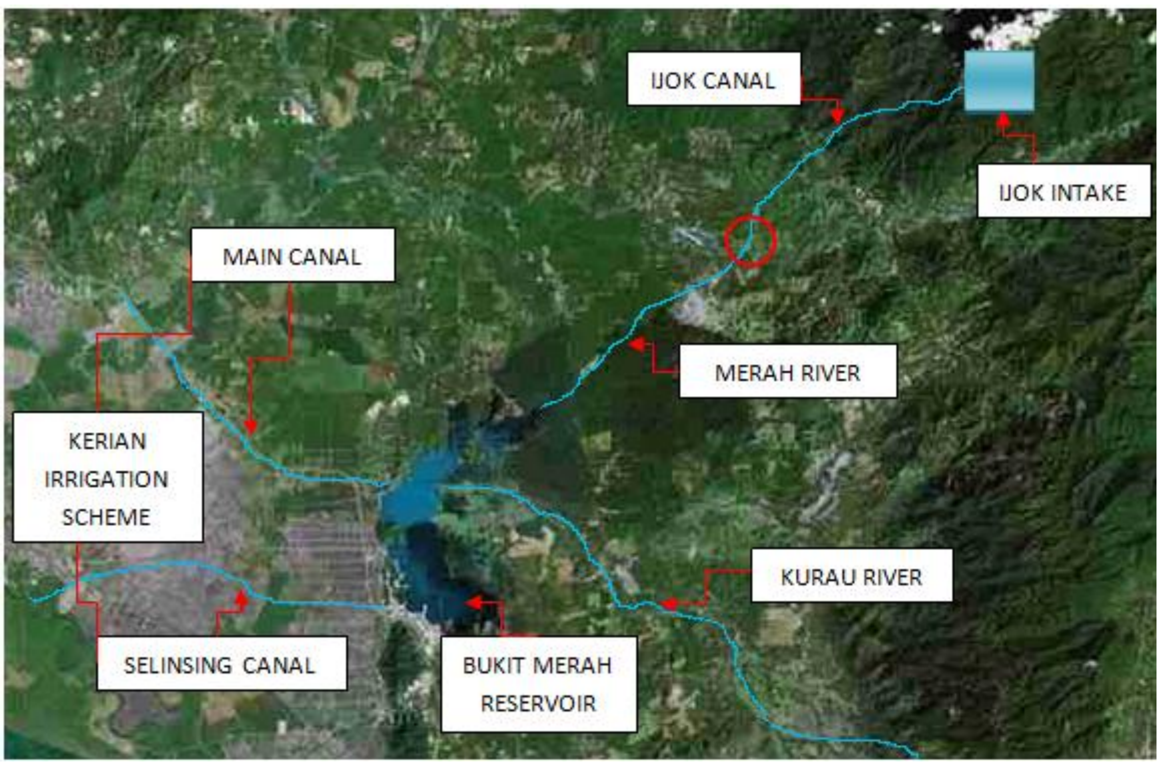


Figure 1.2: Schematic of Flow Kerian Irrigation Scheme

1.3 Problem Statement

It is observed that sediment transport rate is quite high and this cause sedimentation problem at the vicinity of Ijok Intake. The sedimentation had caused the partial blockage at the entrance of intake structure and thus reducing its efficiency to deliver water through the Ijok Canal. Therefore, it is necessary to examine the sedimentation behaviour in order to understand the problem and hence dealing with a better solution.

1.4 The Objectives of the Research

In view of the problems above, a two-dimensional mathematical model and a physical model were used to analyse the sedimentation problem at Ijok Intake. The specific objectives of this research are:

1) To investigate the flow and sediment pattern in the vicinity of Ijok Intake, using mathematical and physical models.
2) To compare the simulation results of mathematical and physical models with field observation.

1.5 Importance of Research

It is important to analyse the sediment and flow patterns in the vicinity of Ijok Intake because it may indicate the location of deposition and erosion that might occur. The findings of this research can be utilized to design more effective solutions, which can minimize the sedimentation problems without affecting the flow of water through the Ijok Intake into the Ijok Canal.

1.6 Scope of Research

The scopes of works in the execution of this research are as follows:

- Study of Literature review
- Data collection which consist of:
  - Survey work to get a cross-section of Ijok Canal
  - Stream flow gauging at Sungai Ijok
  - Sediment sampling such as bed material sampling, bed load measurement and suspended load measurement
- Field data analysis and use as input for model setup
  - River survey data in AutoCAD format was converted into GIS Triangulated Irregular Network (TIN)
- Mathematical model setup
  - Creation of structured mesh for CCHE2D
  - Generate rating curves by using HEC RAS model
- Physical model setup which consist of:
  - Determination of the modelling scale
  - Design and construction of model
  - Model testing
- Model calibration for both mathematical and physical models
  - Adjusting parameters in order to get reliable results
- Model simulation for both mathematical and physical models
  - Simulations of mathematical and physical model covering the various flows and conditions which can influence the pattern of sediment at the

study reach, hence can estimate the rate of sediment accumulation at Ijok Intake

- Analysis output and compare the results between these two models and field results
- Discussion, conclusion and recommendation to overcome the problems

1.7 Structure of Thesis

This thesis is divided into five chapters as follows:

- Chapter 1 briefs an introduction of the research which including research background, problems statement, objectives and scope of the research works.
- Chapter 2 discusses the past study that is related to the research regarding the use of mathematical and physical model to study the flow and sediment pattern at river.
- Chapter 3 explains the detail research methods including data needed for model inputs, construction of mathematical and physical model, and simulations procedure.
- Chapter 4 discusses the analysis of data collection.
- Chapter 5 discusses about model testing and calibration for both physical and mathematical model.
- Chapter 6 discusses the results of simulations output for both models.
- Chapter 7 presents the conclusions and recommendations for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 River Intake

River intake structures are required at many irrigation land, electrical power generation, water-treatment facilities, river navigation systems and other uses. The construction of intake structures on rivers is intended to divert a certain amount of water from the river for several of use (Lauterjung et al., 1984; Dereja, 2003; Erbisti, 2004). These intake structures are provided with suitable arrangements to draw in water into conveyance systems for meeting quantity and quality requirements (Dereja, 2003).

The development of intake structures consists of various methods and techniques. Engineers must carry out proper planning and design to achieve the needs (Erbisti, 2004). An intake designs must be chosen to suit the individual site, the characteristics of the river and the relative magnitudes of river flow, abstraction requirement and prevent the problem of sedimentation in and around intake structure (Dereja, 2003).

In particular, the intake structure should be designed in an approach that minimizes the quantity of bed-load sediment that enters the intake structure. This is important to preserve suitable flow characteristics within pump intakes, prevent clogging and fouling of traveling screens, and eliminate the need for regular maintenance dredging (Nakato et al., 1998)

2.2 Sediment Transport

The sedimentation process in a river is a non-equilibrium state cause by an imbalance between incoming and outgoing water discharge and sediment load (Molinas, 1996; Julien, 2002). A river is stable when all particles along the wetted parameter are not moving. This implies that, without transport of bed material, a cross-sectional geometry cannot change with time (Julien, 2002). FISRWG (1998) and Biedenharn et al. (2008) state that river responds to changes in the controlling variables of water discharged (Q), slope (S), bed material load (Qs) and median size of bed material (d_{50}). When a river is in dynamic equilibrium, it has adjusted these four variables so that the sediments transported into the reach are also transported out, without aggradation or degradation (FISRWG, 1998; Biedenharn et al., 2008). Figure 2.1 (FISRWG, 1998) shows the principle of river equilibrium.

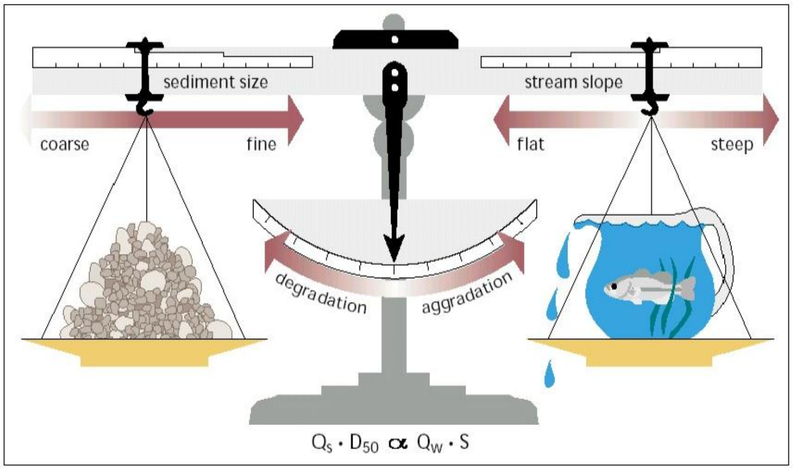


Figure 2.1: Factor affecting channel equilibrium (Source: FISRWG, 1998)

Molinas (1996) classified the sedimentation taking place in a river system under three categories, which are:

1) Aggradations/degradation
2) General scour/deposition
3) Local scour/deposition

Aggradations/degradation of a river takes place over long reaches and relatively long periods of time and is due to changes in river controls, changes in sediment supply and changes in river morphology (Vanoni, 1975; Molinas, 1996; Garcia, 2008). General scour/deposition is a phenomenon caused by expansions and contractions of spurred dikes, bridge piers, abutments and other hydraulics structures changing the flow area and flow velocities (Vanoni, 1975; Molinas, 1996; Garcia, 2008). Local scour/deposition is a localizes the problem associated with intake structures, piers, dikes and more. This is caused by flow separation, where the flow in the immediate neighbourhood of a solid wall becomes reserved causing the boundary layer to separate from it, and vortex formation (Vanoni, 1975; Molinas, 1996; Garcia, 2008).

2.2.1 Description of Sediment Motion

Incipient motion is a condition which particles in the movable bed are unable to resist the hydrodynamic forces and start to move through the river. Incipient motion can be determined by using Hjulstrom curve and Shield's diagram (Vanoni, 1975; Graf, 1984). As particle size increases, higher velocity is needed to transport it and as a velocity and discharge decrease, the ability of the river to move sediment through it decreases. The heaviest particle's deposit on the bed first, with the smaller and lighter particles transported further before accumulating (Graf, 1984).

2.2.2 Modes of Sediment Transport

There are two common classifying transport modes, which are 1) as bed load plus suspended load or 2) as bed material load plus wash load. The bed load is sediment moving on or near the bed by rolling, saltation or sliding. The suspended load moves in suspension which physically occupies the flow depth above the bed load layer. The wash load refers to the finest portion of sediment, generally silt and clay, which is washed through the channel, without a significant amount being found in the bed. The wash load does not have the significant contribution to the channel bed changes. The bed material load consists of particles that are generally found in the bed (Chang, 1988; FISRWG, 1998; Garcia, 2008). Figure 2.2 (Abu Hasan, 1998) shows the sediment transport modes.

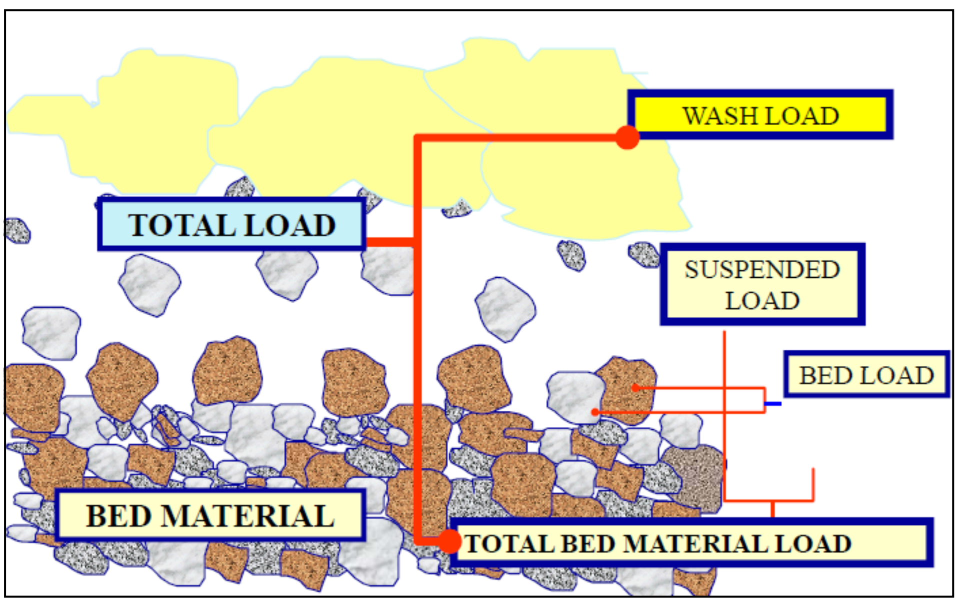


Figure 2.2: Sediment transport modes (Source: Abu Hasan, 1998)

2.3 Sedimentation Problems at River Intake Structure

Most of the intake structures were faced with the problem of sedimentation in and around the intake. The sediments which entering the water conveyance system may cause the closure of entrances of intake structures (Dereja, 2003).

Son et al. (1999) studied about sedimentation problems at the Buyeo water treatment plant in Keum River, South Korea. Intake pumps have the serious impeller erosion and thousands tons of sands were entrapped in the intake. Therefore, the studied by using numerical analysis was carried out. Based on analyses, the best mitigation solution been adapted by channel modification with wing dams, submerged vanes, and intake tower modification to control the sediments.

Guo and Zhen (2001) noted that high sediment concentration in the Yellow River in China is interfered with an irrigation intake. Thus, an intake is needed for the irrigation project, especially during the dry season. Since the sediment problems are so evident, great attention has been paid to the sediment control for irrigation intakes both in construction and management.

Michell et al. (2006) studied about the sedimentation problem at Muskingum River, Ohio. The Muskingam River is used to divert flow to the coal-fired power station for cooling and steam generation. Problems occurred with the bed sediment buildup at and within the station’s river intake, hampered an operation of the intake’s pump and became sucked into the station’s cooling water system. Therefore, intake modification was carried out by using submerged vanes and a skimming wall placed along the bottom of intake entrance.

2.4 River Modelling

Generally, flow in river is three-dimensional, unsteady and in a state of turbulent motion. An accurate analysis of flow and sediment transport in a river is a rather difficult task. The traditional approach for studying flow and sediment transport are based on theory, field measurements and laboratory experiments. All of these techniques are rather tedious and hardly to give accurate results (Shams et al., 2002).

Recent advance techniques of hydraulics modelling are used to predict accurate behaviour of flow and sediment transport in river such as analytical models, mathematical models and physical models. Analytical models are theoretical solutions of the fundamental principles within a framework of the basic assumptions. Mathematical models are computer software which solved the basic fluid mechanics' equations and physical models are a scaled representation of the prototype (Shams et al., 2002; Chanson, 2004; Novak et al., 2007).

For mathematical models, it widely applied for prediction of water levels and velocities in open channels, in the last few years are more often used to solve problems of bed load transport processes in open channels (Shams et al., 2002; Formann et al., 2007; Li et al., 2008; Zhou et al., 2009; Zakaria et al., 2010; Abu Hasan et al., 2011). Mathematical models can be categorized into the one-dimensional model, two- dimensional model and three- dimensional model. The choice of the mathematical model depends on the aims to be analysed and evaluated (Formann et al., 2007).

Usually one dimensional model is used for the longer follow courses and for general prediction. This is because, one-dimensional model required simple geometry (x and y coordinate) and hence need very little computational time (Wurbs, 1994; Fang et al., 2008). There are numerous one-dimensional models available for the simulation of river engineering problems such as HEC-1, HEC-2, HEC-RAS, CCHE1D, FLUVIAL-12 and more (Wurbs, 1994; Chang et al., 2008; Fang et al., 2008).

For more detailed investigation, two-dimensional and three-dimensional model is used. Two-dimensional model and three-dimensional model are much more complex and require much more input data to describe the channel geometry (x, y and z coordinate) and flow resistance characteristics. Sometimes, combinations of the one-dimensional and two-dimensional or three-dimensional model are used to get a better simulation (Formann et al., 2009; Noor Shahidan, 2009). In river engineering, a mostly two-dimensional model is used. This is because 3-D mathematical models impose high demands on field data such as boundary conditions and high resolution topographic survey (Formann et al., 2007). Two-dimensional models that available in river engineering are RMA-2, FESWMS-2DH, CCHE2D and, etc.

As the modelled becomes the more complex and mathematical model had a restricted to approach it, physical modelling is often used for modelling and provides a more reliable estimate of the hydraulics and sediment transport (Waldron, 2008; Schuster et al., 2009).

2.4.1 Mathematical Model of HEC-RAS

Hydrologic Engineering Center - River Analysis System (HEC-RAS) is a computer program that simulates one-dimensional hydraulic calculations for a full network of natural and constructed channels (Brunner, 2008). The HEC-RAS is a computer program develops by US Army Corps of Engineers (USACE). The HEC-RAS system contains four one-dimensional river analysis components for:

1) Steady flow water surface profile computations

2) Unsteady flow simulation

3) Movable boundary sediment transport computations

4) Water quality analysis (Brunner, 2008; Waldron, 2008).

A key element is that all four components use a common geometric data representation and common geometric and hydraulic computation routines (Brunner, 2008; Waldron, 2008). For cases which less complexity, the calibration and validation of HEC-RAS can give a good simulation due to the water depth, velocity changes, shear stresses and sediment transport (Formann et al., 2007).

2.4.2 Mathematical Model of CCHE2D

The Center for Computational Hydroscience and Engineering (CCHE2D) mathematical modeling is a system for two- dimensional, unsteady, turbulent river flow, sediment transport, and water quality evaluation, which have been developed by National Centre for Computational Hydroscience and Engineering, School of Engineering, University of Mississipi (Jia et al., 1998; Zhang, 2006).

The CCHE2D mathematical modeling is an integrated system which consists of a mesh generator (CCHE2D Mesh Generator), Graphical User Interface (CCHE2D-GUI) and CCHE2D Numerical Model (Zhang, 2006). CCHE2D-GUI is the use to provide file management, run management, results from visualization, and data reporting. CCHE2D numerical model is the numerical engine for hydrodynamic simulations. CCHE2D Mesh Generator is a useful tool for structured mesh generation in geometrically complex domains (Zhang, 2006). This two-dimensional model requires x, y, and z coordinate and in most cases, the geometry of the two-dimensional model requires supporting software to generate the mesh before obtaining the bed topology (Abu Hasan et al., 2007).

2.4.3 Mathematical Model Application on Sedimentation Problems

Scott and Jia (2001) studied about sediment transport and channel morphology change at Catfish Point Reach in Mississippi River. Two simulations were conducted in order to evaluate the model capability for reproducing general bed change in a long river reach over a significant period of time. The initial model run was to evaluate the ability of the model to compute general morphology change over a three year time period using the quasy-steady simulation while the second simulation was conducted to evaluate sedimentation in the point bar dike field for ten year period of record flow. The results show (in Figure 2.3) the spatial pattern of sedimentation just downstream of the tip of the dike; however, the near field sedimentation adjacent to the dike was overestimated.

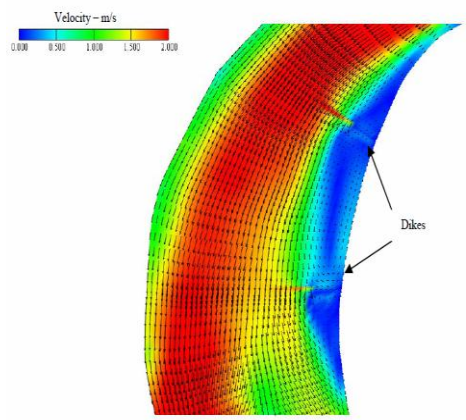


Figure 2.3 (a) : Flow Field

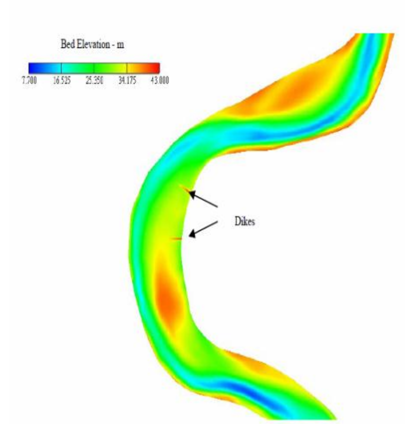
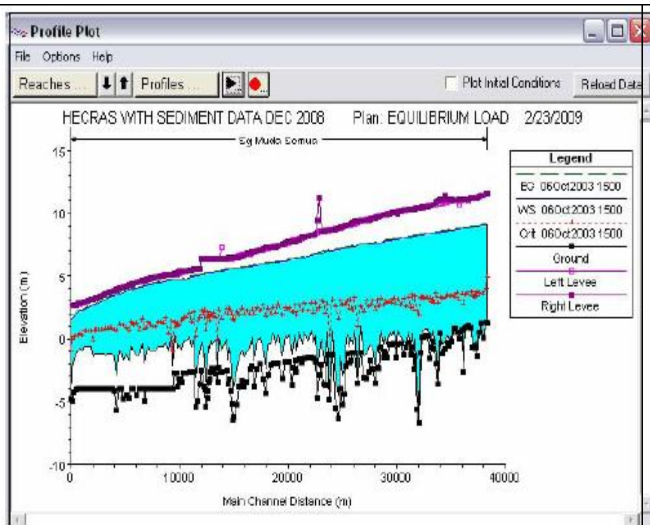


Figure 2.3 (b): Bed Elevation

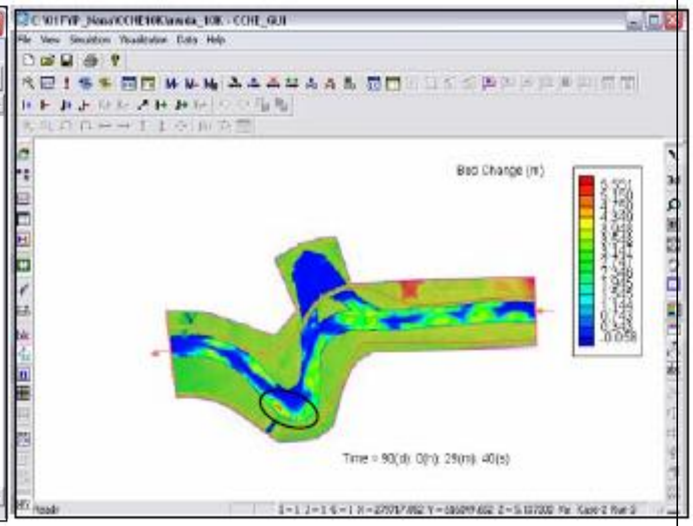
Figure 2.3: Flow field and bed elevation in the vicinity of the Catfish Point Dike Field

(Source: Scott and Jia, 2001)

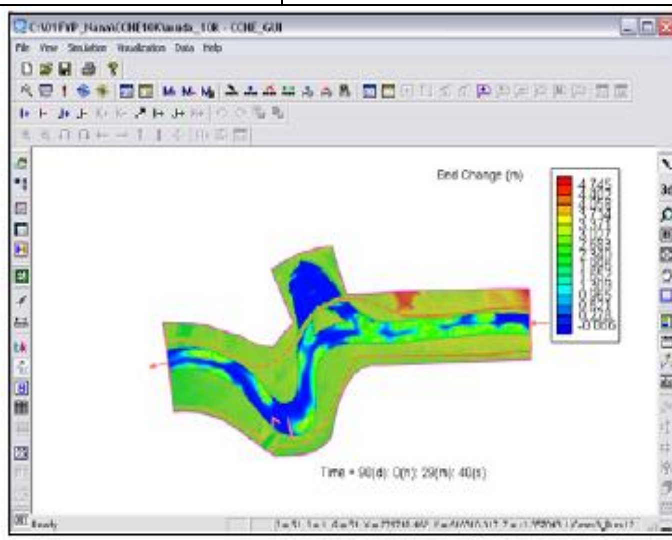
Noor Shahidan (2009) used HEC-RAS (1-D model) and CCHE2D (2D – model) to predict erosion and sedimentation of the proposed Muda River flood mitigation project, Malaysia. HEC RAS model was used to analyse hydraulic and sediment transport along the Muda River cross-section for 180 km while CCHE2D model was used to analyse and check the river stability for selected reach near the pump intake. Results of both model simulations showed that, Muda River was unstable due to sedimentation and erosion problems (Figure 2.4a and Figure 2.4b). HEC-RAS model produce average velocity distribution and bed changes, but in terms of simulation time, HEC-RAS model is much faster to run, required less computer memory and suitable for long-term run simulation. CCHE2D model can determine the specific location of bed changes caused by sedimentation and erosion, hence proposed protection structure by using a dike can reduce and control sediment in river (Figure 2.4c). Therefore, a conclusion was made that combination of these two models are useful in determining the stability of river due to erosion and sedimentation problems.



(a) Bed changes along Muda River reach using HEC-RAS



(b) Bed changes for selected reach using CCHE2D



(c) Bed changes after proposed dike

Figure 2.4: Bed changes by using HEC-RAS and CCHE2D model (Source: Noor Shahidan, 2009)

Mohamed Yusof (2009) conducted a study to investigate the sedimentation pattern in Bukit Merah Reservoir, Malaysia. Qualitative and quantitative assessment was used to verify the sedimentation and hence able to predict the sedimentation pattern. HEC-GeoRAS extension was used to generate input data of bathymetry into HEC-RAS for sediment estimation in qualitative assessment while CCHE2D model was used for quantitative assessment. Analysis results from HEC-RAS showed that, the estimated sediment deposited in Bukit Merah Reservoir after 100 years operation was 51.7×10^5 m^3 with the loss storage about 7.6% of the total storage capacity. Analysis results from CCHE2D showed that the coarsest fractions result in deposits at the reservoir's upstream. Finer sediments are transported further into the reservoir and downstream were likely resulted from the bank and local erosion.

Abu Hasan et al. (2011) conducted the study of flow simulation for Lake Harapan, Malaysia using CCHE2D model. Lake Harapan has been accumulating pollutants, and it is important to locate the area of pollutants. Based on CCHE2D results, few particular locations of the concentrated sediment areas in the lake are detected. It was suspected that pollutants from the upstream will form sedimentation at Lake Harapan. A conclusion was made that this study by using CCHE2D model could assist the maintenance of Lake Harapan to be carried out effectively.

2.5 Physical Modelling

Physical model is a scaled representation of existing conditions, which are usually a smaller-size representation of the prototype. The scale replica is the “model", and the actual river is the “prototype” (ASCE, 2000; Chanson, 2004, Ruesta et al., 2005; Novak et al., 2007; Pugh, 2008). ASCE (2000) state that physical hydraulic model can be use to evaluate the performance of hydraulic structure and hydraulic machines. The common situations which subject to physical model are water movement and sediment transport in rivers, and coastal zones; the hydraulic performance of water intakes, spillways, and outlets; flow around various objects; performance of turbines, pump and, etc.

Physical models can be performed to solve many problems in river engineering. If the application of established design procedures and available information fails to provide a solution to a hydraulic and sediment transport problem, then a physical model study should be made. Physical modelling offers a complementary technique for detailed studies of river reaches where three- dimensional complex flows cannot be analyzed by both field measurements and numerical model (Webb et al., 2010). A major advantage of using physical models over mathematical models is that they do not strictly require data for development as long as similarity is achieved, and the model processes are automatically identical to real phenomena (Molinas, 1996; Peakall et al., 1996).

Molinas (1996) listed three phases of the phases in the execution of river physical modelling study. The phases are composed of:

1) Determination of the model scale
2) Design and construction of model systems
3) Model simulations

Models are designed and operated according to scaling laws that must be satisfied to achieve the desired similarity between model and prototype (Novak et al., 2007). In designing the model, careful consideration of the type of data and method of analysis eases the interpretation of results as the investigation progresses (Amorocho et al., 1980; Molinas, 1996; Ruesta et al., 2005).

2.5.1 Classification of Physical River Models

Physical models (PM) for river system can be classified as the rigid-bed model and movable-bed model. Rigid-bed models are built to simulate flow in a river which implies that the bed is fixed (no sediment transport) and movable bed models are useful when sediment transport is significant (Molinas, 1996; ASCE, 2000; Julien, 2002; Chanson, 2004; Pugh, 2008). Movable bed models are some of the most difficult types of models, and they often give unsatisfactory results. The primary difficulty is to scale both the sediment movement and the fluid motion (Chanson, 2004; Pugh, 2008). However, Peakall et al. (1996) said that to work with both types of physical models, it is the prerequisite to have a basic understanding of the processes in river dynamic before it is possible to design a suitable model or interpret the results.

2.5.2 Principles of Physical River Modelling

The first and most important step in the design is the careful selection of a model scale. In general, large rather than the small model should be built, as permitted by available space and cost (ASCE, 2000). Scaled physical models are based on a similarity theory, which uses a series of dimensionless parameters that fully or at the least, partially characterize the physics of hydraulics and movable bed (Peakall et al., 1996; ASCE, 2000; Julien, 2002; Chanson, 2004). Molinas (1996) and Pugh (2008) state that the main objective of a physical model is to have all the significant characteristics of the prototype and satisfy the model design restriction. A model prototype was designed to be similar geometrical (horizontal, vertical, and longitudinal), hydrodynamic (time, velocity, discharge, slope, etc.) and sedimentation (shear stress, sediment transport capacity, sediment availability, etc.).

2.5.2.1 Fixed-Bed Model

According to Peakall et al. (1996), ASCE (2000), Julien (2002), Chanson (2004) and Webb et al. (2010), scaling of the fixed-bed model is simpler since only the flow and boundary parameters need to be considered compared to movable-bed model, which required consideration of sediment transport. For open channel flow with a fixed bed, the controlling variables are usually as:

$$\pi_1 = \frac{\rho R U}{\mu} = \mathrm{Re} \tag{2.1}$$

$$\pi_2 = \frac{U}{\sqrt{gR}} = \mathrm{Fr} \tag{2.2}$$

$$\pi_3 = \frac{k_s}{R} \tag{2.3}$$

$$\pi_4 = S \tag{2.4}$$

The four $\boldsymbol{\pi}$ terms represent the flow Reynolds number ($\boldsymbol{\pi}_1$), the Froude number ($\boldsymbol{\pi}_2$), the relative roughness ($\boldsymbol{\pi}_3$) and the channel bed slope ($\boldsymbol{\pi}_4$) (Peakall et al., 1996). Where ρ is a density of water; R is the hydraulic radius; U is a velocity; μ is the dynamic viscosity; g is a gravitational constant; k_s is a surface roughness and S is a bed slope.

Scaling an open channel flow hydraulic models are commonly designed to adhere to Froude number, Fr and to maintain turbulent flow conditions for the modelled aspects of interest in order to avoid having viscous forces (commonly referred to as Reynolds effects) impact. Thus, the flow must remain within the fully turbulent flow regime Re > 2000 (Peakall et al., 1996; Chanson, 2004; Pugh, 2008; Gill and Pugh, 2009).

2.5.2.2 Movable-Bed Model

According to Peakall et al. (1996), ASCE (2000), Chanson (2004), Pugh (2008), Gill and Pugh (2009) and Ho et al. (2010), in scaling the movable-bed model, the flow can be considered as a two-phase flow with both fluid and particles. The controlling variables are usually as:

$$\pi_1 = \frac{R}{D} \tag{2.5}$$

$$\pi_2 = \frac{\rho_s}{\rho} \tag{2.6}$$

$$\pi_3 = \frac{\rho\, U_*\, D}{\mu} = Re_* \tag{2.7}$$

$$\pi_4 = \frac{\rho U_*^2}{\gamma_s D} \tag{2.8}$$

The $\boldsymbol{\pi}_1$ and $\boldsymbol{\pi}_2$ terms represent the relative roughness of the sediment and relative density respectively, while the term $\boldsymbol{\pi}_3$ is the grain Reynold's number (Re_*). Term $\boldsymbol{\pi}_4$ expresses the Shields relationship (Peakall et al., 1996). Where D is the grain size of sediment; ρ_s is a density of sediment particle; U_* is the shear velocity and γ_s is the specific weight of sediment.

2.5.3 Scale of Model Sediment Material

A basic requirement for movable bed model is that the bed particles be mobile or entrain able. Good models are that the model bed particles move in about the same bed forms of the prototype (ASCE, 2000; Gill and Pugh, 2009).

Generally, it is not feasible to simply reduce particle size according to geometric model scale. As particle size is reduced, cohesiveness properties may change dramatically, which may completely alter the sediment transport mechanics between model and prototype. Using a model particle size in excess of the scaled value may necessitate using a lower density bed material in the model, increasing the model slope, or combination of density and slope adjustment to produce transport mechanics with a useful degree of similarity between model and prototype (Gill and Pugh, 2009).

The choice of sediment materials depends on specific weight of sediments, sediment properties, duration of simulated events, availability, cost, and difficulties associated with the use of different materials. Sand was the best model sediment because lightweight sediment would more readily be moved under the action which means that lightweight sediments accelerate differently due to flow than prototype sand sediments (Molinas, 1996; ASCE, 2000).

2.5.4 Physical Model Application on Sedimentation Problems

Devries et al. (1988) developed a set of hydraulic models for a portion of the Sacramento River in California, with the objective of studying in detail the behaviour of sediments and the patterns of flow in the vicinity of a proposed major diversion structure for the Peripheral Canal of the state water system. Similitude criteria for a 1:240 horizontal-scale, 1:60 vertical-scale movable bed rivers were based on consideration of gravity (Froude criterion) and friction forces to duplicate the general hydraulic behaviour. To simulate scour and deposition in the model, similarity criteria were based on scaling of the bed shear stress, matching the ratio of the particle fall velocity to the shear velocity, and matching the bed forms in model and prototype. Based on simulation results, additional roughness was added to the model river bank to properly scale friction to the prototype. Devries et al. (1988) used finely ground walnut shell material for the model. Therefore, a conclusion was made that it was not possible to satisfy all criteria simultaneously as long as the bed form matched general scour and deposition patterns after several simulations.

Schuster et al. (2009) studied about the usability of Hydro-GS 2D as numerical hydrodynamic models for simulation of complex sediment transport processes in river.