Hydrodynamics of Lagoon Fringed by a Coral Reef

M.Sc Thesis Report

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Specially dedicate to

My beloved mother and father,

Judy and Irwan

Abstract

Coral reefs are highly diverse ecosystems that provide food, income, and coastal protection for hundreds of millions of coastal dwellers. They are found in tropical and semi tropical areas spread throughout South-east Asia, the Caribbean, the Indonesian archipelago, on Australian coasts and in the Pacific islands. Coral reefs are subject to both anthropogenic and natural threats such as biological perturbations, floods, outflows carrying pollutants from land, runoff sediment, sewage, oil wastes, mining and quarrying processes, fisheries, tourism and coastal urbanization. The period for which these pollutants stay within the lagoon depends on the residence time. The longer a pollutant stays in the lagoon before being flushed away, the more destructive it will be to the lagoon and coral reef ecosystem. Residence time is probably influenced by many factors. This study established two numerical models, a simple model and the Delft3D model, of a lagoon fringed by coral reefs with tides as the boundary conditions. The study compares the simple and Delft3D model. Then a sensitivity analysis is made of several important parameters such as tides, coral reef depth, inlet geometry and lagoon geometry.

Keywords: Coral reef, hydrodynamics, residence time, water circulation

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Parameters

A	inlet/channel area (m$^{2)}$
B	Basin/storage area (m^2)
c	concentration rate (kg/m^3)
C	Courant number
$\sqrt{G_{\xi\xi}}$	Coefficient used to transform curvilinear to rectangular co-ordinates (m)
$\sqrt{G_{\eta\eta}}$	Coefficient used to transform curvilinear to rectangular co-ordinates (m)
g	gravity acceleration (m/s^2)
h	measured tidal level with reference to a fixed level (m)
h_0	mean level (m)
H_1	the water level outside the basin (m)
H_2	the water level at the gap (m)
H_3	the water level inside the basin (m)
h_i	amplitude of component number i (m)
N	number of time steps per tidal period
Q	Discharges (m^3/s)
t	time (h)
T	Residence Time (hours)
u	Velocity (m/s)
V	Volume (m^3))
α_i	phase angle of component number i
δ	the threshold depth (m)
Δt	time-step for Courant Number (s),
Δx	grid length in x direction (m)
Δy	grid length in y direction (m)
ζ	tidal amplitude (m)
υ_{mol}	Kinematic viscosity (molecular) coefficient (m^2/s)
υ_H^{back}	Background horizontal eddy viscosity (m^2/s)
υ_V^{back}	Background vertical eddy viscosity (m^2/s)
υ_{3D}	Part of eddy viscosity due to 3D turbulence (m^2/s)
ω_i	angular velocity of component number i (1/h)

1. Introduction

1.1 Introduction of the issue

Coral reefs are highly diverse ecosystems that provide food, income, and coastal protection for hundreds of millions of coastal dwellers.

Coral reefs are estimated to cover 284,300 square kilometres within the Indo-Pacific region (including the Red Sea, the Indian Ocean, Southeast Asia and the Pacific) accounting for 91.9% of the total. Southeast Asia accounts for 32.3% and the Pacific including Australia accounts for 40.8%. Atlantic and Caribbean coral reefs only account for 7.6% of the world total. SPALDING et al, 2001 classify coral reefs into fringing reef, barrier reef, and atolls.

According to HENCH, 2008 the interaction of coral reef and lagoon system is determined by physical and hydrodynamic mechanisms which influence the transport, dispersal and retention of larval fish, corals and other invertebrates, the supply of nutrients, phytoplankton, and zooplankton to the reef, as well as the flow of the sediment from the watersheds connected to the reef lagoon.

1.2 Delineation of the study

The coral reef and lagoon system in a coastal area is a subject of landward threat. According to HOPLEY AND SUHARSONO, 2000 the coral reef threats are divided into natural and anthropogenic threats. The natural threats are storms, volcanic eruptions, earthquakes, tsunamis, biological perturbations, floods and the outflows carrying land sourced pollutants. The anthropogenic threats are runoff sediment, sewage and other land-based pollutants, oil pollution and shipping, mining and quarrying coral reef, destructive fisheries, tourists, the development of tourism, and coastal urbanization.

The lagoon between the coral reef and land is a subject of the landward threat which accommodates the pollution before being flushed away naturally by natural circulation. The presence of pollutants harms a highly diverse ecosystem in coral reef and lagoon system as well. If the pollutants stay longer in the lagoon, the coral reef and lagoon ecosystem are more disturbed and harmed.

The residence time of the pollutants inside the lagoon depends on many factors. The most influential factor is the hydrodynamics circulation. The hydrodynamics circulation is depending on the tidal, wave and topography.

Another possible threat to the coral reef and lagoon system is the sea level rise. The sea level rise in the future could affect the hydrodynamic circulations of coral reef and lagoon system. However, studies of hydrodynamic circulation of coral reef and lagoon system are still limited. Most of these studies are restricted to a specific study area. Moreover, studies about the impact of the sea level rise to coral reef and lagoon are still very infrequent.

A Previous study by BUDDEMEIER AND SMITH, 1987 found that the growth of coral reef is intimately linked to sea level. According to IPCC, 2001 the sea level rise prediction is in between 90 to 880 mm from 1990 to 2100. GORNITZ, 2001 predict that the sea level rise is 240 to 1080 mm by the 2080 over late 20th century levels.

The vertical accretion rates of protected coral reef flats is accelerating from the present modal rate up to the maximum rate, in response to the more rapidly rising sea level. But this rapid vertical accretion rate is not sufficient to keep up with sea level rise. If the coral reef flat is less protected, it becomes inundated and is subjected to erosion by progressively larger waves.

The terms coral reef and lagoon system in this report means a lagoon fringed by coral reef and bordered with land as one system.

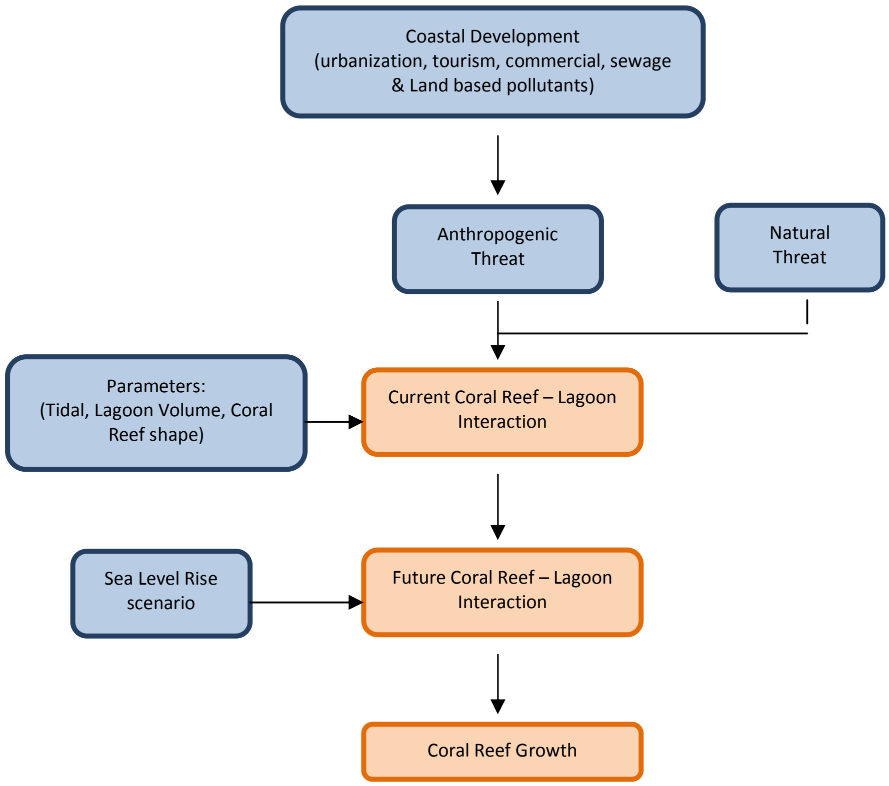


Figure 1 Study of the natural physical phenomena and hydrodynamic of coral reef & lagoon system scheme

1.3 Objectives of the study

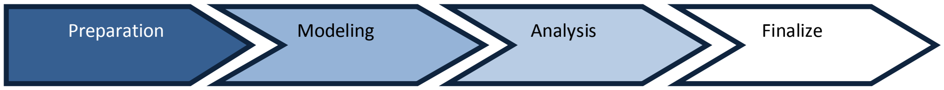
The general objective of this thesis is to understand the natural physical phenomena of hydrodynamic circulations of the integrated coral reef and lagoon system.

The more specific objectives are:

- To understand the tidal effect to the circulation and exchange in integrated coral reef and lagoon system.
- To understand the impact of sea level rise to the circulation and exchange in integrated coral reef and lagoon system, and coral reef growth.
- To understand the relation of the lagoon volume, the coral reef shape, tides and waves to the circulation in coral reef and lagoon system.

1.4 Study approach

For the completion of this thesis following the specific objectives, the following research is planned.



1. Preparation

   This step includes the master thesis proposal preparation and literature study. In the thesis proposal is formulated what will be done during the master thesis project. The literature study is to study the previous hypothesis related to the topics. It comprise of current text books, previous journals, conferences and proceedings.

2. Modelling

   Several options are available to develop the model of coral reef and lagoon system. Principally, the alternatives are physical and numeric modelling. Physical modelling provides accurate data to be used in the analysis, but it takes a longer time and it is more expensive to build the physical model. Because the study is limited due to time and financial constraint, the model chosen is numerical. This study provides two sorts of numerical modelling, a simple and Delft3D model which are explained in chapter three to five. In this particular modelling, an artificial dataset is used which represent the general conditions of coral reef and lagoon system.

3. Analysis

   The analysis is based on the model output and previous hypothesis. It contains the comparison between the output of the simple and the Delft3D model, sensitivity analysis of several variations of the parameters involved, and the sea level rise impact to the coral reef and lagoon system. The comparison between the output of the numerical modelling and measurement based dataset either from physical modelling or field measurement is not taken into account because it is not available.

4. Finalize

   The outcome of this study is presented in this report and presentation.

1. 5 Thesis outline

In the first chapter, the study, objectives, approaches and the structure of the report are described. The second chapter describes the physical of coral reef and lagoon system. Based on the literature review, the third chapter describes the model setup, such as the model layout (grid and bathymetry), parameters and assumptions taken into account for both the simple and the Delft3D model. The forth chapter presents and analyze the output/result of the initial model. The fifth chapter contains the sensitivity analysis of the output of the model with several variations such as tides, coral reef crest height, width and distance, inlet width to the circulation and sea level rise impact. The sixth chapter is the discussion part which produces the synthesis of this study. The last chapter is the conclusion of this study, and the recommendation for further study.

2. Physical description of coral reef and lagoon system

In this chapter the literature review of physical description of coral reef and lagoon system is discussed. It consists of a description of coral reef, tides, hydrodynamics of the lagoon, and circulation and residence time inside the lagoon. A discussion about the sea level rise which might impact the coral reef and lagoon system is also included in this chapter.

2.1 Coral reef

Coral reefs are highly diverse ecosystems in coastal areas that provide food, income, and coastal protection for hundreds of millions of coastal dwellers. They are found in a diverse range of geomorphologies, from a few clusters of coral communities, to numerous structures that can be hundreds of kilometres long.

Coral reefs are found in tropical and sub tropical areas such as south-east Asia, the Indonesian archipelago, Caribbean archipelago, the Australian Coast and Pacific Ocean islands.

2.1.1 Classification of coral reef

Based on geomorphology calcium carbonates, length of the structure, and deposit by component of a coral reef system, McManus, 2001 divides coral reef into a structural coral reef and a non-structural coral community. The structural coral reef grows in a colony or solitary polyps. It grows in several spot such as collapse trees, rocks, metal wreckage, or rubber tires. It has many shapes and varies from less than a kilometre to dozens of kilometres. A visible example of the structural coral reef is 'the great barrier reef' in Australia.

Figure 2 the Great Barrier Reef, Australia (source: panoramio.com)

The non structural coral reef which also known as non structural coral communities grows on rocky outcrops in shallow sea in many tropical and subtropical areas. It varies from few clusters of coral to several squares of kilometres of coral reef area.

According to Spalding, 2001 coral reef is classified into fringing reef, barrier reef, and atolls. The fringing reef is always located contiguous to the land/beach. It is includes a wave-breaking coral reef which is a meter of more above the rest of the reef. It also includes a reef flat, a 'channel' formed between the crest and the land.

Barrier reef is also located contiguous and formed parallel to the land/beach. The distinction between fringing and barrier reef is that the lagoon in the barrier reef is at least 2 meters of depth during the mean water level.

Atoll is donut-shaped coral reef structures with or without island along the rim.

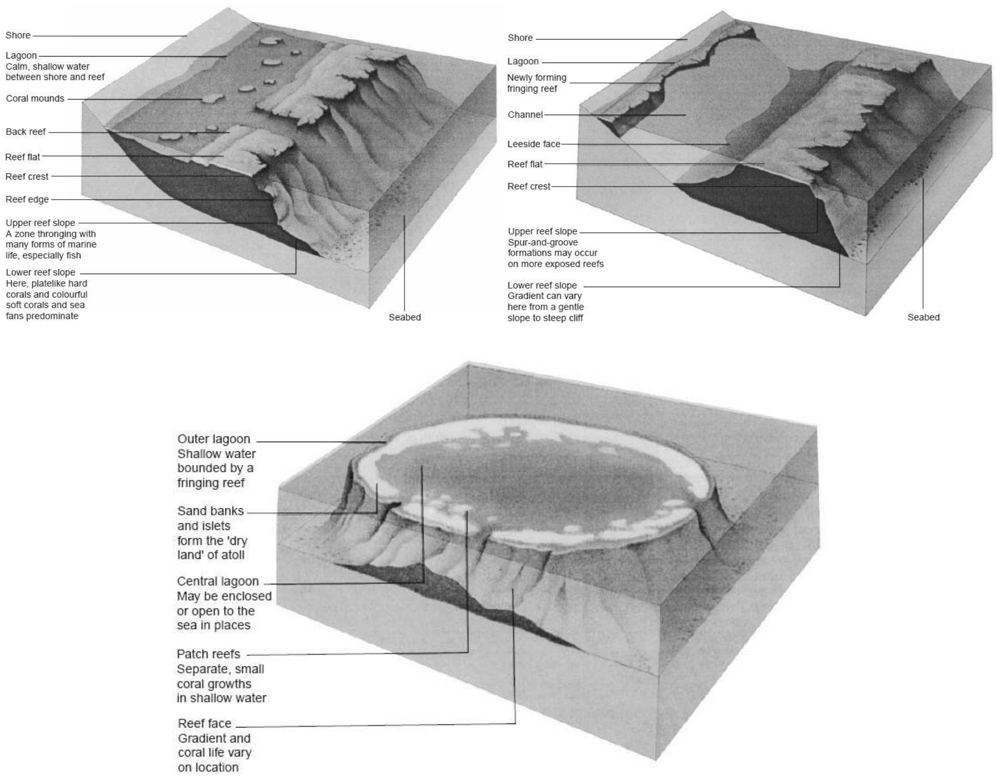


Figure 3 Fringing reef (Upper-left), Barrier reef (Upper-right) and Atolls. (Source: MCMANUS, 2001)

2.1.2 The growth of coral reef

Studies about the rate of the coral reef are still very limited at present. The measurements the coral reef growth rates, either in the laboratory or in the field, are still rare.

According to BUDDEMEIER, 1987 the growing rate of the coral reef is intimately linked to the calcium-carbonate production of the coral reef. A realistic estimation of the sustainable growth rate of coral reef is 10 mm per year.

2.1.3 Sea level rise and coral reef

Coral reef growth is linked to the sea level rise. Sea level rise influences the growth of the coral reef.

Sea level rise is caused by the rise of global temperature. Since 1993, sea level rise was contributed to thermal expansion of the ocean (57%), decrease in glaciers and ice caps (28%), and the melting of the polar ice sheets.

The IPCC in their "Third Assessment Report" has calculated global sea-level rise. The IPCC predictions of sea level rise range in 2020, 2050 and 2080 are shown in a table below.

Table 1 Sea Level Rise (relative to 1990) based on IPCC Third Assessment Report

Time Scale	Sea-Level Rise (cm)			
	Low	Medium-Low	Medium-High	High
2020	4 – 14	4 – 14	4 - 14	4 – 14
2050	7 – 30	7 – 32	8 - 32	9 – 36
2080	9 – 48	11 – 54	13 - 59	16 - 69

However, BUDDEMEIER, 1987 concludes that the sea level rise is definitely linked to the growth of the coral reef as the coral reef growth will not keep pace with the sea level rise.

2.2 Tides and coral reef

Tides are the vertical and horizontal movement of the water surface in the ocean caused by tidal force of the moon and the sun. According to the tides, earth has a relation to the sun and the moon.

Sun and earth are rotating, attracting each other by a force that is proportional to the masses and inversely square to their distances. This law is also valid in the relationship between the earth and the moon. Due to distances between the moon and the earth is significantly less compared to the distances between the sun and the earth, the lunar is larger than the solar influence on forming the tides. D'ANGREMOND, 2001b expresses that the lunar influence is approximately 4 times the solar influence.

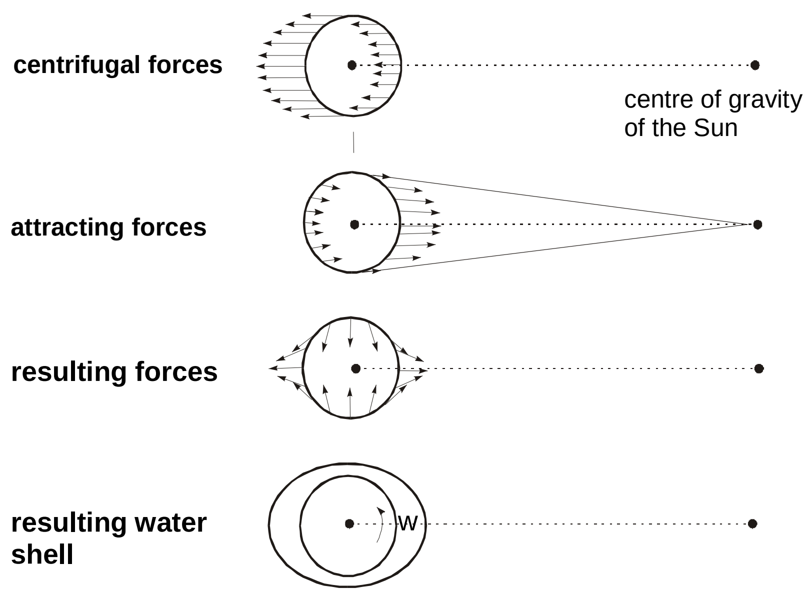


Figure 4 Forces of the earth – sun system (source: D'ANGREMOND, 2001b)

When the earth, sun and moon form one line, the full or the new moon, the solar and the lunar tides are mutually totalize producing bigger tidal amplitudes. This phenomenon is called *spring tide*. Different phenomena occur when solar and lunar tides are 90^o out of phase. Their effects are reducing each other resulting less tidal amplitude. This phenomenon is called *neap tide*. See figure 2-4 about the spring and neap tide.

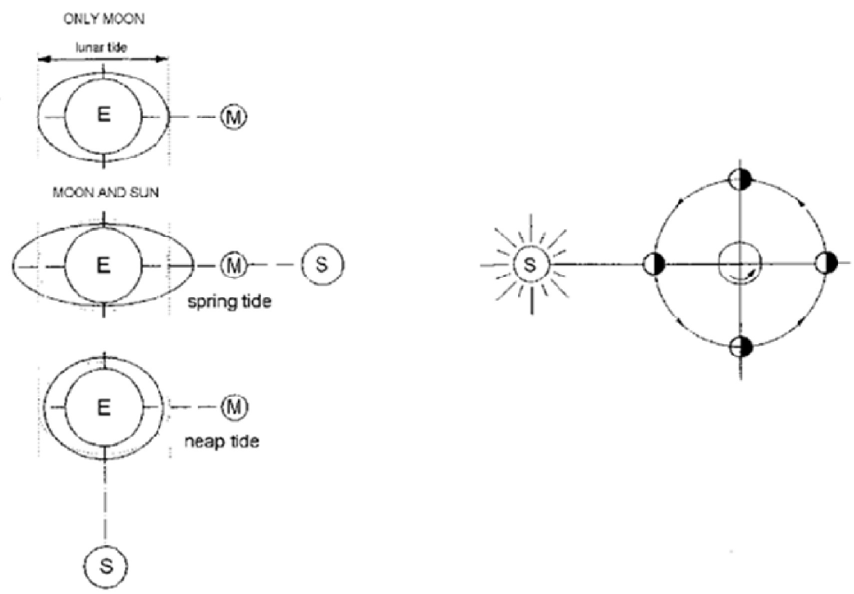


Figure 5 spring and neap tide (source: D'ANGREMOND, 2001b)

2.2.1 Harmonic analysis

Tides are caused by regular astronomical phenomena. It can be predicted accurately and scientifically for a long time ahead. The tide prediction method used is called harmonic analysis. The water level at certain locations as a function of time is expressed by following formula:

$$h(t) = h_o + \sum_{i=1}^{N} h_i \cos(\omega_i t - \alpha_i)$$

Where:

h (t) = measured tidal level with reference to a fixed level (m)

h_0 = mean level (m)

h_i = amplitude of component number i (m)

ω_i = angular velocity of component number i (1/h)

α_i = phase angle of component number i

t = time (h)

In the harmonic analysis, the influence of the sun and moon to the tides is characterized by the letter S and M. Phenomena occur once a day (diurnal), carry a subscript 1, phenomena that occurs twice a day, called semi-diurnal effects, carry a subscript 2, higher order components carry a subscript 3,4 or higher. M_2 and S_2 are representing the most common tidal components.

2.2.2 Diurnal and semidiurnal tides

The types of tide are determined by a complex process which considers many factors. In particular areas where the coral reef is present, such as in south-east Asia, Australia, pacific islands, and the Caribbean, the tides is varies. It is diurnal and mixed semidiurnal in the Indonesian archipelago. Tides are semidiurnal in south-east and north Australia, mixed semidiurnal in north, north-west, and south Australia, and diurnal in south-west Australia. In pacific islands, the tides are semidiurnal. While in Caribbean, the tides are semidiurnal and mixed semidiurnal (see figure 2-5).

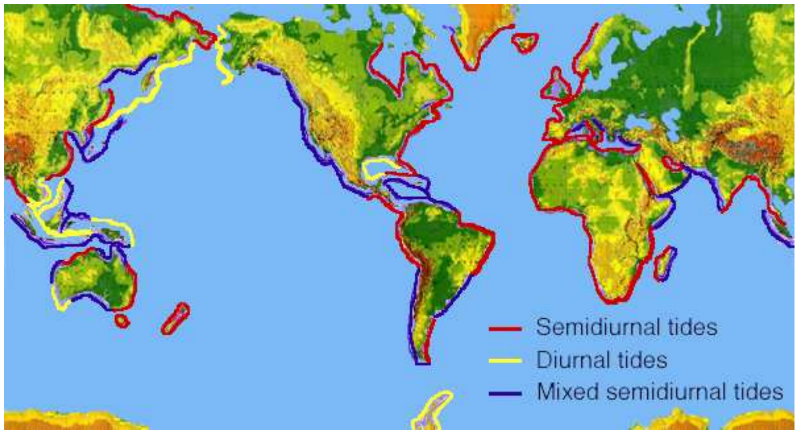


Figure 6 Diurnal and semi-diurnal tide locations

2.2.3 The tide currents

Apart from the vertical tides, the currents resulting from the tidal variation are called the horizontal tide or the tide currents. According to D'ANGREMOND, 2001b these currents can be calculated using the driving force of the vertical tides, the friction, and the storage capacity of the area concerned.

This calculation can be simplified by neglecting storage capacity and friction. Hence, the simple model is merely based on the driving force of the vertical tides, which can be defined as water level and flow variation.

2.3 Hydrodynamics of coral reef and lagoon

According to ROBERT, 1980 cited by PRAGER, 1991 the water circulation in the coral reef and lagoon system is mainly the combination of tides, wind, and over the reef flow. Previous field studies indicate that flow over the reef is a result from wave breaking and setup at the reef crest. Other research indicates that that 70-95 % of the wave energy over the reef is dissipated due to friction and breaking. Wave breaking and the transformation of energy at the coral reef crest results in a water level increase at the reef crest. It drives strong reef-normal surge currents. Mass transport over the reef is increased during low tide as a result of decreased depth and increased wave breaking.

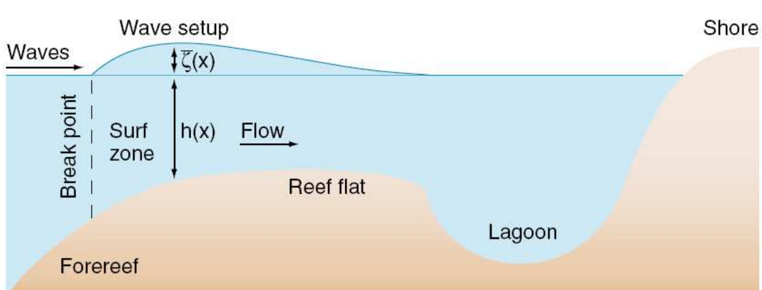


Figure 7 wave-driven flows over a reef and into a lagoon (MONISMITH, 2007)

2.4 Circulation and residence time

According to PRAGER, 1991 residence time is the average amount of time water residing within a given lagoon. It plays an important role in environmental impacts by determining the exposure time of residence biota to water-borne materials, and in influencing the accumulation of sediments or adsorbed substances.

Residence time within tropical or subtropical lagoons is a function of lagoon geometry, depth and bathymetric complexity, as well as circulation near reef inlets, mixing and flow over the reef.

According to ROBERT and SUHAYDA 1983, cited by PRAGER, 1991 in shallow, narrow lagoons flushing periods may be relatively rapid, less than one day. ATKINSON et al, 1981, cited by PRAGER, 1991 stated that the period is one to four months in more isolated or larger system.

PRAGER, 1991 suggests two approach to determine the residence time (T):

T = lagoon volume/daily volume input (ATKINSON et al, 1981)

And

T = (lagoon depth x tidal period)/tidal range (PUGH and RAYNER, 1981)

Equations mentioned above are assuming a steady state, well-mixed system. The equations are also neglecting wave breaking and wave set-up.

3. Numerical modelling approach

Chapter 3 treats the description of numerical modelling approach for both the simple and the Delft3D model. It covers the basic concept of the numerical scheme, boundary conditions, initial conditions and assumptions.

3.1 Simple model set-up

3.1.1 Tides and water-level

In the model, tides are designed to be semi-diurnal with the amplitude of 2 m. The period of one semi-diurnal tidal cycle is 12.5 hours, which means the angular velocity is 360/12.5 or 28.8°/hour. Hence, the harmonic analysis equation for the model is:

$$h(t) = h_o + \sum_{i=1}^{N} h_i \cos(\omega_i t - \alpha_i) = 0 + \sum_{i=1}^{N} 2.\cos(28.8t - 0)$$

$$h(t) = 2.\cos(28.8.t)$$

3.1.2 Hydrodynamic

D'ANGREMOND, 2001a introduce the storage area approach to determine the local boundary conditions for a closing structure, which in this particular study is coral reef & lagoon system. This method is based on a basin connected with inlet without any friction or inertia. In this particular study, this approach is used to determine the water level inside lagoon, velocity and discharge (inflow and outflow) through the inlet channel/gap. Flow over the coral reef is neglected in this manual calculation.

The basic equation for the discharge (Q) is:

$$Q = B\frac{dH_3}{dt}$$

Where, the discharge is depending on storage area (B) and water depth inside the basin (H_3). Discharge capacity of the gap is:

$$Q = \mu.Au = \mu.A.\sqrt{2.g(H_1(t) - H_2(t))}$$

Velocity (u) through the gap is:

$$u = \sqrt{2.g(H_1 - H_2)}$$

Hence, the formula to determine the water depth inside and outside the basin in this calculation is:

$$\mu.A.\sqrt{2.g(H_1(t) - H_2(t)} = B\frac{dH_3}{dt}$$

Where μ is the ratio between the cross-sectional flow areas of the gap and the flow gorge (in this study is assumed to be 1), A is inlet/channel area in m^2, g is gravity acceleration in m/s^2, H_1 (m) is the water level outside the basin, H_2 (m) is the water level at the gap, H_3 (m) is the water level inside the basin, B is storage area in m^2. In this particular study, the water level inside the basin is $h_3 > 2/3*H_1$. Hence $H_3 = H_2$

This approach is valid for a short distance basin, which can be considered as less than 1% of the wave length. In this model, the wave length is derived from tides. The period is 12.5 hours. Since it is located on the shallow sea, the wave celerity is square root of gravity acceleration multiplied with water depth. The celerity for this basin is 8.85 m/s.

The wave length is the multiply of celerity and period. In this model, the wave length is 398.65 km. Hence 1% of the wave length is 3.98 km. It means this approach is valid to applied in the model.

3.1.3 Concentration and residence time

For the initial condition, the concentration is divided exactly in coral reef crest line. The initial concentrations inside and outside the lagoon are 1 kg/m^3 and 0 kg/m^3. During the low tide where the water inside and outside the lagoon are completely divided by coral reef crest, the inflow concentration is assumed to be completely mixing the existing concentration of the water inside the lagoon to produce the new concentration. The concentration rate inside the lagoon is:

$$V\frac{dc}{dt} = flux_{in} - flux_{out}$$

$$V_{lagoon}\frac{c_{(t+1)} - c_{(t)}}{dt} = Q_{\inf low}c_{offshore} - Q_{outflow}c_{(t)}$$

$$V_{lagoon}\left(c_{(t+1)} - c_{(t)}\right) = V_{\inf low}c_{offshore} - V_{outflow}c_{(t)}$$

$$c_{(t+1)} = \frac{V_{lagoon}c_{(t)} + V_{\inf low}c_{offshore} - V_{outflow}c_{(t)}}{V_{lagoon}}$$

Where c is concentration and V is volume. In this model, concentration in the offshore is 0, Volume of water inside the lagoon, Inflow and Outflow are constant. The formula can be simplified into:

$$c_{(t+1)} = \frac{(V_{lagoon} - V_{outflow})c_{(t)}}{V_{lagoon}}$$

The residence time of the concentration inside the lagoon is determined using the graphic of concentration and time relationship.

Similarly like storage area approach, this approach is valid only for a short distance basin (less than 1% of the wave length).

3.2 Delft3D model set-up

Delft3D is a multi-dimension simulation program design to deal with several different physical, chemical and biological processes in estuary and coastal areas. This program is applicable for areas of hydrodynamic, sediment transport, morphological, water quality, particle tracers and ecology.

In this study, the numerical model is applied to investigate the natural physical phenomena of circulation and exchange in coral reef and lagoon system. This particular model will be based on the FLOW module (Hydrodynamic simulation) of Delft3D. According to DELFT3D USER MANUAL, 2007 this module calculates non-steady flow and transport phenomena which delivered from tidal and meteorological forcing on a rectilinear or a curvilinear, boundary fitted grid.

The results from this model could be the basis for a water quality model (hydro-chemical and hydro-biological). The model should be simple enough but considers important aspects (combination of essentials components)

3.2.1 Numerical model approach and method

a. Boundary Condition

The relevant boundary condition of the numerical model is the tide.

b. Initial conditions

Initial conditions for water level is depend on the tides, which is set to be at maximum tide level at the beginning. Concentrations during the initial condition are distinguished along the coral reef crest line. The concentration inside and outside the lagoon are set to be 1 kg/m^3 and 0 kg/m^3. This difference is made on purpose to study residence time. Water is assumed to be quiet and not moving at the initial conditions, hence the water velocity is 0 m/s.

c. Processes

Constituents of the model (sediments, salinity, temperature and pollutants) are neglected since these are not relevant to the study.

The main consideration of the model is tides. Winds, waves and secondary flows are neglected. Man made processes, such as dredging and pumping are also neglected.

d. Physical parameters

Several physical parameters are taken in order to have a realistic model. The relevant physical parameters taken in this model are gravity accelerations, water density, bottom roughness, viscosity and diffusivity.

e. Numerical parameters

The relevant numerical parameters to be taken into account for the model are time-step and threshold depth (see sub-chapter 3.2.3 for detail).

The rates of the parameters involved in the model are presented in the appendix A.

3.2.2 Grid and bathymetry

A simple coral reef and lagoon system is built in order to study the hydrodynamic circulation and the residence time. The coral reef crest is 100 m width and submerged for 20 cm. It is located 750 m away from the beach and classified as the barrier reef. The length of the study area is limited to 2 km and enclosed at both ends. The depth of the lagoon is varied to 8 m. The depth outside the lagoon is increased significantly to 50 m.

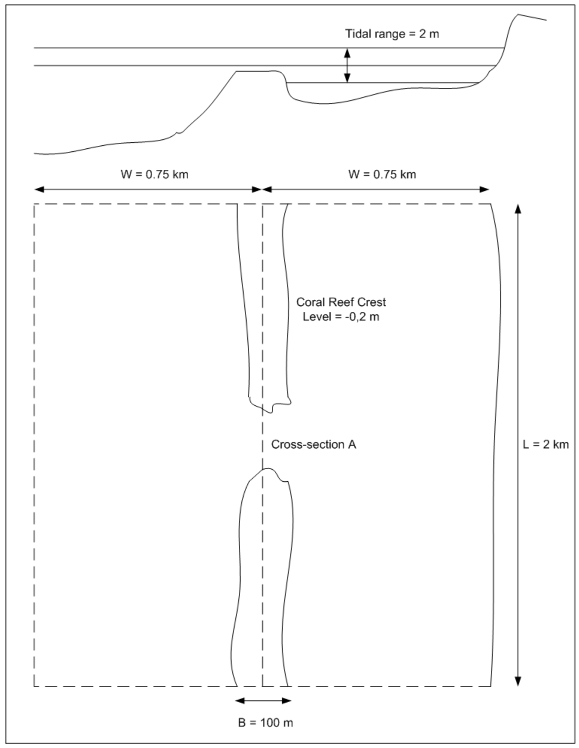


Figure 8 Sketch of the model layout

Dataset required are tides and topography. These datasets are an artificial, in order to simplify the model. The reef crest is 0.2 m below MWL. The reef crest is emerging during the low tide but submerges during the high tide.

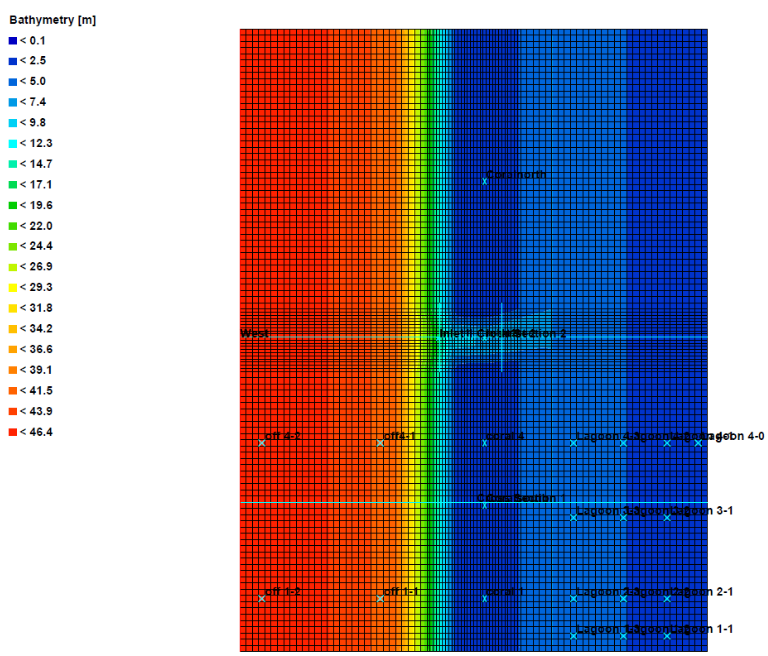


Figure 9 Top view of Grid & Bathymetry layout of the Delft3D model

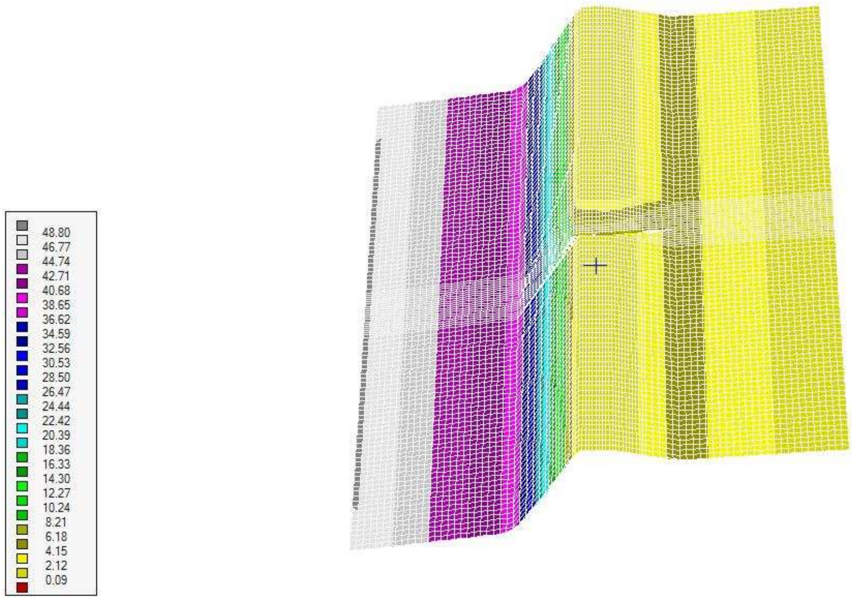


Figure 10 3D view of grid & bathymetry layout of the Delft3D model

The grid is designed to be a size 20 m x 20 m, except in the inlet (passage) the model is smaller (10 m x 10 m) because the hydrodynamic phenomena occurring in the inlet could be unique and really related to the water circulation of the coral reef & lagoon system.

3.2.3 Overview of the computations

a. Boundary Conditions

The choice of the boundary condition used depends on the phenomena to be studied. To model a tidal flow in a coral reef & lagoon system, a similar approach to model a tidal flow in a large basin by prescribing water levels only is used.

Then, tides are generated from the offshore border. Hence, the boundary is located along the west border (offshore border) of the model.

The water level is set to be the harmonic function with initial tidal amplitude of 2 m with a time period of 12.5 hours (semi-diurnal). Since the boundary is parallel to the shoreline, the phase along boundary is similar.

Frequency [deg/h]	Amplitude Begin [m]	Phase Begin [deg]	Amplitude End [m]	Phase End [deg]
0	0	0	0	0
28.8	2	0	2	0

Figure 11 Harmonic boundary layer of the model

The initial water level is set to the maximum tide level (in this model is 2 m), because the tides is derived from the co-sinus harmonic equation. The gravity acceleration used in this model is 9.81 m/s^2 because the model is settled relatively near 0 m altitude.

In order to study the hydrodynamic and residence time of the circulation, the diffusivity should be neglected. After running some preliminary model which the Eddy diffusivity is set to be 0 m^2/s, the output of some observation points has shown that concentrations are raised. This result is impossible since the concentration on the boundary conditions is set to be 0 kg/m^3. This problem might be caused by an error of Delft3D numerical scheme. Hence, to minimize the diffusivity effect, the horizontal Eddy diffusivity is reduced to be 0.1 m^2/s (which previously 10 m^2/s).

Thatcher-Harleman time lag is the return time for concentrations from their value at outflow to their value specified by the boundary condition at inflow. In this model, the time lag has to be realistic. The time lag used for this model is 60 minutes.

b. Numerical Stability

To indicate the numerical stability and accuracy of the model in Delft3D-Flow, the courant number is used. For a model with large different in bottom geometry, the courant number should not exceed 10. The Courant number (C) is:

$$C = 2.\Delta t\sqrt{g.h\left(\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}\right)}$$

Where Δt is time-step (s), g is gravity acceleration (m/s^2), h is local water depth (m), Δx and Δy are grid length in x and y direction (m)

In the model, the deepest water depth is 50 m, Δt is 0.05 minute (3 s), Δx is 20 m and Δy is 20 m. Hence, the Courant number is:

$$C = 2.3\sqrt{9.81.50\left(\frac{1}{20^2}+\frac{1}{20^2}\right)} = 9.4$$

Beside the Courant number, it is important to determine the threshold depth of the model. To determine the threshold depth, the following rule of thumb is used:

$$\delta \geq \frac{2\pi|\zeta|}{N}$$

Where ζ is the tidal amplitude, δ is the threshold depth and N is the number of time steps per tidal period.

In the model, the tidal amplitude is 2 m, and the time step is 0.05 minute. Hence, the threshold depth should be at least 0.0058 m.

4. Initial model

The initial model objectives are to study the hydrodynamics, circulation, concentration rate, and residence time in more detail & specific. The sensitivity analysis of decisive factors such as tides, inlet geometry, lagoon geometry and sea level rise are presented in the next subchapter. The calculations are both by simple and Delft3D model calculation.

4.1. Simple model calculation

1. Hydrodynamic

In this model, the initial water level is set to be at high tide which is 2 m. The basin area is 1400000 m2 (length of 2000 m and width 700 m). The channel inlet is trapezium shaped with bottom and upper width of 40 and 200 m. The maximum depth of the lagoon is 8 m. The channel depth is designed to be similar to the maximum depth of the lagoon.

The time step used in the simple model is 0.2 minutes. The time-step highly determines the model output. A bigger time-step affects to the accuracy and the 'noise' in the graphic.

Output of this model shows that the difference between the water level inside (H_3) and outside (H_1) is up to 0,011 m. The difference is generating the velocity and discharge through the inlet channel. The maximum velocity through the inlet is 0.45 m/s (inflow) and 0.45 m/s (outflow). The maximum flow discharges are 392 m^3/s (inflow) and 390 m^3/s (outflow).

The output also indicates the time lag between the peak velocity and the discharges. Outputs of the numerical iterations are presented in the figure below.

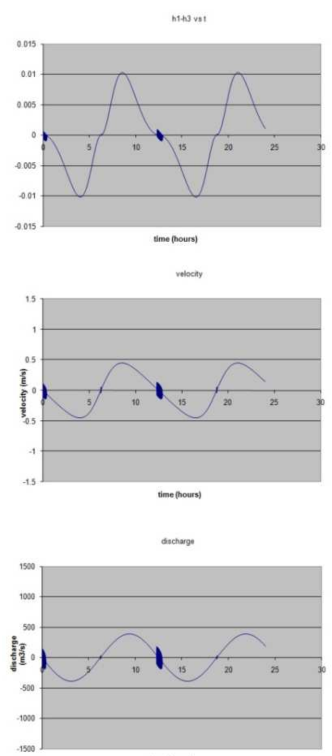


Figure 12 Concentration rate in the lagoon, Inlet and above Coral reef (Left) and offshore (Right)

2. Concentration & Residence Time

The outflow volume is the cumulative discharge through the inlet, while the inflow is reversible of the outflow. The $Q_{cumulative}$ graphic below is derived from previous discharge calculation. The difference between the maximum and minimum value of $Q_{cumulative}$ indicates the total outflow and inflow during ebb and flood tides in one period.

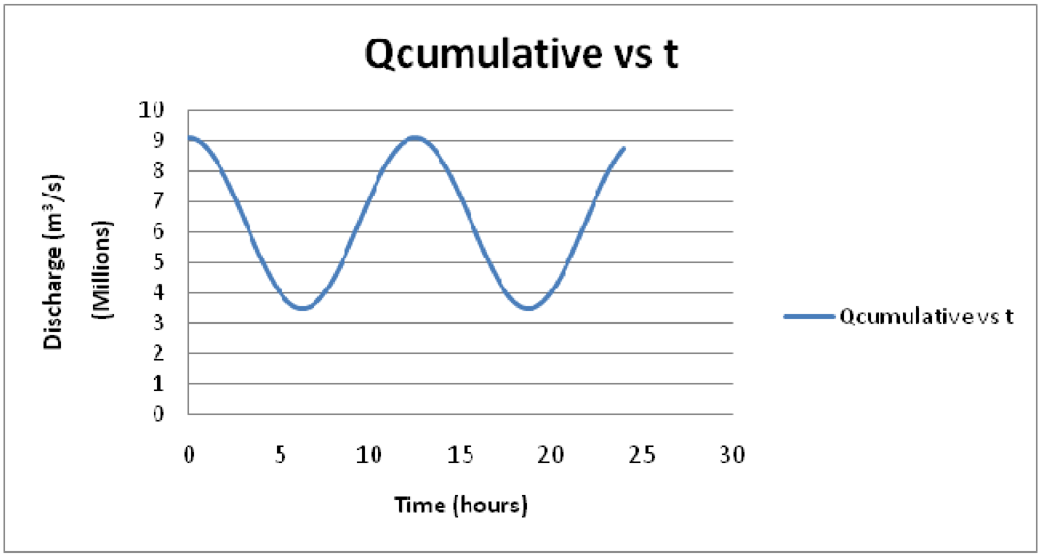


Figure 13 Relation between total water volume inside the lagoon during inflow and outflow

The iteration of concentration inside the lagoon using formula above is shown in the table below.

Table 2 Concentration rate in the lagoon during the inflow and outflow

t (h)	Volume (m^3)			Concentration (kg/m^3)	
	Inflow	Outflow	Total	Offshore	Lagoon
0			9101075	0	1.0000
12.5		-5601075	3500000	0	1.0000
25	5601075.3		9101075	0	0.3846
37.5		-5601075	3500000	0	0.3846
50	5601075.3		9101075	0	0.1479
62.5		-5601075	3500000	0	0.1479
75	5601075.3		9101075	0	0.0569
87.5		-5601075	3500000	0	0.0569
100	5601075.3		9101075	0	0.0219
112.5		-5601075	3500000	0	0.0219
125	5601075.3		9101075	0	0.0084
137.5		-5601075	3500000	0	0.0084
150	5601075.3		9101075	0	0.0032
162.5		-5601075	3500000	0	0.0032
175	5601075.3		9101075	0	0.0012
187.5		-5601075	3500000	0	0.0012

The concentration inside the lagoon is plotted with respect to time to produce exponential representation between concentration and time. The residence time is determined using the graphic.

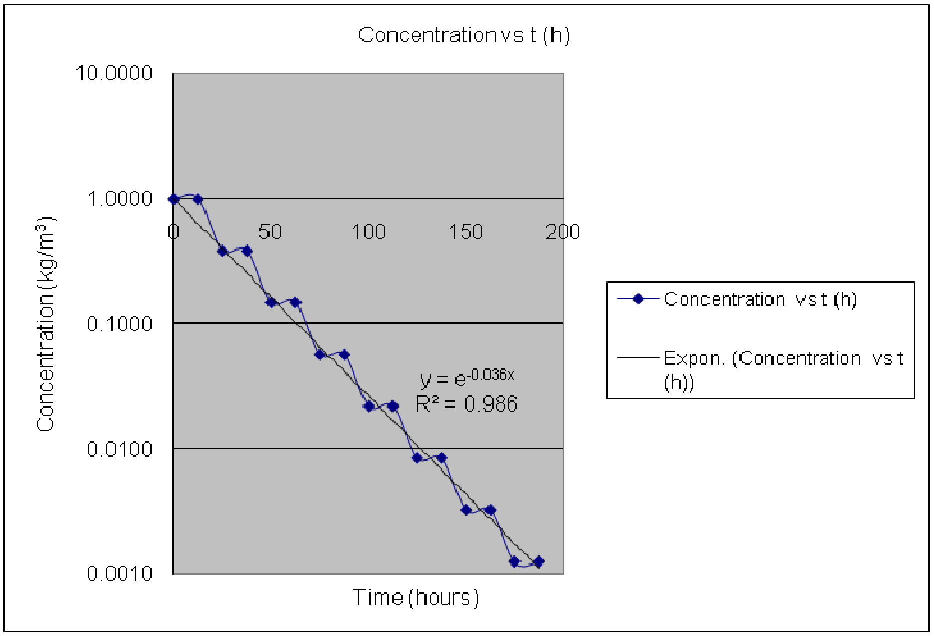


Figure 14 Concentration rate inside the lagoon

During the first 6.25 hour, the water inside the lagoon is going out (outflow) which means the concentration inside the lagoon is stayed constant at 1 kg/^{3}. The residence time of this model is 28 hours.

4.2 Delft3D model output

In this model, the initial water level is set to be similar at high tide which is 2 m. The basin area is 1400000 m2 (length of 2000 m and width 700 m). The channel inlet is trapezium shaped with a bottom width of 40 m, a top width of 200 m and a depth of 8 m. The hydrodynamic output (water level and velocity) of this model is shown below

1. Hydrodynamic

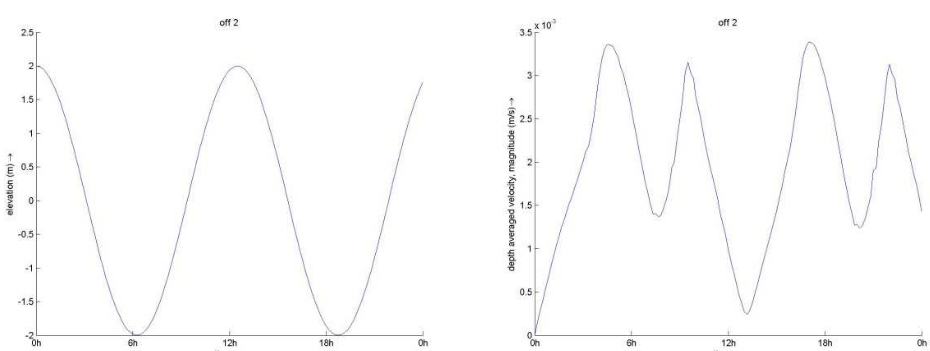


Figure 15 Water level and Velocity at offshore observation point

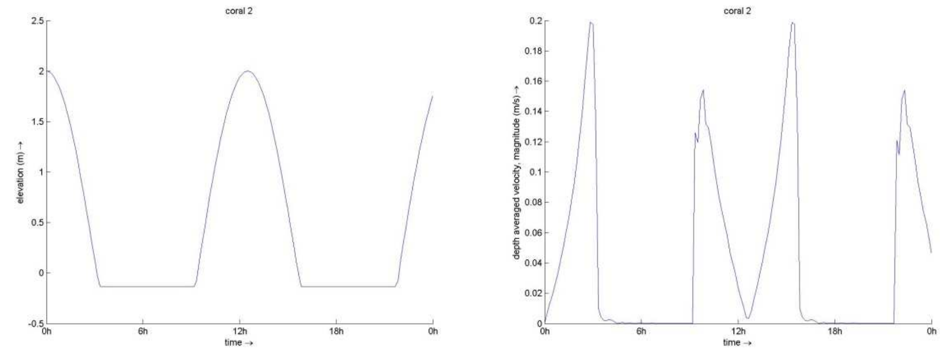


Figure 16 Water level and Velocity at coral reef observation point

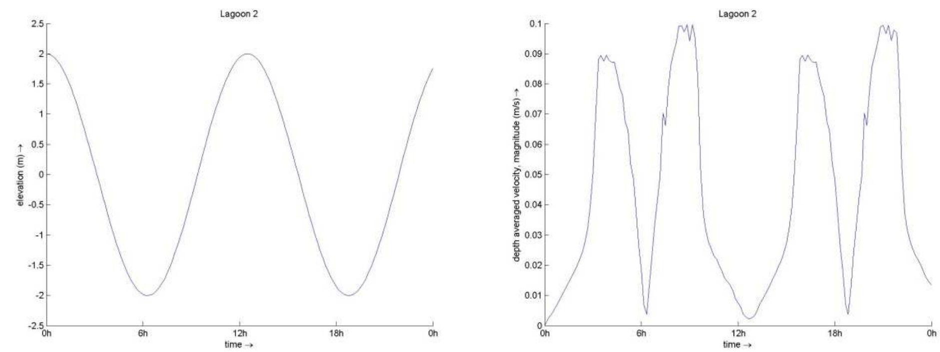


Figure 17 Water level and Velocity at lagoon observation point

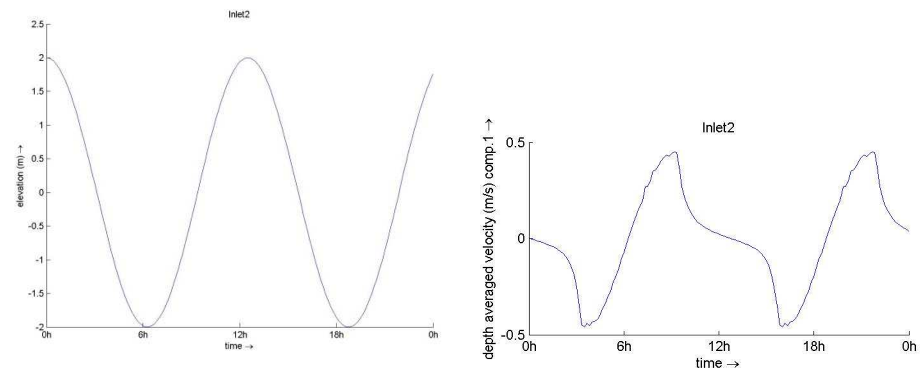


Figure 18 Water level and Velocity at inlet observation point

The water levels vary between 2 m to – 2 m with an exception in the coral reef. In the coral reef the water level is not less than 0,2 m because at the low tide (below 0,2 m) the coral reef is exposed.

In the inlet, the velocity is much bigger compare to other observation points. The maximum velocity is 0,45 m/s in both directions. Between the maximum and minimum velocity, time-lag is occurred. The velocity is strongly decreased after the peak condition, and then become less steep before it reached 0 m/s.

2. Concentration

The concentrations are introduced to the model with 1 kg/m^3 inside the lagoon and 0 kg/m3 outside the lagoon as shown in figure below. At the peak outflow (after 6 hours) the concentration is spreading outside carried by the outflow (hydrodynamic), the small gradient of concentration is because the diffusivity is not neglected (horizontal eddy diffusivity of 0,1 m^2/s). After 12 hours (at the peak inflow), the concentration inside the lagoon is reduced because of the inflow. The wider gradient is because of the diffusivity (see Figure below).

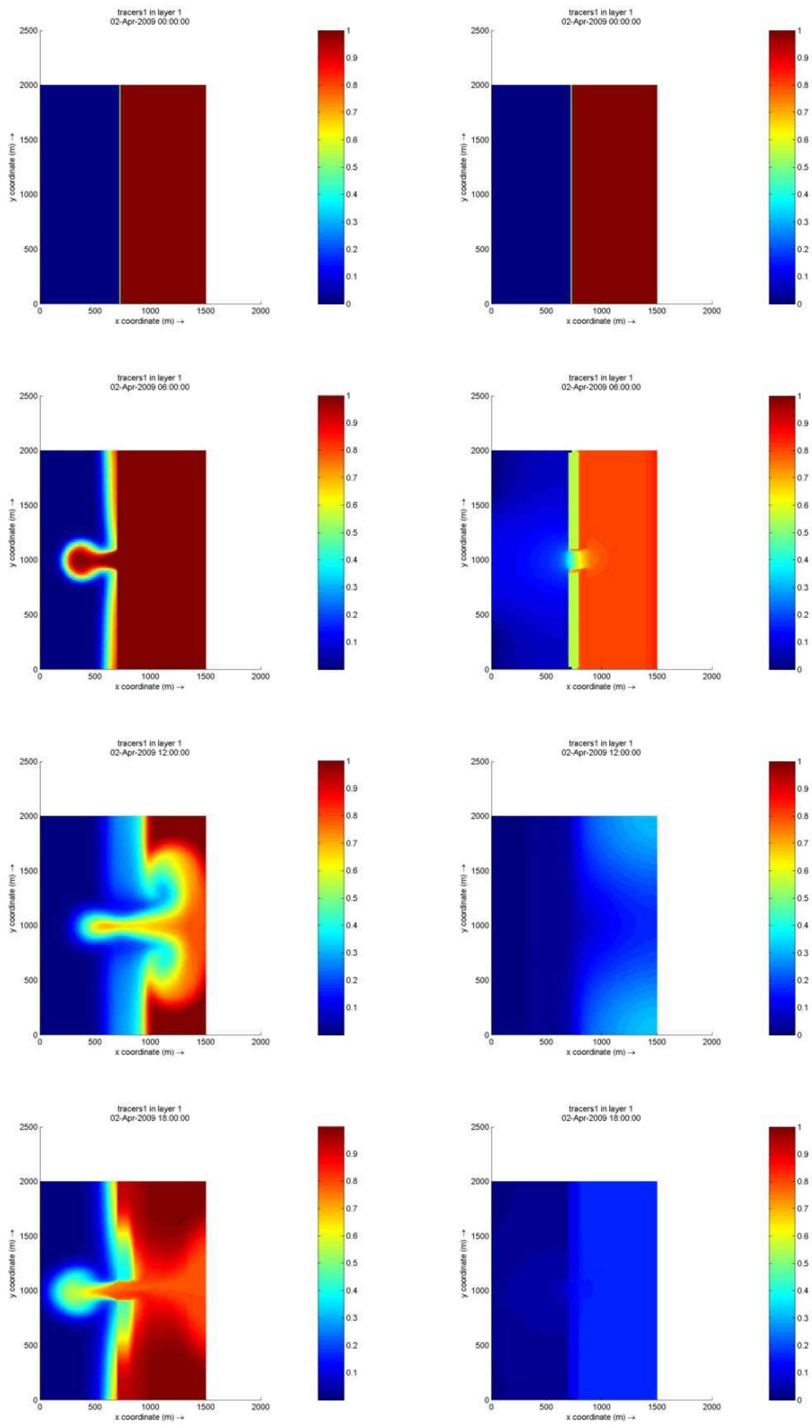


Figure 19 Comparison between Diffusivity rate of 1 (Left) and 10 (Right)

The graphic of concentration is decrease in the Inlet, Lagoon and coral reef. In the inlet the decrease of concentration is bigger compare to the lagoon.

During the outflow, the concentration is varying in sinusoidal pattern, and exponential in globally. The sinusoidal behaviour shows that the concentration rate is significantly dependant on the diffusivity, but also depends on the hydraulic, especially in the inlet where the flows are very dynamic and the location which is close to the border of the separation lines between concentrations of 0 and 1 kg/m^3 . During the outflow, the high concentration in the border (coral reef) diffuses more compared to inside the lagoon. As an impact of diffusivity, the concentrations are decline during outflow period.

The graphics of the concentration rate are shown below.

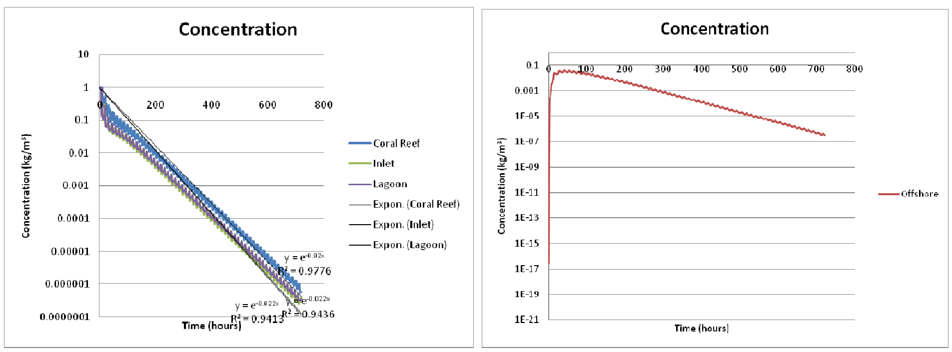


Figure 20 Concentration rate in the lagoon, Inlet and above Coral reef (Left) and offshore (Right)

3. Residence Time

From figure 4-9 above, the concentration at the lagoon, inlet and above the coral reef start at 1 kg/m3, and decreasingly respect to time as a result of hydrodynamic and diffusion phenomena. But in the offshore observation point, the condition is significantly different compare to others. At the beginning, the concentration start at 0 kg/m2 and increase for some time until it reaches the maximum magnitude. After that, it begins to decrease as the whole area is decreasing its concentration.

The most interesting part of this segment is how to determine the residence time from the concentration rate dataset. The definitive method of determining the residence time is by providing the exponential equation of concentration rate.

$$c(t) = e^{\frac{t}{T}}$$

Where:

c(t) = concentration (kg/m^3)

t = time (h)

T = residence time (h)

Residence time in the inlet, lagoon, and above the coral reef can be calculated using the method mentioned above, but it is not possible for the offshore observation points. The concentration rate in the offshore point has shown no exponential form.

Another enticing part is how to obtain an accurate and scientific residence time. If an exponential equation of concentration rate is drawn, the residence time is extracted from the equation delivered. The question will be 'Is the residence time is valid and scientific?'

To answer this question, one example is taken from 4 observation points. The point taken is in the lagoon because the study is focussed on the residence time in the lagoon.

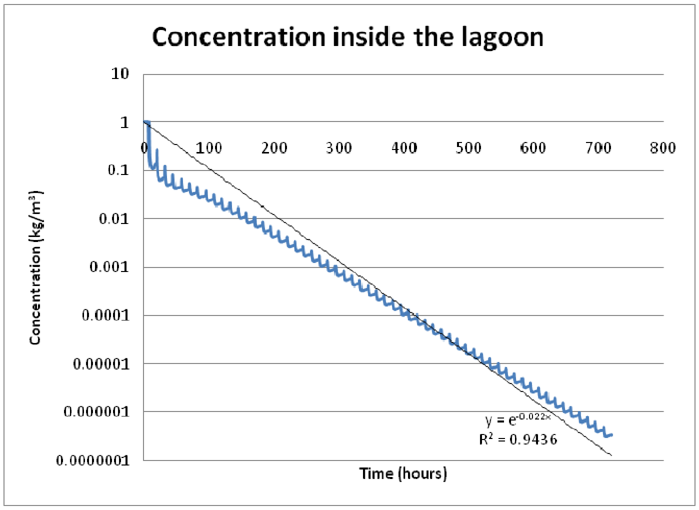


Figure 21 Concentration rate in the lagoon observation point

From the figure above, it is clear that the exponential expression is not valid. During the first 25 hours, the concentration decreased sharply. Then, from 25 to 125 hours the graphic becomes less steep (the steepness is decreasing significantly). After that, the gradient becomes slightly bigger and stable until the end of simulation.

To solve this inaccuracy, the concentration rates are divided, at the beginning (until 25 hours), from 25 to 125 hours, and from 125 hours till the end of the simulation. This division introduce three different exponential equations, and ends at three different residence times.

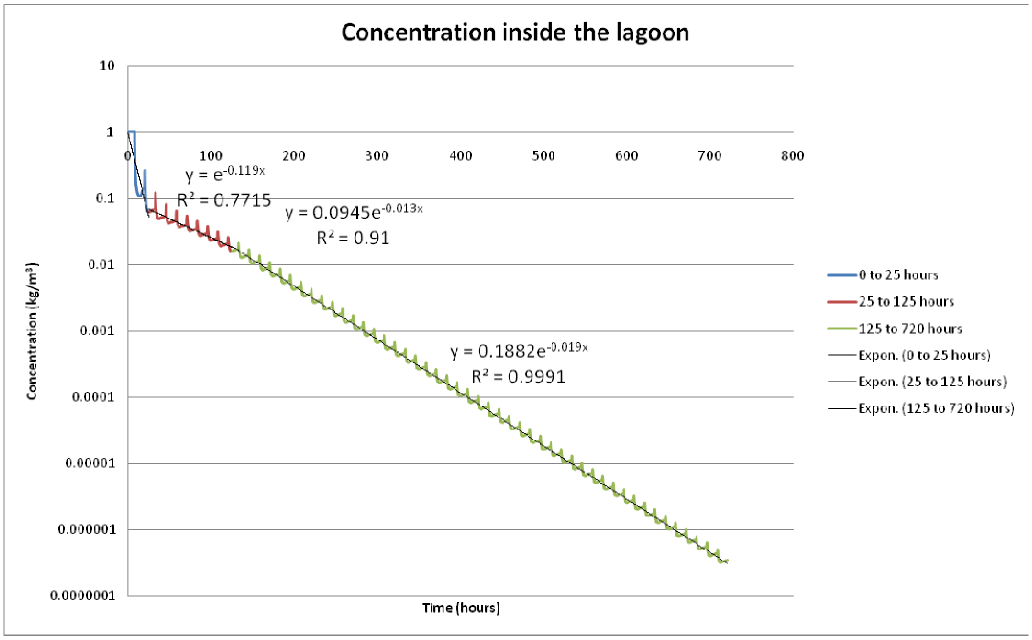


Figure 22 Divided Concentration rates in the lagoon observation point

The exponentials equations derived for these conditions:

- For t up to 25 hours, $c(t) = e^{-0.119.t}$
- For t between 25 to 125 hours, $c(t) = 0.0945.e^{-0.013.t}$
- For t between 125 to 720 hours, $c(t) = 0.1882.e^{-0.019.t}$

The residence times for t up 25 hours, between 25 to 125 hours and between 125 to 720 hours are 8.4, 77 and 56 hours respectively.

Another approach is to add the coefficient in front of the equation to produce the more representative gradient without dividing into three parts.

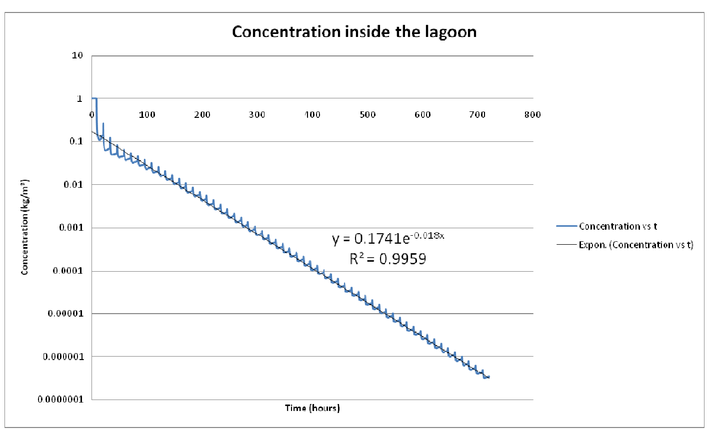


Figure 23 Concentration rate in the lagoon observation point

The concentration equation is:

$$c(t) = 0.1742.e^{-0.018.t}$$

Hence, the residence time for the general terms in the lagoon observation point is 56 hours.

Similar approaches and procedures are taken to the inlet and coral reef observation points. The residence time of these observation points are presented in the table below.

Table 3 Residence time of the lagoon, inlet and coral reef observation points

Observation Point	Residence Time (hours)			
	t 0 to 25 hours	t 25 to 125 hours	t 125 to 720 hours	**t 0 to 720 hours**
Coral Reef	16	63	56	**56**
Lagoon	8	71	71	**53**
Inlet	8	77	53	**56**

4.3 Analysis & synthesis

1. Hydrodynamics

The outflow is consisting of the discharge through the inlet and over the coral reef. The magnitude of the flow over the coral reef depends on the tide. Bigger tide generates bigger flow over the coral reef. Beside the tides, friction also determines the flow over the coral reef. During the high tide, the flow over the coral reef sometime is bigger than the flow through the channel (strongly depending on the water level), but sometime is lower. But during the low tide when the coral reef is exposed, no flow over the coral reef and the flow over the inlet are greater than the maximum flow over the coral reef ever.

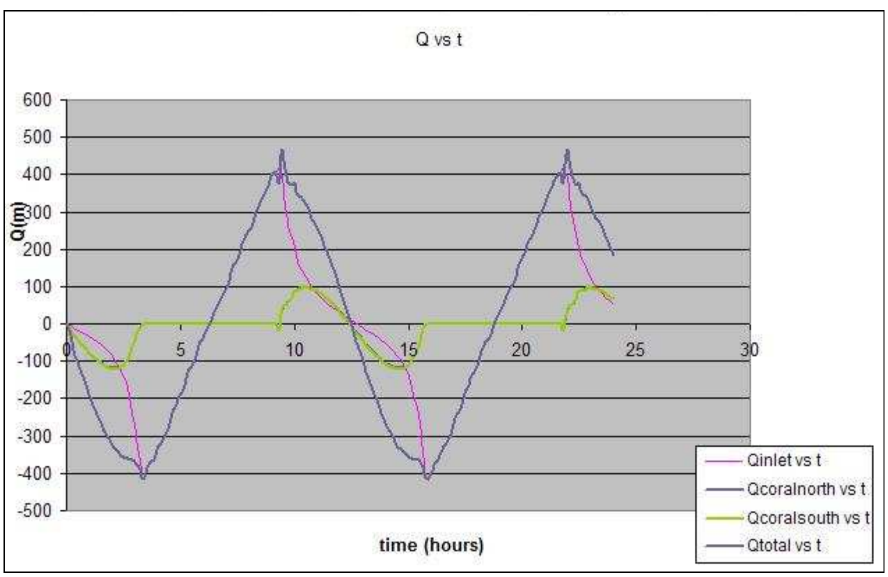


Figure 24 Discharge amounts pass through the inlet, above coral reef and total.

In the graphic below, it is shown that the flow and discharge through the inlet are considerably similar. The velocity and discharge output from the Delft3D model are perhaps more complex and realistic since it considers the friction. But, it has shown that the velocity and discharge in both calculations (manual and Delft3D) pattern is close to each other. The maximum flow of Delft3D model output is 0,45 m/s. The comparison of the discharges through the inlet indicates an identical pattern, and the maximum magnitude for both the simple and the Delft3D model is almost similar.

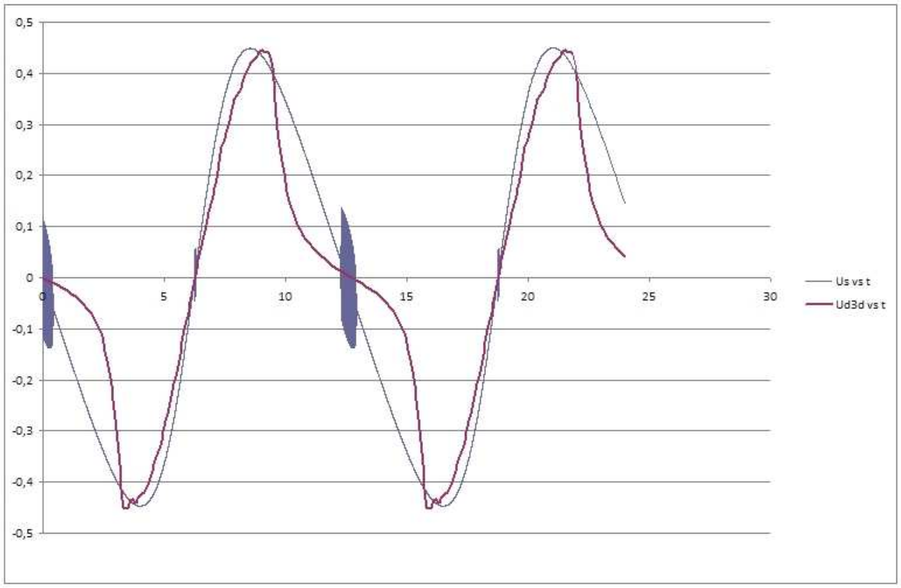


Figure 25 Comparison of velocities inside the lagoon of simple and Delft3D model

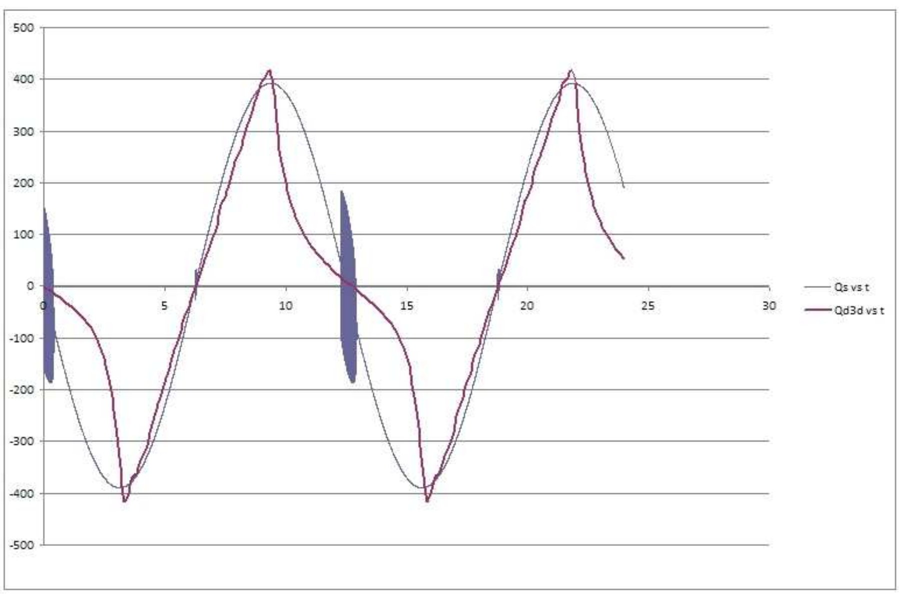


Figure 26 Comparison of discharges of simple and Delft3D model

2. Concentration & Residence time

In the simple model, concentration rate are figured perfectly as an exponential function, while this does not take place in Delft3D model. The residence time in the simple model is 28 hours, while in the Delft3D model are far exceed.

4.4 Summary

It can be concluded that:

- The flow over the inlet is generated by water level and water gradient driven.
- The output of velocity and discharge, particularly the small different to the maximum, indicates that the friction is very small and neglect able in the channel flow.
- The concentration rate is strongly depending on the diffusivity. But, if the diffusivity is neglected or set into a very small rate, the hydrodynamics plays an important role.
- In the delft3D model, the period of concentration rates is distinguished into the initial, transitional and stable period.

5. Sensitivity analysis

In the previous chapter, the model is based by fixed value in all parameters. This chapter is discovering the influence of parameters to the output. Several variations are made in this modelling such as tides, lagoon geometry (coral reef distance), inlet geometry, and coral reef geometry (coral reef height). At last, a model of sea level rise impact to the coral reef & lagoon system completes this chapter. Double scenarios are made to get the impression of the sea level rise issue. The first scenario is sea level rise without the growth of the coral reef, and the other is with the growth of the coral reef.

5.1 Tides influence to circulation

The objective of modelling a several different tides is to determine the effect and relationship of the tide to the hydrodynamics circulation and residence time. In this study, 6 different tides are used (0.25 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m and 2.5 m)

5.1.1 Manual calculation

1. Hydrodynamic

The water level, velocity and discharge depend on the tides. Since the approach used for the calculation is the simple storage area method, the velocity and discharge are depending on the tides. A bigger tide certainly produces bigger difference between the water level outside and inside the basin ($H_1 - H_3$). In the end, bigger tides and velocity are obtained (see figure below).

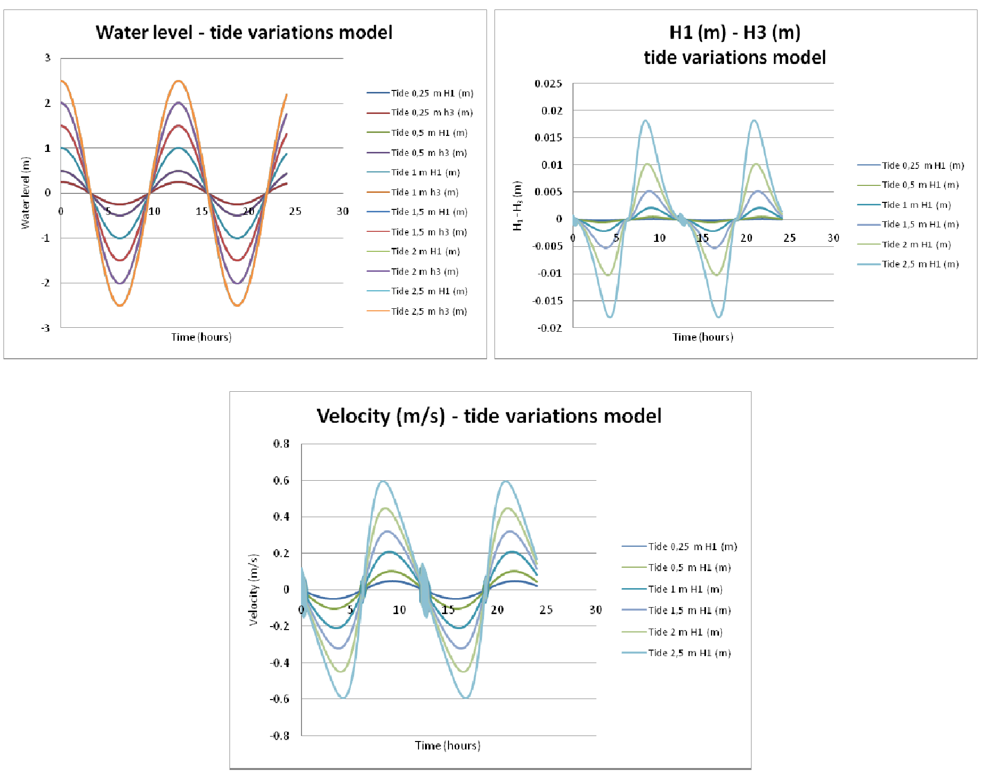


Figure 27 Hydrodynamics conditions of simple tides variation model

The maximum value of discharge and velocity of the simple tides variation model are presented in the table below.

Table 4 Maximum velocity and discharge for tides variation calculation

Inflow			Outflow		
Tide (m)	Q_{max} (m^3/s)	u_{max} (m/s)	Tide (m)	Q_{max} (m^3/s)	u_{max} (m/s)
0.25	49	0.051	0.25	49	0.051
0.5	98	0.102	0.5	98	0.102
1	196	0.208	1	195	0.208
1.5	294	0.322	1.5	293	0.321
2	392	0.449	2	390	0.447
2.5	491	0.598	2.5	486	0.594

The values indicate that maximum magnitude of discharge and velocity are proportionally linear to the tides. The specific relationship between the maximum discharge and velocity are:

Velocity-tides: $U_{\max} = 0.23.tidalrange$

Discharge-tides: $Q_{\max} = 195.tidalrange$

In these relationships is shown that either maximum velocity or discharge is linearly parallel to the tides. The maximum velocity and discharge are increased in relationship to the tide.

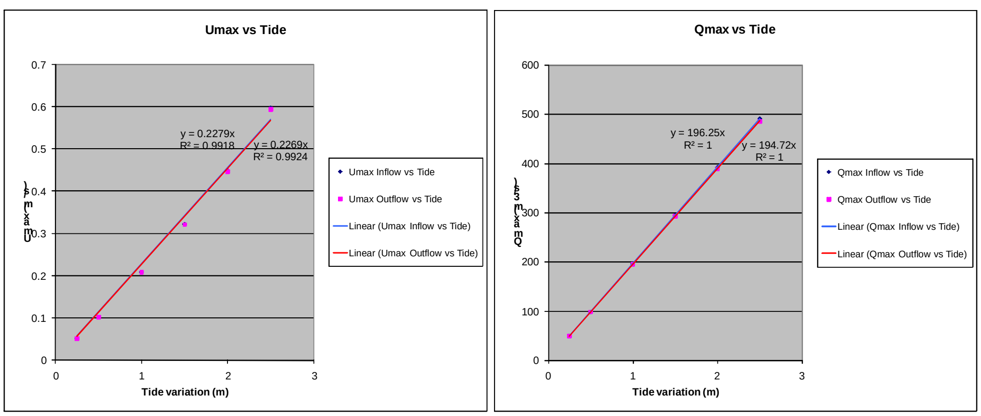


Figure 28 Maximum velocity and discharge of simple tides variation model

2. Concentration and Residence Time

The concentrations are determined using the simple approach described in the previous sub-chapter. Several different tides produce a very different concentration rate and gradients. The output indicates that the gradient is increased due to tides (see figure below).

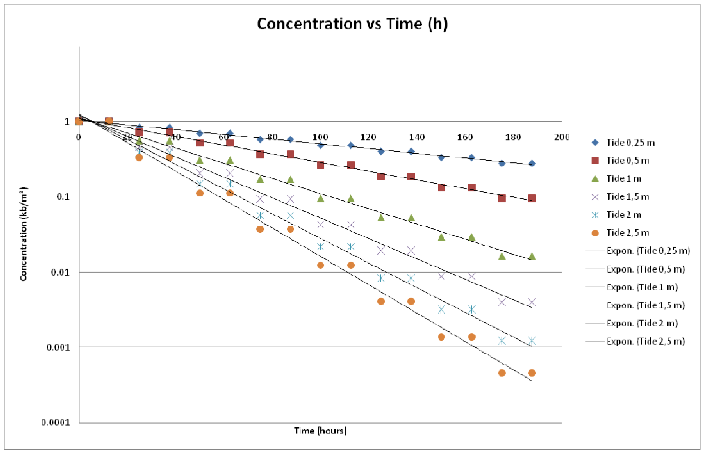


Figure 29 Concentration rates for tides variation calculation

Residence time depends on the concentration rate. Since tides directly determine the concentration rate, the residence time also depends on the tides. It can be concluded that the residence time is reverse to the tides (see table below):

Table 5 Residence times of simple tides variation calculation

Tide (m)	Residence Time (h)
0.25	143
0.5	77
1	45
1.5	33
2	28
2.5	24

The specific relationship between tides and residence time is shown in the figure below. Residence time is increased exponentially due to an increase of tides.

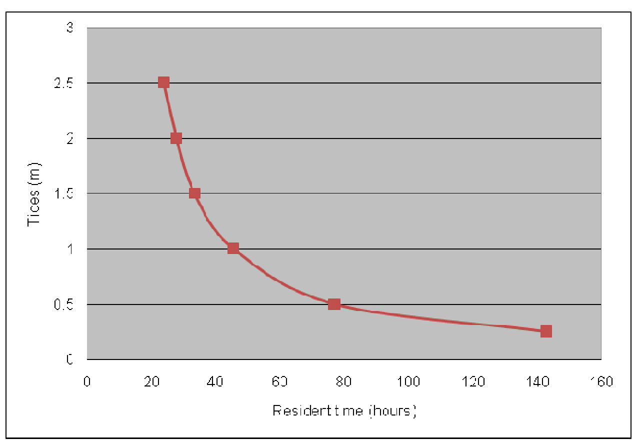


Figure 30 Concentration rates for tides variation calculation

5.1.2 Delft3D model output

The output of Delft3D will be presented from 3 different observation points, in the inlet (inlet2), centre of the lagoon (lagoon 4-2), and far inside the lagoon (lagoon 1-1). Each observation point is expected to produce a unique outcome.

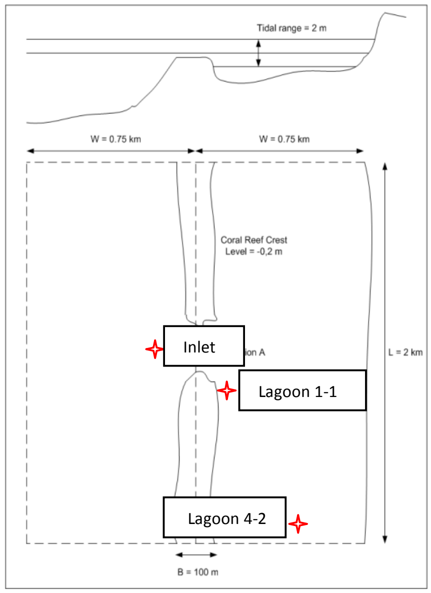


Figure 31 Observation points sketch in the layout

1. Inlet

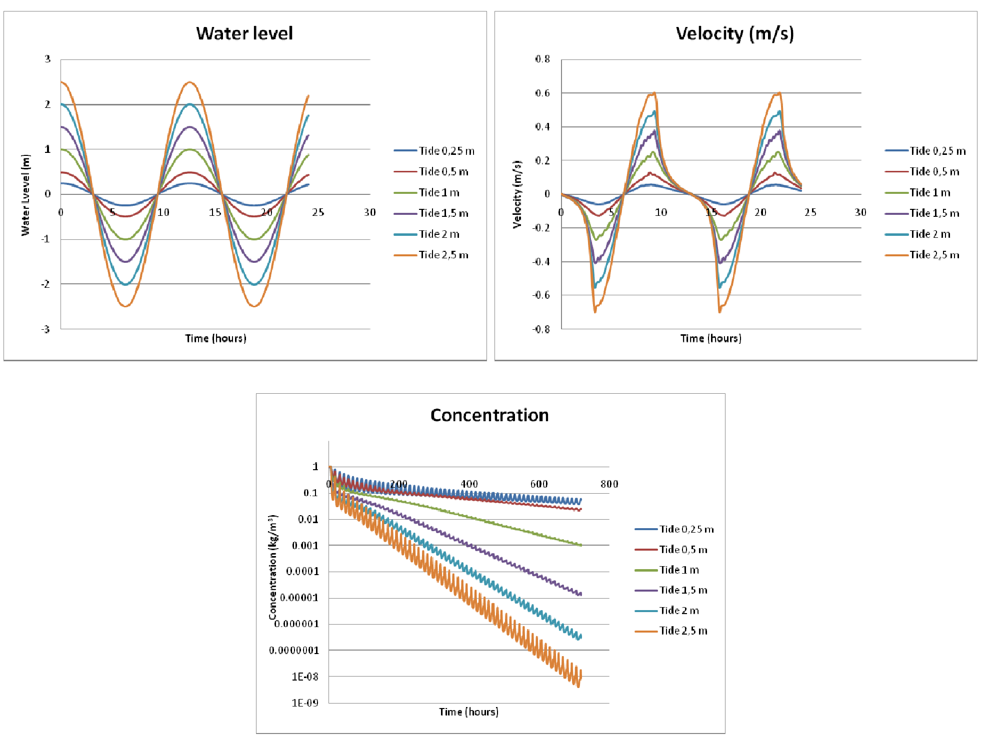


Figure 32 Water level, velocity and concentration rate at inlet observation point

In the inlet, the flow is very dynamic. The magnitude of velocity and discharge through the inlet is much bigger to the lagoon. The magnitude of velocity also increases parallel to the tides. It also reaches the peak magnitude during the water level of 0 m.

In the long term, the concentration rate is exponential, but for the short term the concentration rate is sinusoidal. The sinusoidal form is mainly because of the hydrodynamic circulation. The other minor factor is the effect of diffusivity and location. Because this observation point is located near the concentration distinction line, the diffusivity also determines the concentration rate.

2. Lagoon 1-1 (centre of lagoon)

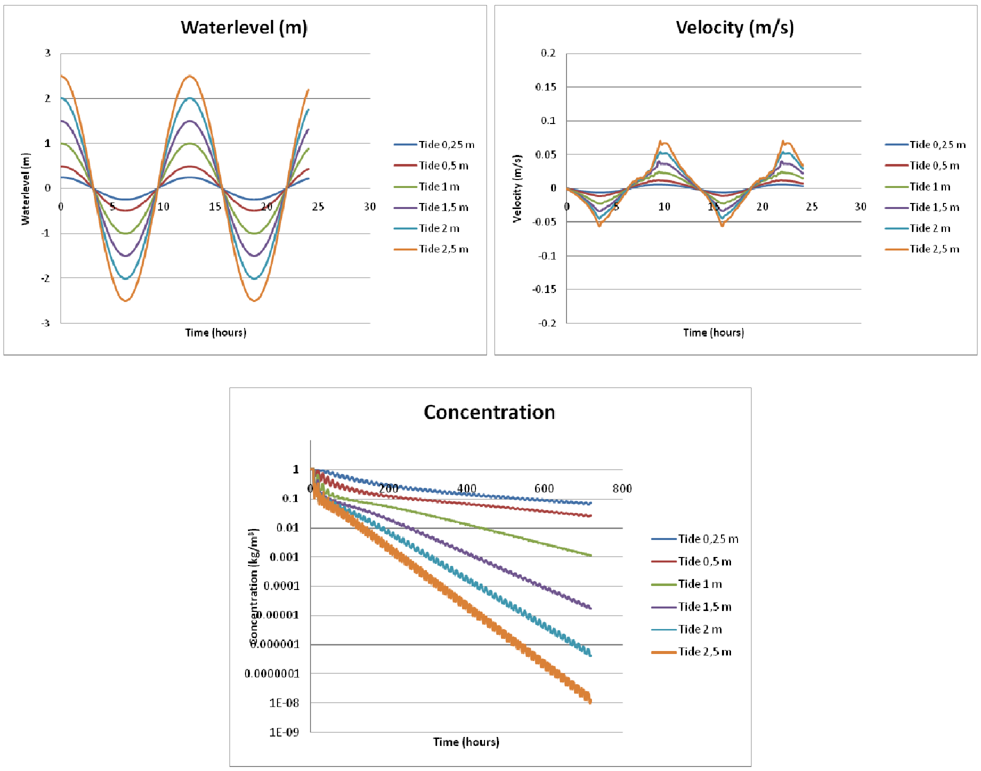


Figure 33 Water levels, velocity and concentration rate at lagoon 1-1 observation point

Similarly to the inlet, the velocity inside the lagoon increases due to the tides and it reaches the maximum at water level of 0 m. But the magnitude in this observation point is much small smaller compare to the inlet observation point (approximately less than 10%).

The concentration rate is generally exponential (more exponential compare to the inlet), but it is still has sinusoidal form for a short term. The decrease of sinusoidal form is caused by the location of the observation points which is farther to the concentration distinction line.

3. Lagoon 4-2 (corner end lagoon)

This observation point is located in the corner of the lagoon and far away from the coral reef and inlet. The velocity magnitude is very small but more dynamic compared to the previous observation points. During the low tide (below -0.8 m), the observation point is exposed (see the figure 5-8).

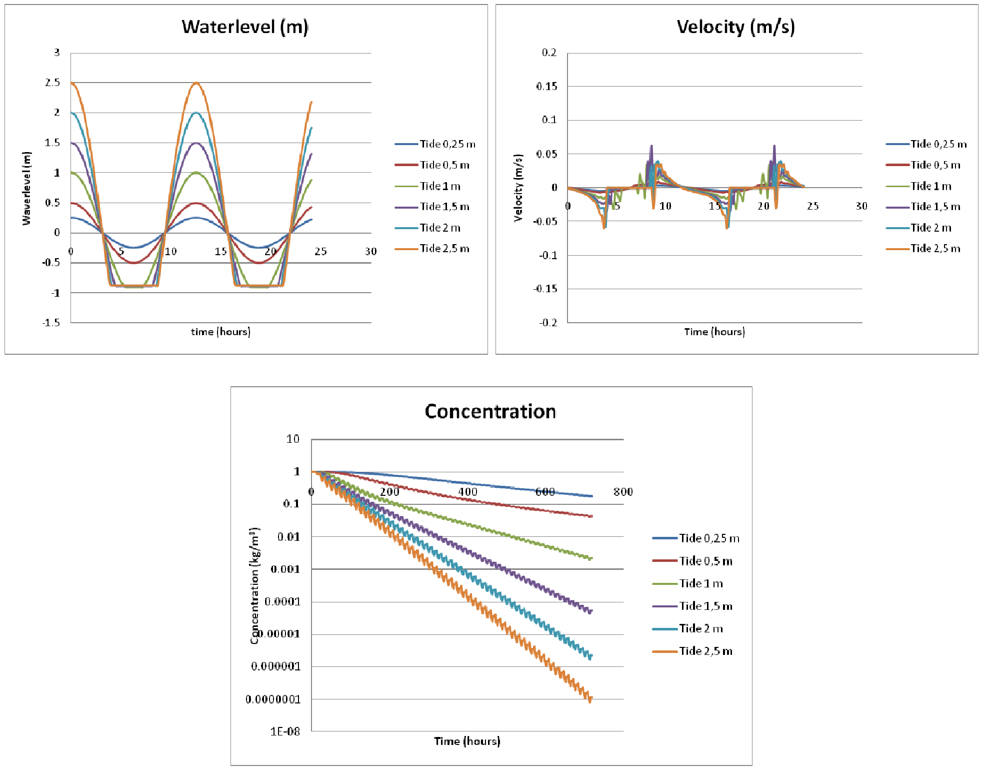


Figure 34 Water levels, velocity and concentration rate at lagoon 4-2 observation point

In a long term perspective, the concentration rate is almost perfectly in exponential formed. But in a short term, it perspective sinusoidal forms although smaller compared to both previous observation points. This phenomenon still occurred as a result of hydrodynamic circulation.

The distribution of the relationship between tides and residence time for inlet, lagoon 1-1 and lagoon 4-2 observation points are shown on the table 5-3. The residence time is divided into the initial, transitional, and stable period. The distinction is based on the numerical processes period. The initial period is the earliest period of the numerical modelling which is counted from start until 25 to 100 hours depend on the concentration gradient. The characteristic of this period in the concentration graphic is the extreme steep or flat condition.

The stable period is the latest period which start varied 125 to 200 hours until the end (720 hours). The visible characteristic of this period is the stable gradient of the concentration rate. The transitional period is in between the initial and stable period.

During the initial period, the residence time is decresed respect to the tides, and increses when the location is landward. The second phenomena show that the concentration rate decreses sharply closer to concentration distinction line during the early period. Different phenomena occured during the stable period. When the tide is lower than 0.5 m, the resicende time tends to decrease when it goes landward. This phenomenon is reverse to the initial period. But when the tides is higher than 1.0, the residence time tends to increase (similar phenomena during the initial period). During the transitional period, the residence time tends to decrease. The output of the tidal variaton of Delft3D model are shown in table 5-3.

Table 6 Residence time of Delft3D tides variation model

	Residence Time (hours)								
	Inlet			Lagoon 1-1			Lagoon 4-2		
Tide	Initial	Transitional	Stable	Initial	Transitional	Stable	Initial	Transitional	Stable
(m)	(h)	(h)	(h)	(h)	(h)	(h)	(h)	(h)	(h)
0.25	36	250	500	200	143	333	200000	500	333
0.5	36	200	333	48	143	333	10000	167	250
1	24	167	125	24	167	143	125	83	250
1.5	20	100	71	20	100	77	71	67	91
2	17	63	53	18	67	56	56	56	59
2.5	16	43	43	17	45	43	43	45	48

5.1.3 Analysis & synthesis

The tides variation model (either simple or Delft3D model) show the unique and different hydrodynamics behaviour and residence time. It can be concluded that

- The magnitude of discharge and velocity are proportionally linear to the tides.
- The residence time is reversibly exponential to the tides
- Major factor determining the concentration rate is the hydrodynamic circulation (inflow-outflow). During the outflow period, the concentration can be stable or increase. While during the inflow period, the concentration is decrease.
- Diffusivity plays an important role to the concentration rate in the Delft3D model. Even small value of eddy diffusivity coefficient is still produce a visible output. Diffusivity is also plays an important role to the residence time.
- Location is also determines the concentration and residence time. When the location close to the concentration distinction line, the hydrodynamic is more dynamic, and the residence time tends to be smaller.

5.2 Coral reef crest depths influence to circulation

This variation is to study the impact and relationship of the coral reef geometry, which is represented by coral crest depth below mean level, to the hydrodynamics and residence time. In this model, 4 different coral reef depth below mean water are used in the model (0.1 m, 0.2 m, 0.5 m, 1.0 m and 2.0). For all coral reefs crest depths conditions, the coral reef is exposed during the lowest water level.

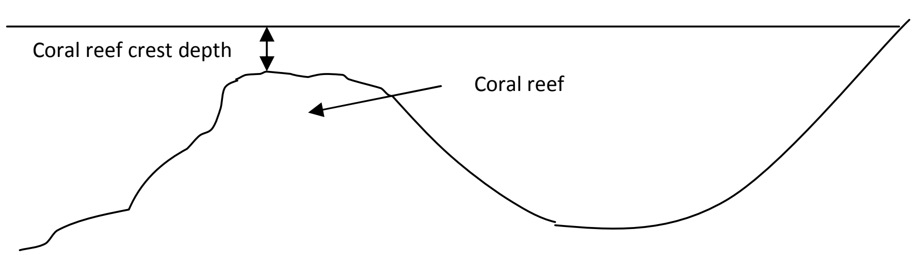


Figure 35 Model of coral reef crest depth variation sketch

5.2.1 Manual calculation

The manual calculation is based on the assumptions of a simple model into a basin with an inlet without considering the depth of coral reef. It is not possible to make a sensitivity analysis of coral reef crest depth to the coral reef & lagoon system. Hence, it is only available on Delft3D model.

5.2.1 Delft3D model output

1. Inlet

In this model, the water level is similar for all variations. In a condition of the coral reef crest depth less than 1 m, the velocity is almost similar, increase of the coral reef crest depth from 1 to 2 m decreases the velocity significantly. The concentration rate is also related to the hydrodynamic, lower velocity produce less steep concentration gradient.

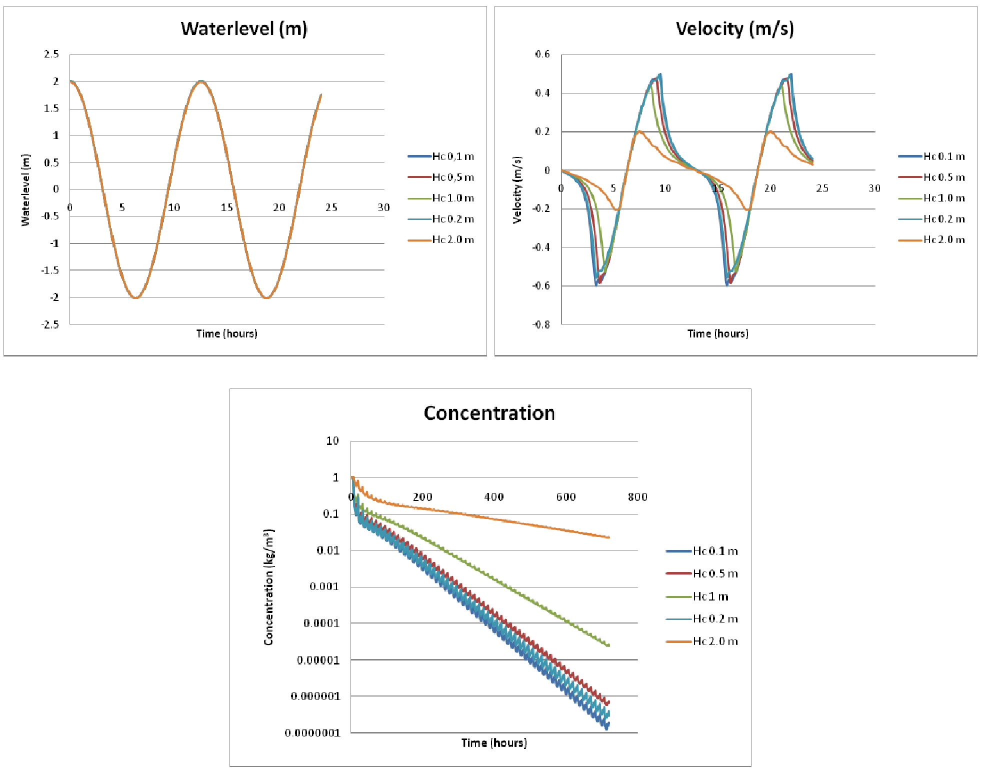


Figure 36 Water levels, velocity and concentration rate at inlet observation point

It can be concluded that either hydrodynamic or concentration conditions tend to be constant if the coral reef crest depth less than 1 m. If the coral reef is deeper than 1 m, the hydrodynamics condition and the concentration gradient change significantly. However, the concentration gradient is different to others when the coral reef crest is 2 m depth,.

2. Lagoon 1-1 (the centre of lagoon)

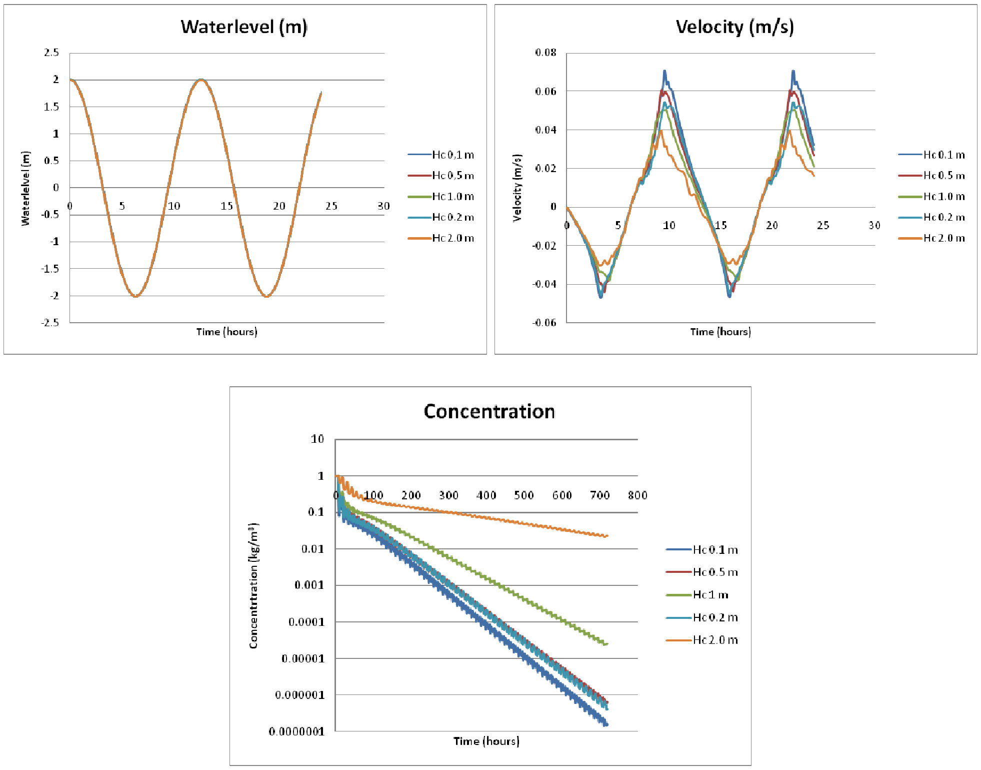
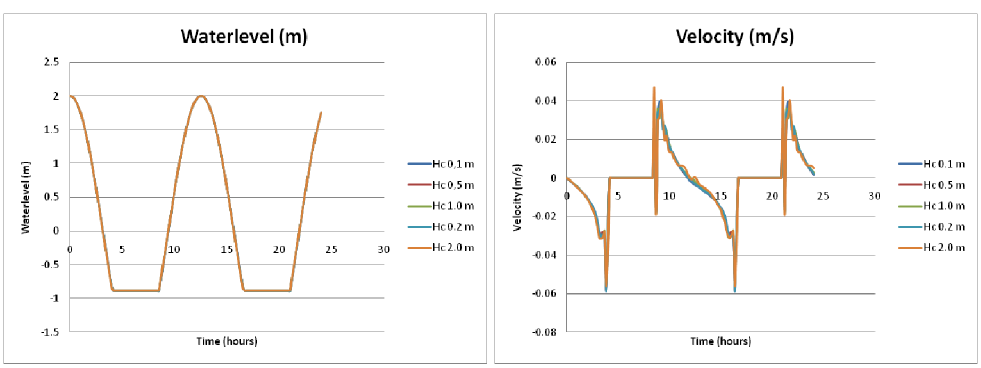


Figure 37 Water levels, velocity and concentration rate at lagoon 1-1 observation point

In the centre of the lagoon observation point, the magnitude of velocity is significantly lower compared to the inlet observation point, but the velocity change is more dynamic. The concentration rate gradient is related to the hydrodynamics condition, lower velocity produces a less steep concentration gradient which means a longer residence time.

3. Lagoon 4-2 (corner end)

Located in the corner of the lagoon and far away from the coral reef, the velocity magnitude is very small but more dynamic formed compared to the inlet or the centre of the lagoon observation point. During the low tide (below -0.8 m), the observation point is exposed because the depth is less than 1 m. The concentration rate in respect to water height above the coral reef is also similar to in the inlet or in the centre of the lagoon.



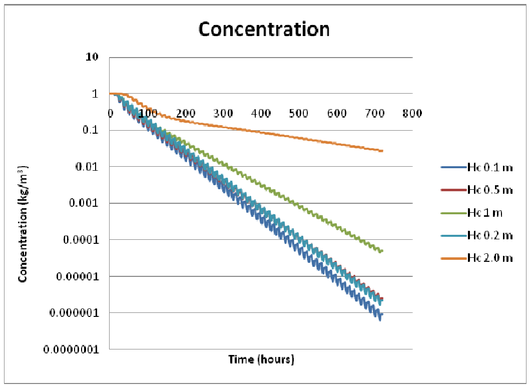


Figure 38 Water levels, velocity and concentration rate at lagoon 4-2 observation point

The distribution of the relationship between tides and residence time is shown on the table below.

Table 7 Residence time of Delft3D coral reef crest depth variation model

Coral reef crest Depth	Residence Time (hours)								
	Inlet			Lagoon 1-1			Lagoon 4-2		
	Initial	Transitional	Stable	Initial	Transitional	Stable	Initial	Transitional	Stable
(m)	(h)	(h)	(h)	(h)	(h)	(h)	(h)	(h)	(h)
0.1	17	56	53	17	56	50	45	50	50
0.2	17	63	53	18	67	56	56	56	59
0.5	19	63	56	19	63	56	56	56	50
1	23	100	77	23	91	77	59	67	77
2	38	200	250	40	200	250	333	100	250

The result indicates that when the coral reef crest depth is less than 1,0 m, residence time is not affected and tends to be constant for all periods (initial, transitional and stable). But if the coral reef depth is deeper than 1.0 m, the residence time is significantly increased. This simulation also indicates that during the stable period, the residence times for all observation points are constant or slightly different. It shows that a different condition occurs during the initial period. During the initial period, the residence time is increased landward.

5.2.3 Analysis & synthesis

From the Delft3D model, it can be concluded that several different coral reef geometries (height) less than 1.0 m have not shown significant different hydrodynamics conditions and residence time.

5.3 Coral reef distances influence to circulation

The objective of this variation is to study the relationship of the lagoon geometry (represented by the distance of the coral reef crest from land) related to the hydrodynamic conditions and residence time in the coral reef & lagoon system. 6 different coral reef distances are made in the model (250 m, 500 m, 700 m, 1000 m, 1500 m and 2500 m).

5.3.1 Manual calculation

1. Hydrodynamic

The water level, velocity and discharge are depending on the storage area/basin (B). Since the approach used for the calculation is a simple storage area method, the velocity and discharge are depending on the storage area. Longer distance to the coral reef will produce bigger storage area/basin (m^2) that will produce bigger and velocity and discharge (see figure below).

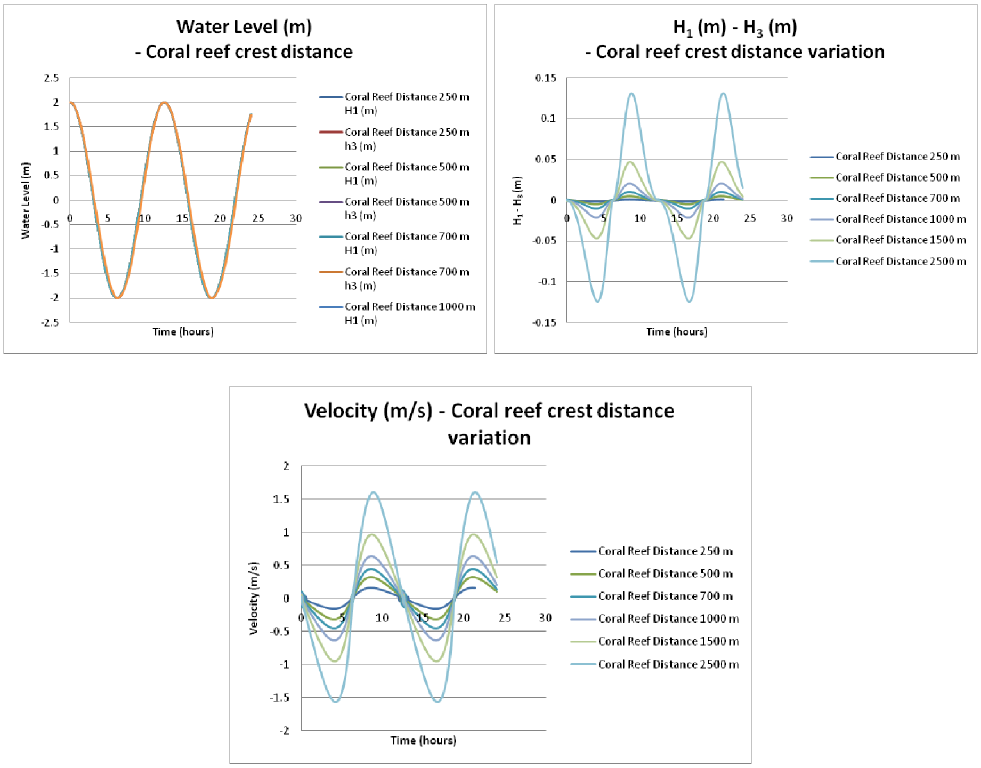


Figure 39 Hydrodynamics conditions of simple coral reef crest distance variations model

The maximum magnitude of discharge and velocity are presented in the table below. The maximum velocity and discharge are linearly parallel to the size of the basin.

Table 8 Maximum velocity and discharge for simple coral reef crest distance variation model

Coral reef crest Distance (m)	Inflow		Outflow	
	Q_{max} (m^3/s)	u_{max} (m/s)	Q_{max} (m^3/s)	u_{max} (m/s)
250	140	0.160	140	0.160
500	280	0.320	279	0.320
700	392	0.449	390	0.447
1000	563	0.642	554	0.638
1500	851	0.964	824	0.953
2500	1457	1.604	1338	1.562

The maximum magnitude of discharge and velocity are proportionally linear to the tides. The relation between the maximum discharge and velocity are:

Velocity: $U_{max} = 0.0006.Distance_{Coralreef}$

Inflow and outflow Discharge:

Q_{max} = $05419.Distance_{Coralreef}$ and Q_{max} = $05758.Distance_{Coralreef}$

From the equation mentioned above, it is shown that the relationship between velocities to the distance of the coral reef crest is linear. The relationship between the discharge (both inflow and outflow) is also linear and proportional.

The difference between the coefficients in the inflow and outflow discharge equation is because the maximum difference of the H1 and H3 during the inflow period is bigger compare to outflow period. And the difference is increase in relationship to the basin volume, in this particular model represented by the coral reef crest distance.

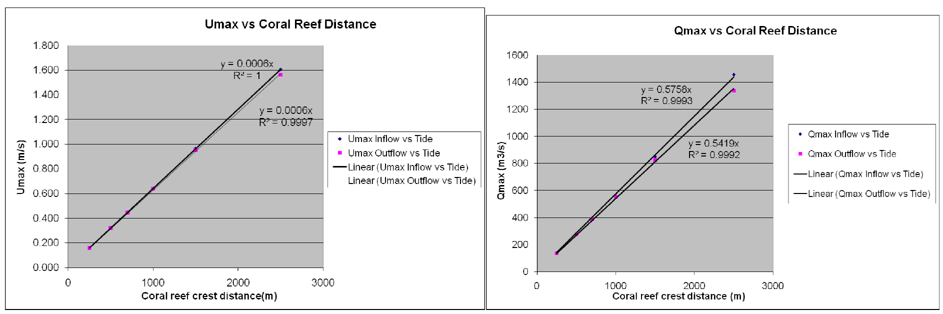


Figure 40 Maximum velocity and discharge of simple tides variation model

2. Concentration and Residence Time

The concentrations are determined using the simple approach described in sub-chapter 3.1.1. Several different lagoon geometries produce a similar concentration gradient.

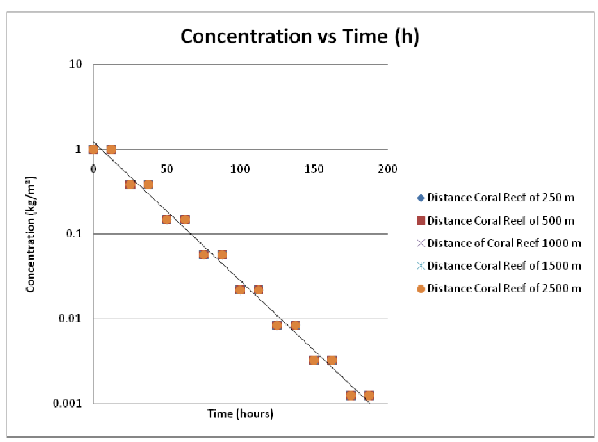


Figure 41 Concentration rates of simple coral reef crest distance variation calculation

Because the concentration gradients of several coral reef distances are similar, the residence times are constant at 28 hours. It can be concluded that in the simple coral reef distance variation model, the size of the residence time is not affected by the coral reef distance.

5.3.2 Delft3D model output

1. Inlet

In this model, the water level is similar for all variations. The magnitude of velocity is increased respect to the coral reef distance. It which means parallel to the lagoon geometry. It reaches the maximum magnitude during the mean water level.

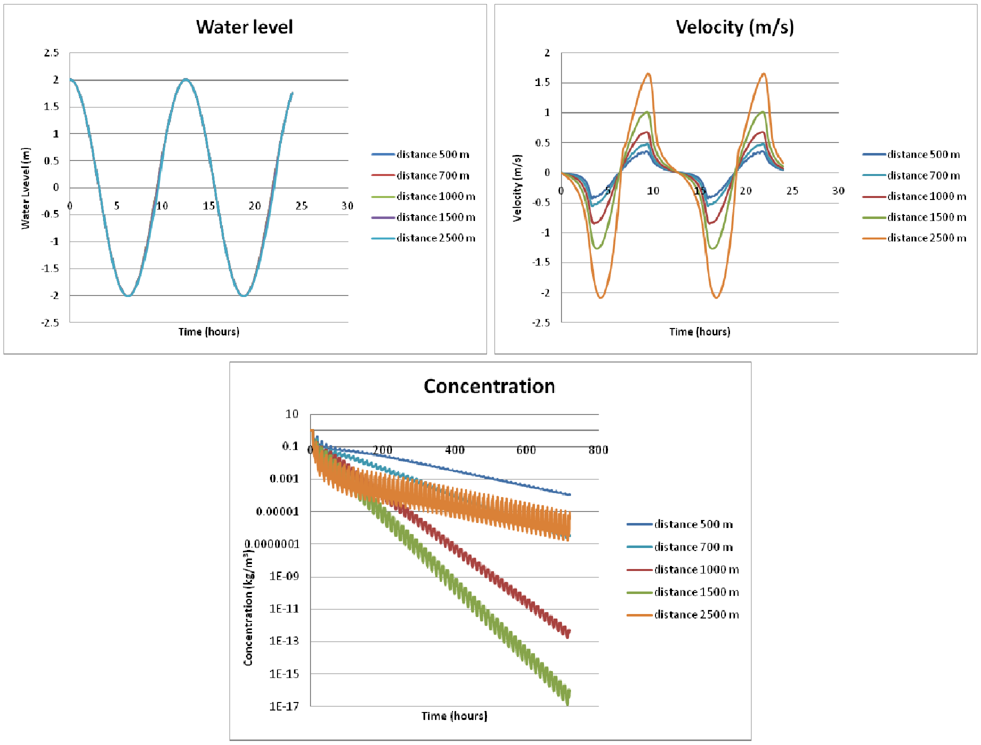


Figure 42 Water levels, velocity and concentration rate at inlet observation point

With an exception to the model with the coral reef crest distance of 2500 m, the concentration gradient is increased when the coral reef crest is farther from the land. The concentration in the model of 2500 m coral reef crest distance is more dynamic and complicated compared to others. This form indicates that the hydrodynamic circulation is more involved in the concentration rate when the coral reef crest is at a farther distance from the land.

2. Lagoon 1-1 (centre of lagoon)

Similarly to the inlet observation point, the water level is almost constant for all simulations, the velocity is increased if the coral reef crest is increased, and the peak velocity is occurrs during the mean water level

Generally, the concentration gradient increases when the coral reef distance is bigger. But this phenomenon is not occurring in the model of 2500 m coral reef distance. In this model, the concentration gradient is significantly less steep.

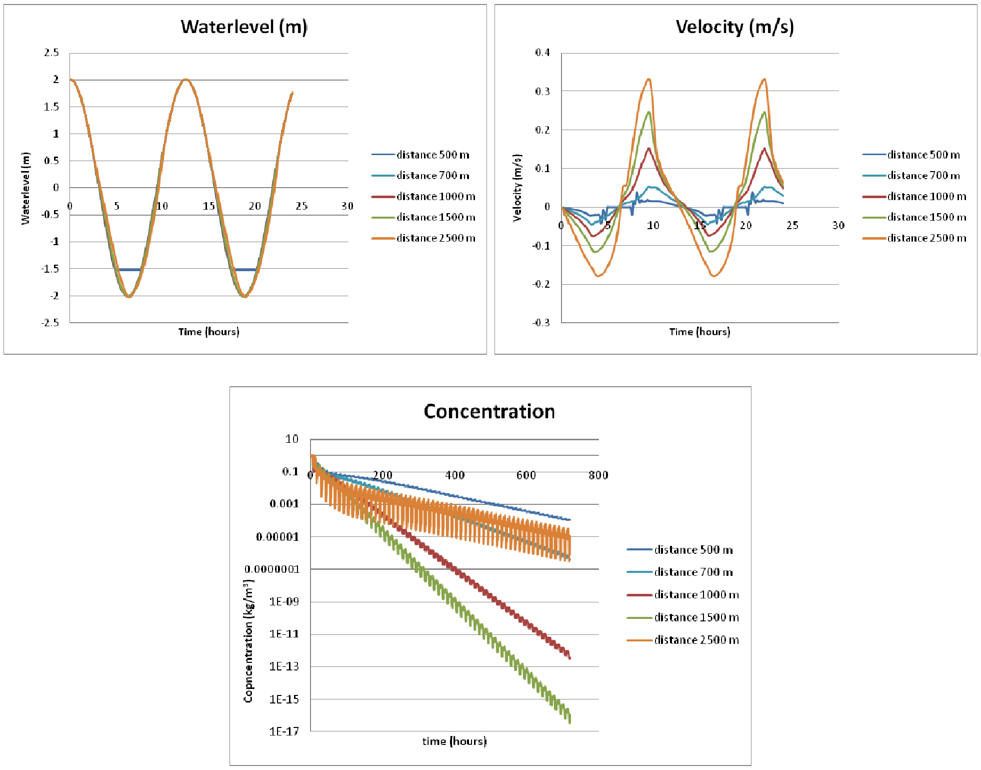


Figure 43 Water levels, velocity and concentration rate at lagoon 1-1 observation point

In general, the residence time decreases if the coral reef crest is farther away from land. This relationship is definite in the initial period of the model where the residence time is reduced systematically. An exception occurred during the transitional and stable period. Initially the residence time is reduced as the coral reef distance increased until 1500 m. But, it increased when the coral reef distance is 2500 m.

Table 9 Residence time of Delft3D coral reef crest distance variation model

Distance	Residence Time (hours)					
	Inlet			Lagoon 1-1		
	Initial	Transitional	Stable	Initial	Transitional	Stable
(m)	(h)	(h)	(h)	(h)	(h)	(h)
500	20	143	91	19	143	91
700	17	63	53	18	67	56
1000	15	26	26	16	26	26
1500	11	20	20	14	20	20
2500	8	59	100	11	63	91

5.3.3 Analysis & synthesis

Based on the output of both simple and Delft3D of coral reef crest distance variation model, it can be concluded that:

- The magnitude of discharge and velocity are proportionally linear to the lagoon geometries.

- The simple model indicates that the coral reef crest distant is not a factor determining the residence time.
- Due to an increase of the coral reef crest distance, the inflow and outflow discharge is increased as well. The increase of inflow and outflow discharge is proportional to an increase of the lagoon volume which causes a stagnant residence time in the simple model.
- In contrast to the simple model, the output of Delft3D model produces a different outcome. The distance of coral reef crest determines the residence time.
- Generally, the increase of the coral reef crest will reduce the residence time, with an exception to the transitional and stable period of 2500 m coral reef crest distance model.

5.4 Inlet widths influence to circulation

5.4.1 Manual calculation

1. Hydrodynamic

Water level, velocity and discharge are determined by the simple storage area method which is described in the third chapter.

Several different inlet widths produce a unique relationship and behaviour.

In this model, the variation is in the width of the inlet.

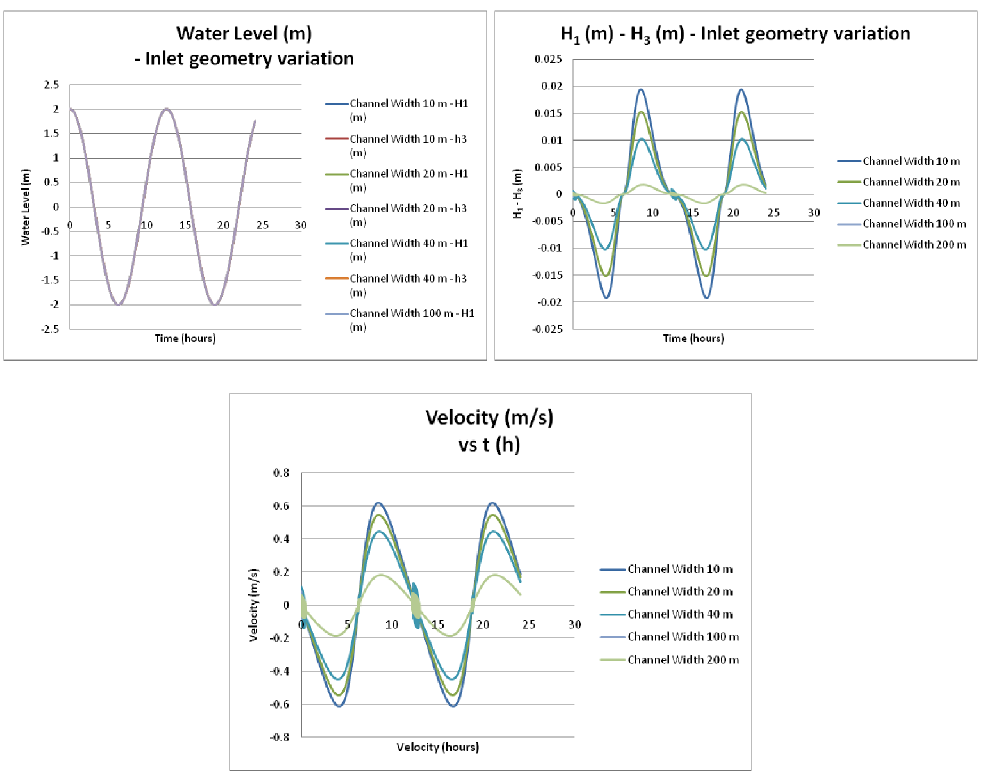


Figure 44 Hydrodynamics conditions of simple inlet width variations model

The maximum magnitude of discharge and velocity are presented in the table below.

Table 10 Maximum velocity and discharge for simple inlet width variation model

Inlet Width (m)	Inflow		Outflow	
	Q_{max} (m^3/s)	u_{max} (m^3/s)	Q_{max} (m^3/s)	u_{max} (m^3/s)
10	394	0.618	388	0.614
20	393	0.549	389	0.546
40	392	0.449	390	0.447
100	391	0.291	390	0.291
200	391	0.184	391	0.184

A wider inlet does not increase of decrease the discharge through the inlet significantly. If the inlet is wider, the inflow discharge is decreases slightly but the outflow is increases slightly. Different to the discharge, the maximum velocity is reduced sharply if the inlet is wider (see figure 5-19)

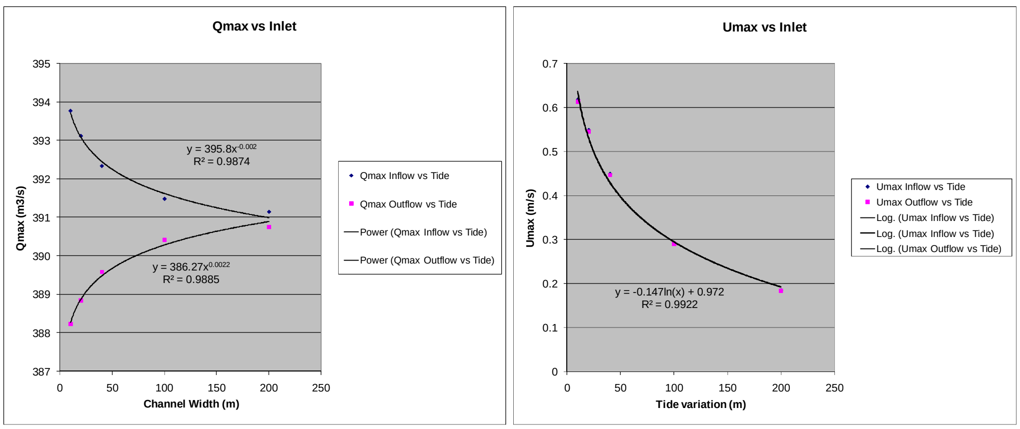


Figure 45 Maximum velocity and discharge of simple inlet width variation model

2. Concentration and Residence Time

The residence times for the simple inlet width variation model are constant at 28 hours. An output of the simple model indicates that there is no relationship between the inlet geometry is and the residence time.

5.4.2 Delft3D model output

1. Inlet

The hydrodynamic conditions are mostly similar to others variation except the tides variation model where the water level for all inlet geometries is almost constant. The velocities also reach the peak magnitude during the mean water level. In relation to the inlet width, velocity is reduced if the inlet is wider. At last, the concentration gradient is less steep in the wider inlet.

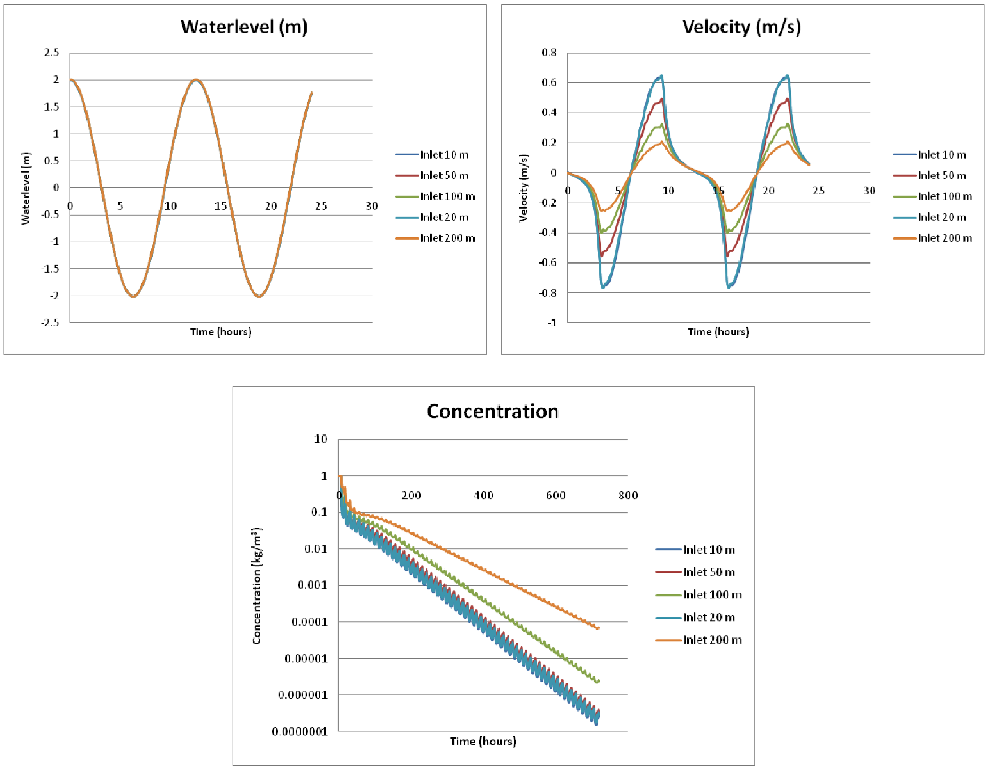


Figure 46 Water levels, velocity and concentration rate at inlet observation point

2. Lagoon 1-1

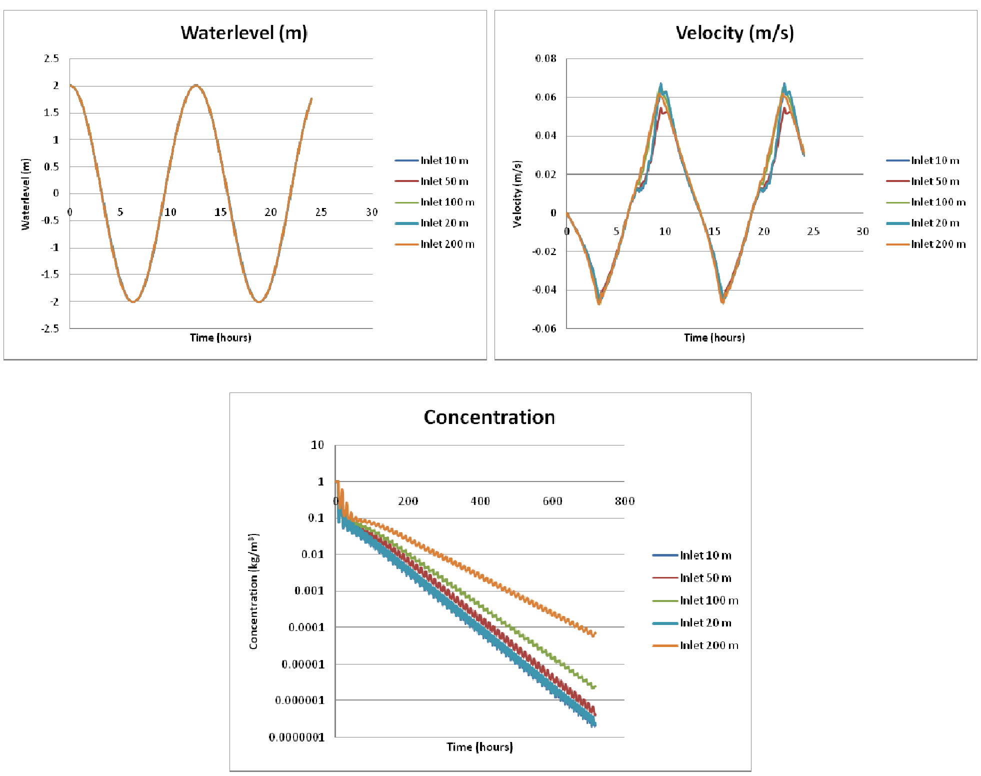


Figure 47 Water levels, velocity and concentration rate at lagoon 1-1 observation point

In this observation point, the water level is similar for all variations and the velocity reaches the peak magnitude during the mean water level. Different to the inlet observation point, the velocity almost does not depend on the inlet width because the velocity is almost constant. The concentration gradients are almost similar to the inlet points where the gradient is less steep when the inlet is wider.

3. Lagoon 4-2

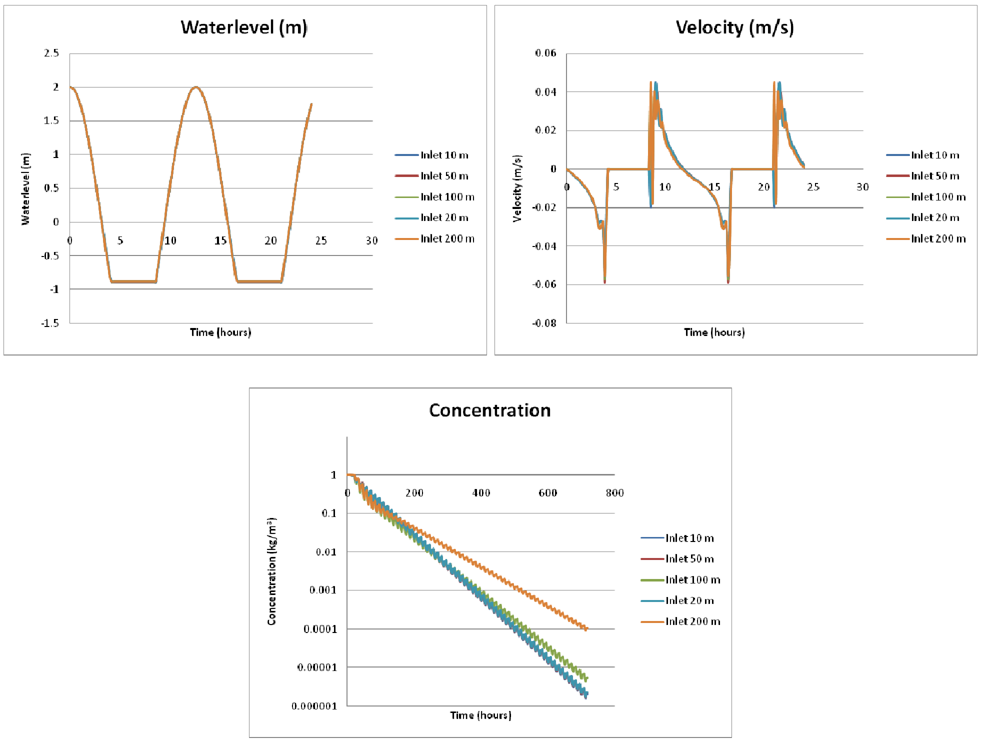


Figure 48 Water levels, velocity and concentration rate at lagoon 4-2 observation point

The water level is similar for all variations and the maximum velocity occurred during the mean water level. The maximum velocity in this point is only slightly less compare to the lagoon 1-1 observation point. During the low tide, the observation point is exposed because the water depth in this point is 0.8 m. The magnitude of velocity is almost constant which indicates that the velocity is not depending on the width of the inlet. The concentration gradient is less steep when the inlet is wider.

Table 11 Residence time of Delft3D inlet width variation model

Inlet width	Residence Time (hours)								
	Inlet			Lagoon 1-1			Lagoon 4-2		
	Initial	Transitional	Stable	Initial	Transitional	Stable	Initial	Transitional	Stable
(m)	(h)	(h)	(h)	(h)	(h)	(h)	(h)	(h)	(h)
10	17	56	53	17	56	53	56	56	53
20	17	56	56	17	56	56	56	56	56
50	17	63	53	18	67	56	59	56	56
100	18	77	63	19	77	63	43	59	63
200	19	125	83	20	111	83	50	77	83

During the initial period, the residence time is constant if the inlet width is less than 20 m. Residence time begin to increase slightly when the inlet is wider. The residence time is also incresed when the location is landward.

During the transitional period, the residence time is parallel to the inlet width but it is declining when it closer to the land. Because residence time is constant for all locations during the stable period, It indicates that there is no relationship between location and residence time.

5.4.3 Analysis & synthesis

Several different tides have shown the different hydrodynamics behaviour and residence time. It can be concluded that:

- According to the simple model output, the magnitudes of discharge are considered to be constant. The outflow and inflow are slightly increased and decreased when the inlet is wider. The velocity, either inflow or outflow, is reversible to the inlet width.
- The residence time is constant at 28 hours, according to the simple model simulation. It exhibits that there is no relationship between the inlet width and the residence time.
- According to the Delft3D model, the velocity is increase when the inlet is wider in the inlet observation point. The velocity is only slightly increased in the observation points inside the lagoon. It indicates that the wider inlet only affects the hydrodynamic conditions nearby the inlet and does not affect the overall system.
- The Delft3D model output shows that residence time is slightly increased when the inlet is wider. The residence time during the initial period is much smaller compared to the transitional and stable period.
- Hydrodynamic circulation is the main factor determining the concentration rate gradient and the residence time. Another factor which also has to be taken into account is the diffusivity.
- In the simple manual calculation, the residence time is constant. In contrast to the simple manual calculation, the residence time of the Delft3D model is slightly increase when the inlet is wider. The change of residence time is because the Delft3D model is considering the effect of diffusivity, while in the simple model, the diffusivity effect is neglected.
- Location of the observation point also determines the hydrodynamics, concentration rate and residence times. The locations close to concentration distinction line is more dynamic and result in less residence time.
- Compared to the tides and distance variation simulations (with an exception to coral reef crest distance of 500 and 700 m simulations), the residence time during the transitional period is far exceed during the stable period simulation.

5.5 Sea level rise impacts to circulation

In this particular model, the sea level rise scenario is developed for the maximum sea level rise prediction. According to the IPCC Third Assessment Report, the maximum sea level rise will be 14 cm in 2020, 36 cm in 2050 and 69 cm in 2080.

Two scenarios are made in this sensitivity. In first scenario, the sea level rise and the coral reef is not growing. In the second, the sea level rise is balanced with the coral reef growth. In the second scenario, the coral reef is growing at a rate of 10 mm per year linearly. The coral reef crest will increase 11 cm in 2020, 41 cm in 2050, and 71 cm in 2080.

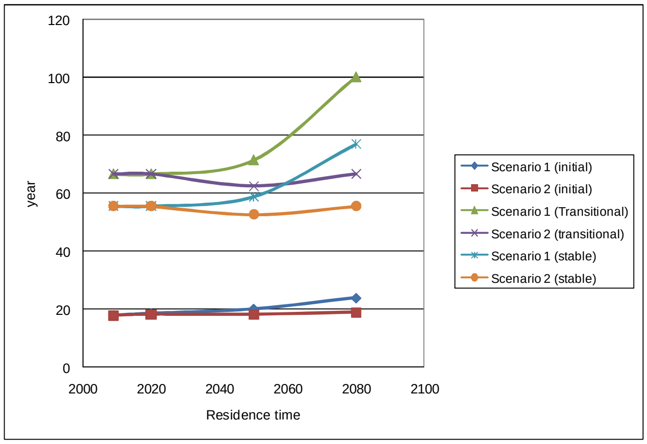


Figure 49 Comparison of scenario 1 and 2 at initial, transitional and stable conditions

The Delft3D model shows that the sea level rise will only slightly increase the residence time if the coral reef is not growing (scenario 1). In 2020, the residence time predicted to be similar as at present, while in 2050 and 2080 space it will raise about 5 % and 10 %.

In the second scenario where the sea level rise is balanced by coral reef growth, the residence time is almost constant.

Table 12 Residence time of Delft3D sea level rise model

	Residence Time (hours)								
	Inlet			Lagoon 1-1			Lagoon 4-2		
year	Initial	Transitional	Stable	Initial	Transitional	Stable	Initial	Transitional	Stable
(m)	(h)	(h)	(h)	(h)	(h)	(h)	(h)	(h)	(h)
Scenario 1 (Sea Level Rise)									
10	17	63	53	18	67	56	59	56	56
20	18	63	56	19	67	56	56	56	56
50	20	67	59	20	71	59	53	59	59
80	23	91	77	24	100	77	56	71	77
Scenario 2 (Sea Level Rise and Coral Reef Growth)									
10	17	63	53	18	67	56	59	56	56
20	17	63	53	18	67	56	56	56	56
50	17	59	53	18	63	53	50	53	53
80	19	63	56	19	67	56	45	56	56

With this result it can be conclude that sea level rise is not a threat to the residence time since it plays a far less important role compare to a tides, inlet geometry and lagoon geometry. Scenario 1 output shows that sea level rise out of balance by the coral reef growth has an identical impact with the increase of coral reef crest depth.

Sea level rise may have significantly more impact on the morphology and the erosions of land and lagoon instead affecting the residence time.

6. Discussion

This chapter is encompassing summaries the previous chapter and especially the last three chapters which describe the model set-up, comparison between simple and Delft3D model, and sensitivity analysis. The following questions are still need to be answered.

- Are the two models reliable?
- What are the advantages of the Delft3D model, which is more sophisticated, compare to the simple model? What is the disadvantage?
- Which parameters are important in determining the residence time of the coral reef and lagoon system?

6.1 Numerical model of coral reef and lagoon system.

The simple model only considers basin volume, gap, and the water level. Other important factors in this study such as coral reef crest depth, diffusivity, viscosity and friction are neglected in the simple model although they are relevant to this study.

The factors neglected in the simple model are introduced in the Delft3D model. Hence, the outcome of this model is more accurate and scientific. According to the output, the simple model indicates that the residence time is constant in respect to coral reef distance and inlet width. It means that there is no relationship between residence time to coral reef distance and inlet width. Based on the Delft3D model, the residence time is not constant but it changes slightly in respect to the coral reef distance and inlet width. At this point, it is very clear that the Delft3D model provides more accurate results although the process is more difficult and time consuming.

However, the simple model is powerful enough to provide an early estimation residence time in coral reef & lagoon system. The Delft3D model, which is more sophisticated and complex provides more detail and accuracy of the residence time estimation.

6.2 Sensitivity analysis

Parameters involved in the sensitivity analysis are tides, coral reef shape (represented as coral reef crest height), lagoon geometry (represented as coral reef crest distances), and inlet geometry. The study about sea level rise impact to the hydrodynamics and residence time of the coral reef and lagoon system completes the sensitivity analysis.

Both the simple and the Delft3D model indicate that the tides play an important role in the residence time. Both models indicate that the increase of the tides is significantly reduce the residence time.

In contrast to the tides, the coral reef crest depth, distance and inlet width plays less important role in determining the residence time. These only increase or reduce the residence time slightly. The coral reef crest depth and the inlet width have a similar behaviour related to the flow over the reef. When the flow over the reef is small, which is represented by the shallow coral reef crest depth and narrow inlet, the residence time tends to constant. If the coral reef crest is deeper and the inlet is wider, the residence time is slightly increased.

The coral reef distance sensitivity analysis is more related to comparison between the volume of the lagoon and the daily inflow. According to ATKINSON et al, 1981 residence time is parallel to the lagoon volume and inverse to the daily inflow. The output of the model has shown that the residence time is increased when the coral reef crest is farther away from land (lagoon volume is bigger).

According to the comparison of the velocity and discharges through the inlet (explained in chapter 4), the maximum velocity and discharge through the inlet is almost similar. The distinction between the simple and the Delft3D model is in the flow over the reef. In the simple model is assumed that there is no flow over the reef. But, in the Delft3D model, the flow over the reef is taken into account and contributes to the hydrodynamics circulation. The flow over the reef contributes the difference in the residence time for coral reef crest depth, distance and the inlet width variation model.

Table 13 Sensitivity analysis output

Parameters	Simple Model	Delft3D Model
Tides	Residence time is reverse to the tides	Residence time is reverse to the tides
Coral reef crest depth	(simple model not available)	- Depth less than 0.5 m: The residence times is almost constant or slightly increase in respect to the coral reef crest depth. - Depth above 0.5 m: The residence time is increase in respect to the coral reef crest depth.
Coral reef crest distance	Residence time is constant. No relation between the coral reef distance and the residence time	- Distance less than 1500 m: The residence time is decrease in respect to the coral reef crest depth. - Distance more than 1500 m: The residence time is increase in respect to the coral reef crest depth.
Inlet width	Residence time is constant. No relation between the inlet width and the residence time	- Inlet width less than 20 m: The residence times is almost constant or slightly increase in respect to the coral reef crest depth. - Inlet width more than 20 m: The residence time is increase in respect to the coral reef crest depth.

It can be concluded that tide is the most influencing factor determining the residence time. Coral reef crest depth, distance and inlet width determine the residence time for less compared to tides. This result indicates that the residence time is highly determined by natural phenomena. To change the residence time by cut or growth the coral reef crest, or change the inlet size is possible to change the residence time in a limited magnitude.

The sea level rise, if not balanced with the coral reef growth, increases the residence time. If the coral reef can balance the sea level rise in an equal magnitude, the residence time is possibly constant. It is difficult to maintain coral reef growth because the existing study of the coral reef growth is limited.

6.2 Synthesis application

The lagoon between the coral reef and land is a subject of landward threat. Various pollutants from landward such as sewage, industrial and commercial waste come and stay temporarily in the lagoon. If the pollutant is not flushed away soon, it may settle and disadvantage many aspects.

If the residence time is small, the pollutant might be flushed away soon before it settles in the lagoon. But if the residence time is long, the pollutant will be a problem. One of many solutions is to reduce the residence time of the coral reef and lagoon system. Unfortunately, the residence time is highly determined by natural phenomena, and hard to reduce with an engineering approach. Growing the coral reef or decreasing the inlet width may reduce the residence time in a limited magnitude.

However, it is urgent to have a comprehensive multi-disciplinary analysis consisting approach of engineering, environmental and financial analyses to solve problems. Another solution offered is to do nothing in an engineering approach, but prevent the pollution from landward by formulating an environmental policy.

7. Conclusions and recommendations

7.1 Summary of results

A Coral reef and lagoon system is an integrated system which contains a highly diverse ecosystem that provides foods, income, and coastal protection. Unfortunately this system is challenged by multiple natural and anthropogenic threats from both land and sea. The residence time is important in predictions of how long a pollutant will stay inside the lagoon before being flushed away.

To study residence time either physical or numerical modelling is possible. In this study, a simple model and the Delft3D model have been used. The simple model that considers less parameter is easier and takes less time. The Delft3D model is more sophisticated with more parameters involved.

The simple model utilizes the simple harmonic equation to analyze the tides. The water level which is an output of harmonic equations is the basic information for the storage area approach. The storage area approach is used to analyze the hydrodynamics, and a simple concentration exponential equation is used to determine the residence time of pollutant in the coral reef & lagoon system. A step by step approach is followed in the simple model with each step being linked to the next.

The Delft3D model is based on several hydraulic equations such as the momentum equation, hydrostatic pressure equation and continuity equation. Compared to the simple model, more parameters are involved. The outputs are obtained directly after the running process is completed.

Compared to the Delft3D model, the simple model output may be less accurate, but it can be utilized for preliminary prediction and as a calibration of the Delft3D model. The outputs of the Delft3D model are probably more realistic and accurate. However, the process is more difficult and takes longer. It can be concluded that both models – the simple and the Delft3D model, produce unique outputs. In some case, for example the velocity through the inlet, the results from both models are identical. But in other cases, for example the residence time in lagoon and inlet geometry variations, the output is different.

From the sensitivity analysis, it can be concluded that the residence time is significantly determined by tides. The coral reef crest depth, lagoon geometry and inlet geometry influence the residence time to a lesser degree but still have to be taken into account. Wave, wind, or a combination of tides, wave and wind maybe play an important role in determining the residence time.

Sea level rise plays a less important role compared to tides, coral reef depth, and lagoon and inlet geometry. But it still influences the residence time if it is not balanced by the growth of the coral reef. According to the model, if the sea level rise is not balanced by the growth of the coral reef, the residence time is predicted to increase by up to 25% in 2080. If the sea level rise is balanced by a coral reef growth of 1 cm per year, the residence time is predicted to remain constant or change slightly in future.

Natural and anthropogenic threats are the main threat to the health of lagoon fringed by a coral reef. The period for which a pollutant stays in the lagoon is highly dependent on the residence time. A longer residence time means the pollutant will stay longer at the lagoon. However, a shorter residence time is much better for contending with the threat of the pollutant.

According to the sensitivity analysis, the residence time is highly determined by the tides. Waves may also be important in determing the residence time. On the other hand, the inlet geometry, coral reef crest depth and lagoon geometry play a significantly less role compared to tides. This means that natural phenomena are important in determining the residence time. With regard to the pollutant inside the lagoon, it is really difficult to solve the problem because a change in the inlet geometry, coral reef crest depth and lagoon geometry does not significantly change the residence time.

7.2 Recommendation

Recommendations for further numerical modelling study include:

- Changing the coral reef into a more representative model instead of bathymetry. The coral reef could possibly be represented by a certain friction coefficient.
- Water circulation in the coral reef and lagoon is also influenced by wind, and over the reef flow. Further studies which consider wind and over the reef flow are suggested.
- A sensitivity analysis of wind and wave induced residence time of coral reef and lagoon system.
- A sensitivity analysis that combines tides, wind and waves of determining residence time
- A sensitivity analysis of various oblique incoming waves in determining residence time
- Some of the coral reef are located in diurnal tides area. A simulation of diurnal tides condition is suggested.
- A study about wave dissipation in the coral reef crest.

Recommendations for physical modelling and field measurement related study are:

- Comparison between the computational model output to the physical model output to study the power of Delft3D in modelling the coral reef & lagoon system.
- Calibration of the numerical modelling using field measurements and the physical modelling.

Preferences

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Appendix A – Numerical Model Conditions and Assumptions

For using Delft3D-FLOW the following utilities are important:

- Delft3D-RGFGRID and Delft3D-QUICKIN to provide the grid, bathymetry, and initial file for water level, velocity and concentration.
- Delft3D-QUICKPLOT to extract the output of the model.

b. Boundary Conditions

- The tides are 2 m and assume to be **semidiurnal** with **period of 12,5 hours** (Frequency : 360/12.5 = 28.8 deg/hour)
- Transport condition is set to be **constant** because the study is not focused on the sediment transport and morphology. (Thatcher-Harleman time lags for both surface and bottom are set to be 0)
- West border of the model is assumed to be open offshore. The open boundary (quantity) of open offshore in the west in Delft 3D are assumed to be "**Water Level"** with **'Harmonic'** tide variation.
- Thatcher-Harleman time lag for transport condition is 60 minutes. (see chapter 3.3)

c. Initial conditions

The initial conditions for water level is depend on the tides, which is set to be maximum tide level at the initial.

d. Processes

Constituents for the model (**Sediments, Salinity**, **temperature** & **pollutant)** are neglected since it is not relevant to the study.

The main consideration of the model is **tides**. **Winds**, **waves** and **secondary flows** are neglected. Man made process, such as **dredging** and **pumping,** is also neglected.

e. Physical parameters

- **Constants**: **Gravity** is 9.81 m/s2 and **water density** is 1025 kg/m3 (ocean salt water)
- **Bottom roughness**, Formula: **Manning**, with uniform values of u = 0.035 and v = 0.035). While, slip condition of wall roughness is free.
- Viscosity is set to be uniform with horizontal **eddy viscosity** of 10 m^2/s
- Horizontal Diffusivity is set to be uniform with horizontal **eddy diffusivity** is 0.1 m^2/s (see chapter 3.3)

f. Time-step

The time-step chosen for the model is 0.05 minutes (see sub-chapter 3.2.3 for detail)

g. Threshold Depth

The threshold depth is 0.0058 m (see chapter 3.2.3 for detail)

Appendix B – Delft3D-Flow Governing Equation

B1 Hydrodynamic equations

1. Coordinates
   The coordinates system used in this study is cartesian co-ordinateds (ξ,η)

2. Continuity equation
   The depth-averaged continuity equation is given by:

$$\frac{\partial \zeta}{\partial t} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \left[(d+\zeta) U \sqrt{G_{\eta\eta}} \right]}{\partial \xi} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \left[(d+\zeta) U \sqrt{G_{\xi\xi}} \right]}{\partial \eta} = Q$$

With Q representing the contributions per unit area due to the discharge withdrawal of water, precipitation and evaporation

$$Q = H \int_{-1}^{0} (q_{in} - q_{out}) d\sigma + P - E$$

Where q_{in} and q_{out} are the local source and sink water per unit volume. P is the non-local source term of precipitation and E non-local sink term due to evaporation.

3. Momentum equation in horizontal direction
   The momentum equation in ξ and η directions are:

$$\frac{\partial u}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}} \frac{\partial u}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}} \frac{\partial u}{\partial \eta} + + \frac{\omega}{d+\zeta} \frac{\partial u}{\partial \sigma} - \frac{v^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\eta\eta}}}{\partial \xi} +$$

$$\frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} - fv = -\frac{1}{\sqrt{G_{\xi\xi}}\rho_0} P_\xi + F_\xi + \frac{1}{(d+\zeta)^2} \frac{\partial}{\partial \sigma}\left(\upsilon_v \frac{\partial u}{\partial \sigma} \right) + M_\xi$$

And

$$\frac{\partial v}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}} \frac{\partial v}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}} \frac{\partial v}{\partial \eta} + + \frac{\omega}{d+\zeta} \frac{\partial v}{\partial \sigma} - \frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\eta\eta}}}{\partial \xi} +$$

$$\frac{u^w}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} - fu = -\frac{1}{\sqrt{G_{\eta\eta}}\rho_0} P_\eta + F_\eta + \frac{1}{(d+\zeta)^2} \frac{\partial}{\partial \sigma}\left(\upsilon_v \frac{\partial v}{\partial \sigma} \right) + M_\eta$$

Where P_ξ and P_η represent the pressure gradients, F_ξ and F_η is the forces represent the unbalance of horizontal Reynolds stresses, M_ξ and M_η represent the contributions due to external withdrawal of water, wave stresses, etc.

4. Eddy-viscosity
   The horizontal eddy-viscosity coefficient defined by:

$$\upsilon_H = \upsilon_{SGS} + \upsilon_{3D} + \upsilon_H^{back}$$

   And the vertical eddy-viscosity is defined by:

$$\upsilon_V = \upsilon_{mol} + \max(\upsilon_{3D}, \upsilon_V^{back})$$

5. Eddy-diffusivity
   The horizontal eddy-diffusifity coefficient defined by:

$$D_H = D_{SGS} + D_{3D} + D_H^{back}$$

   And the vertical eddy-viscosity is defined by:

$$D_V = D_{3D} + \frac{\upsilon_{mol}}{\sigma_{mol}}$$

B2 Boundary conditions

The zero order boundary condition which called Riemann invariants for the linearized 1D equation normal to the open boundary:

$$R = U \pm 2\sqrt{gH}$$

The linearized Riemann invariant is:

$$U \pm 2\sqrt{gH} = U + 2\sqrt{g(d+\zeta)} \approx U + 2\sqrt{gd} + \zeta\sqrt{\frac{g}{d}}, \frac{|\zeta|}{d} << 1$$

The boundary conditions used in this study is water level., hence $\zeta = F_\zeta(t)$

Appendix C – MDF File Example

```
Ident = #Delft3D-FLOW  .03.02 3.39.28#
Commnt=
Filcco= #..\Quickin\Model2.grd#
Fmtcco= #FR#
Anglat=  0.0000000e+000
Grdang=  0.0000000e+000
MNKmax= 92 112 1
Thick =  1.0000000e+002
Commnt=
Fildep= #..\Quickin\depth50m.dep#
Fmtdep= #FR#
Commnt=
Commnt=                              no. dry points: 0
Commnt=                              no. thin dams: 0
Commnt=
Itdate= #2009-04-02#
Tunit = #M#
Tstart=  0.0000000e+000
Tstop =  4.3200000e+004
Dt    = 0.5
Tzone = 0
Commnt=
Sub1  = #    #
Sub2  = # C #
Namc1 = #tracers1            #
Commnt=
Wnsvwp= #N#
Wndint= #Y#
Commnt=
Commnt=                              initial conditions from initial
conditions file
Filic = #..\Quickin\concentration.ini#
Fmtic = #FR#
Commnt=
Commnt=                              no. open boundaries: 1
Filbnd= #t2m.bnd#
Fmtbnd= #FR#
FilbcH= #t2m.bch#
FmtbcH= #FR#
FilbcC= #t2m.bcc#
FmtbcC= #FR#
Rettis=  6.0000000e+001
Rettib=  6.0000000e+001
Commnt=
Ag    =  9.8100000e+000
Rhow  =  1.0250000e+003
Alph0 = [.]
Tempw =  1.5000000e+001
Salw  =  3.1000000e+001
Rouwav= #    #
Wstres=  6.3000000e-004  0.0000000e+000  7.2300000e-003
1.0000000e+002
Rhoa  =  1.0000000e+000
Betac =  5.0000000e-001
Equili= #N#
Tkemod= #           #
Ktemp = 0
Fclou =  0.0000000e+000
Sarea =  0.0000000e+000
Temint= #Y#
```

```
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Roumet= #M#
Ccofu =  3.5000000e-002
Ccofv =  3.5000000e-002
Xlo   =  0.0000000e+000
Vicouv=  1.0000000e+001
Dicouv=  1.0000000e-001
Htur2d= #N#
Irov  = 0
Commnt=
Iter  =      2
Dryflp= #YES#
Dpsopt= #MAX#
Dpuopt= #MOR#
Dryflc=  1.0000000e-001
Dco   = -9.9900000e+002
Tlfsmo=  6.0000000e+001
ThetQH=  0.0000000e+000
Forfuv= #Y#
Forfww= #N#
Sigcor= #N#
Trasol= #Cyclic-method#
Momsol= #Cyclic#
Commnt=
Commnt=                              no. discharges: 0
Commnt=                              no. observation points: 23
Filsta= #t2m.obs#
Fmtsta= #FR#
Commnt=                              no. drogues: 0
Commnt=
Commnt=
Commnt=                              no. cross sections: 4
Filcrs= #t2m.crs#
Fmtcrs= #FR#
Commnt=
SMhydr= #YYYYY#
SMderv= #YYYYYY#
SMproc= #YYYYYYYYYY#
PMhydr= #YYYYYY#
PMderv= #YYY#
PMproc= #YYYYYYYYYY#
SHhydr= #YYYY#
SHderv= #YYYYY#
SHproc= #YYYYYYYYYY#
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PHhydr= #YYYYYY#
PHderv= #YYY#
PHproc= #YYYYYYYYYY#
PHflux= #YYYY#
Online= #N#
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Flmap =  0.0000000e+000 20  4.3200000e+004
Flhis =  0.0000000e+000 10  4.3200000e+004
Flpp  =  0.0000000e+000 1440  0.0000000e+000
Flrst = 1440
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Commnt=
```
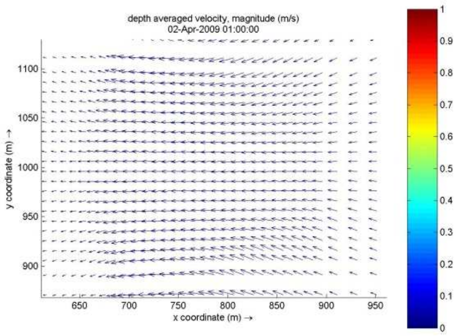
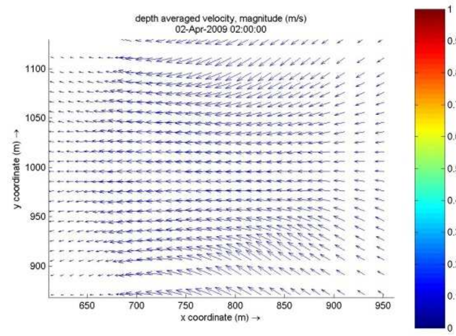
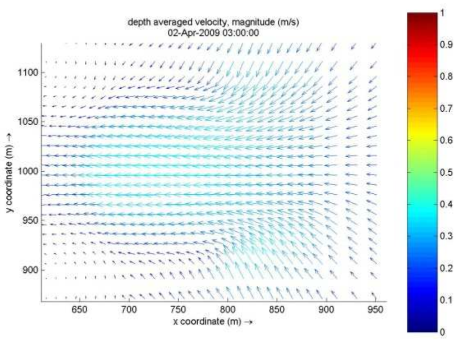
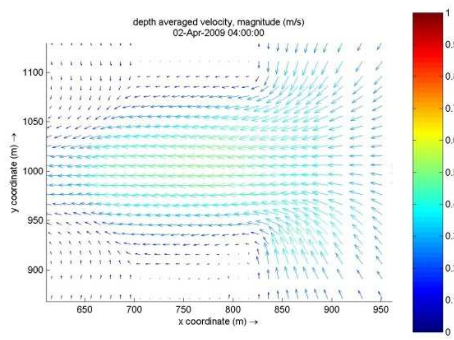

Appendix D – Velocity Distribution

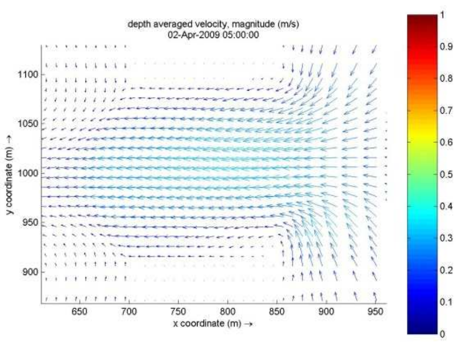
1. Inlet

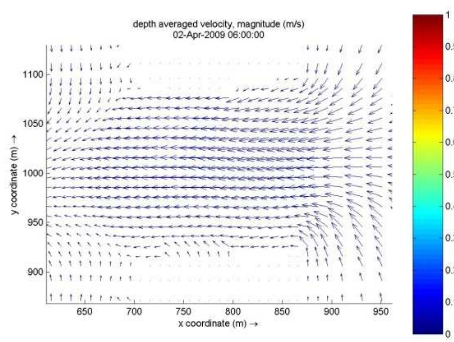


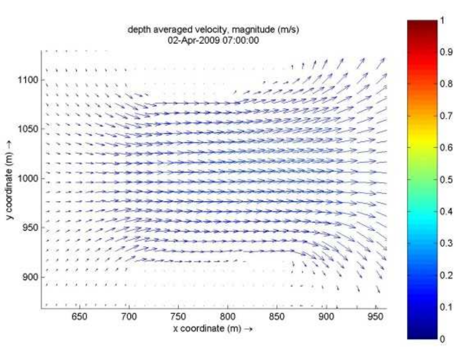


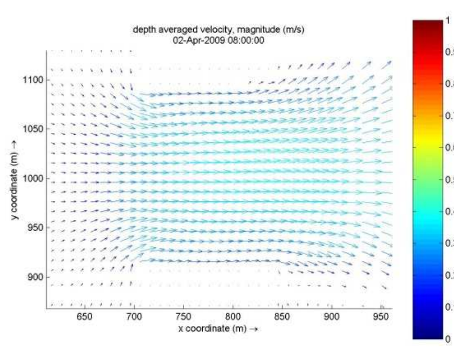


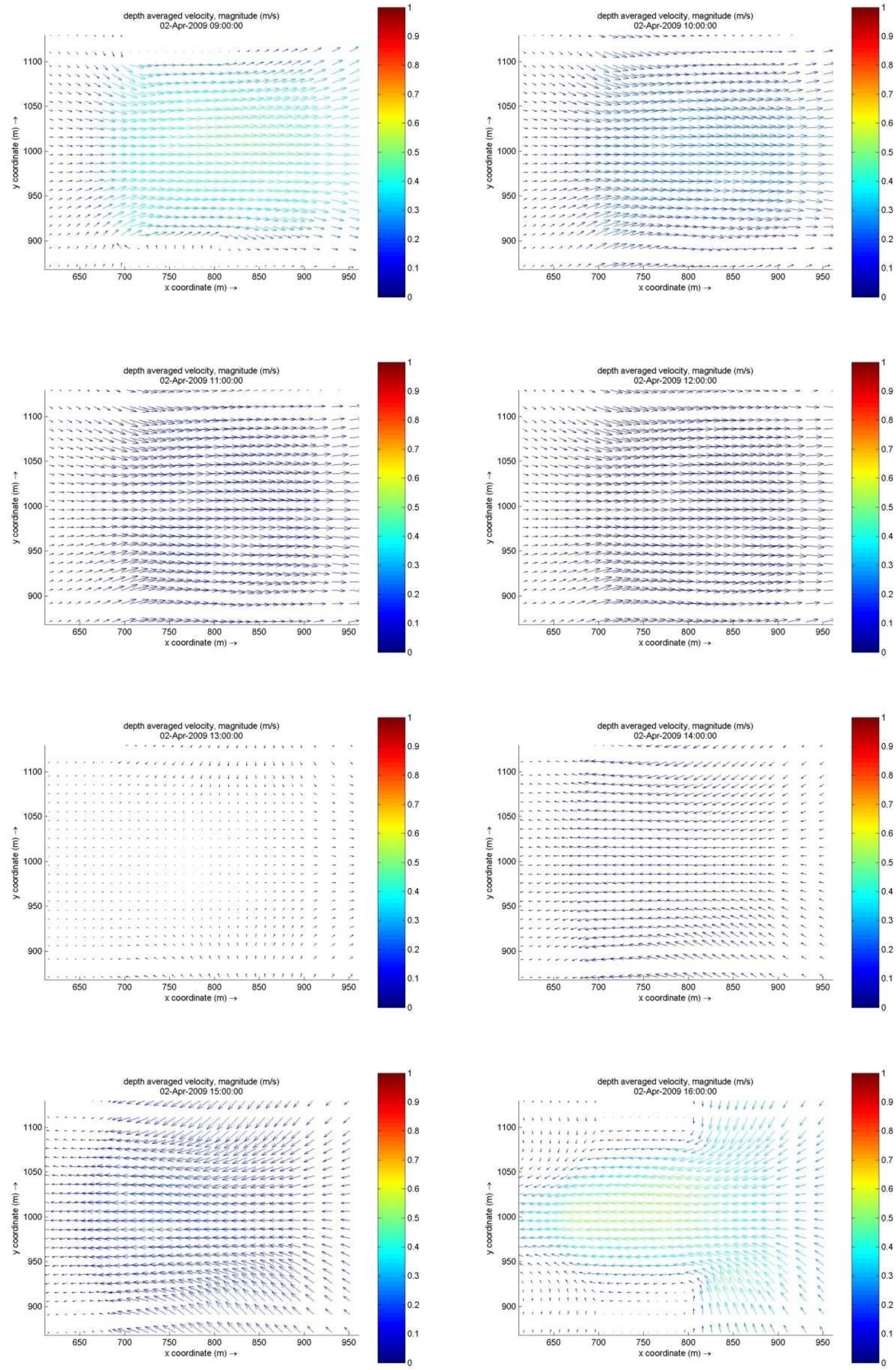








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depth averaged velocity, magnitude (m/s)
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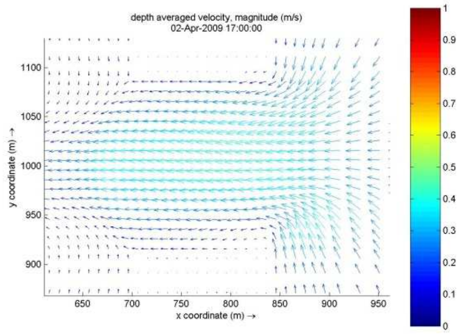
y coordinate (m) →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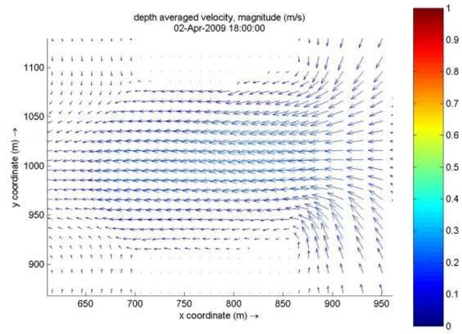
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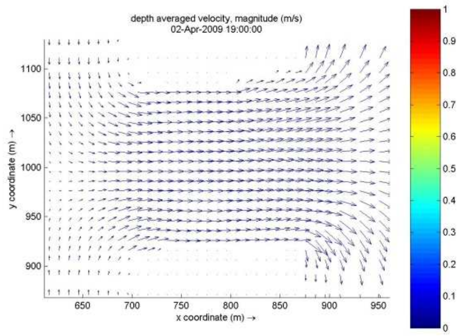
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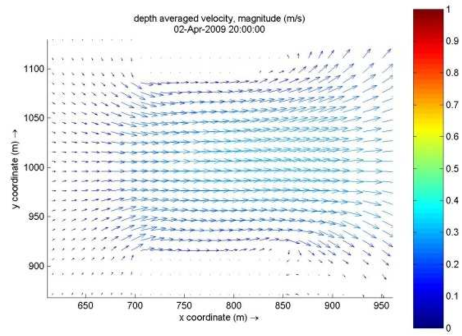
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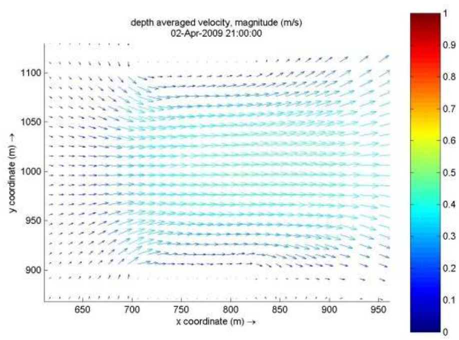
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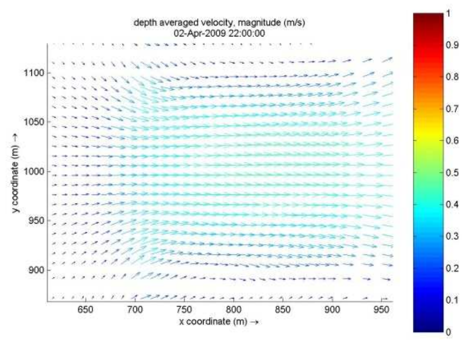
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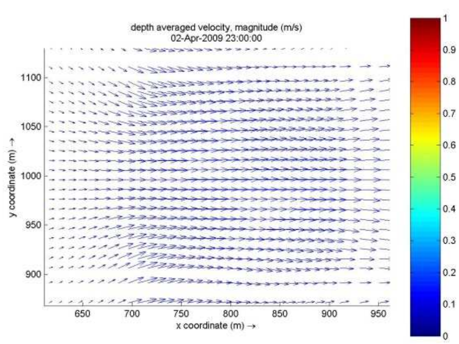
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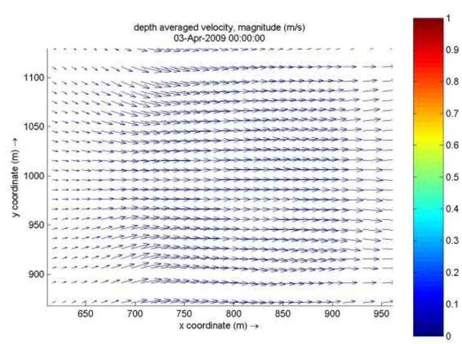
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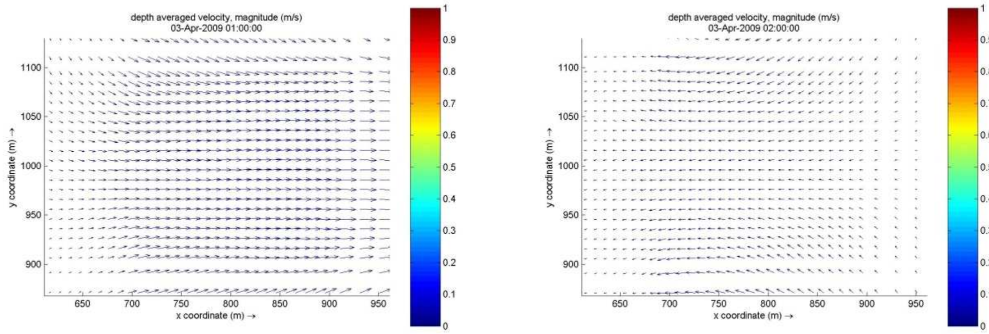
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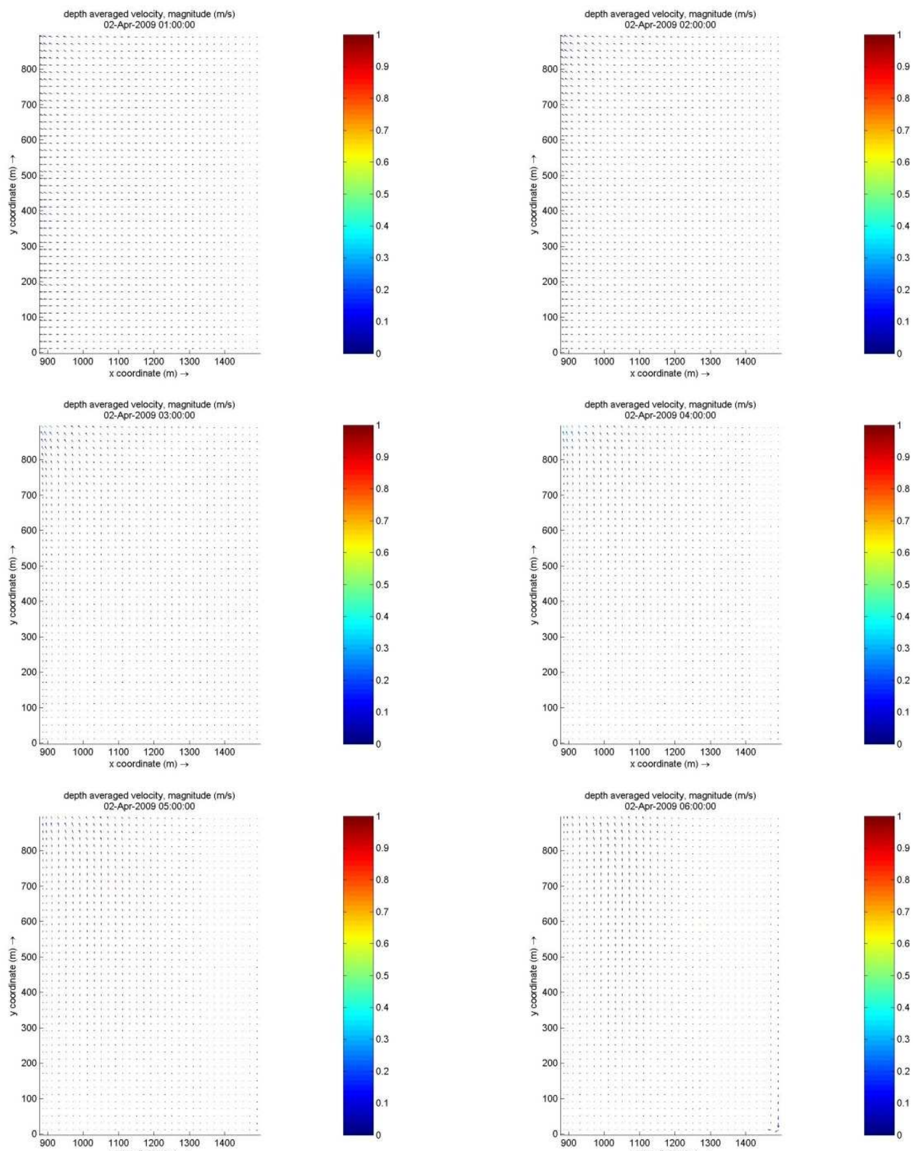
2. Lagoon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depth averaged velocity, magnitude (m/s)
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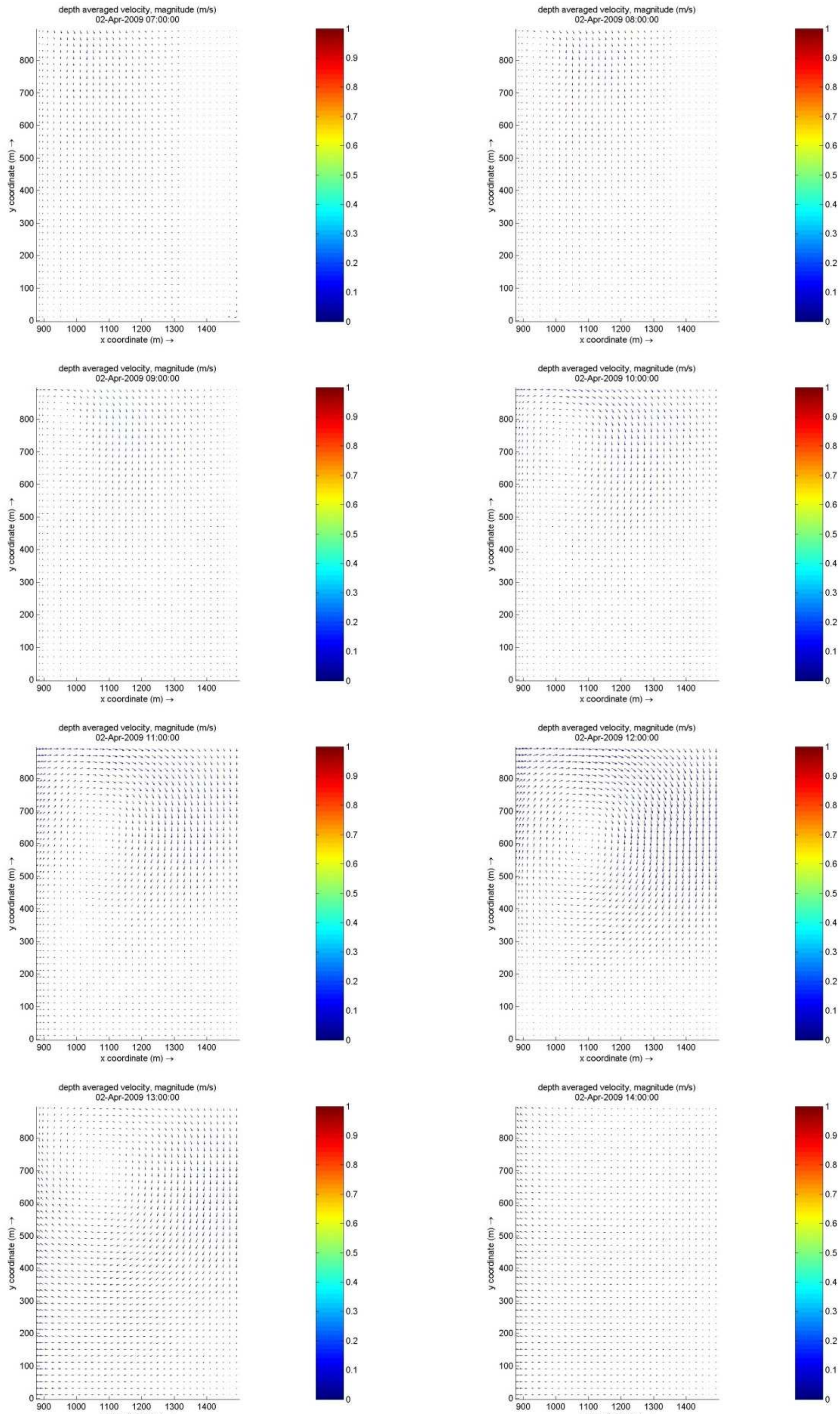
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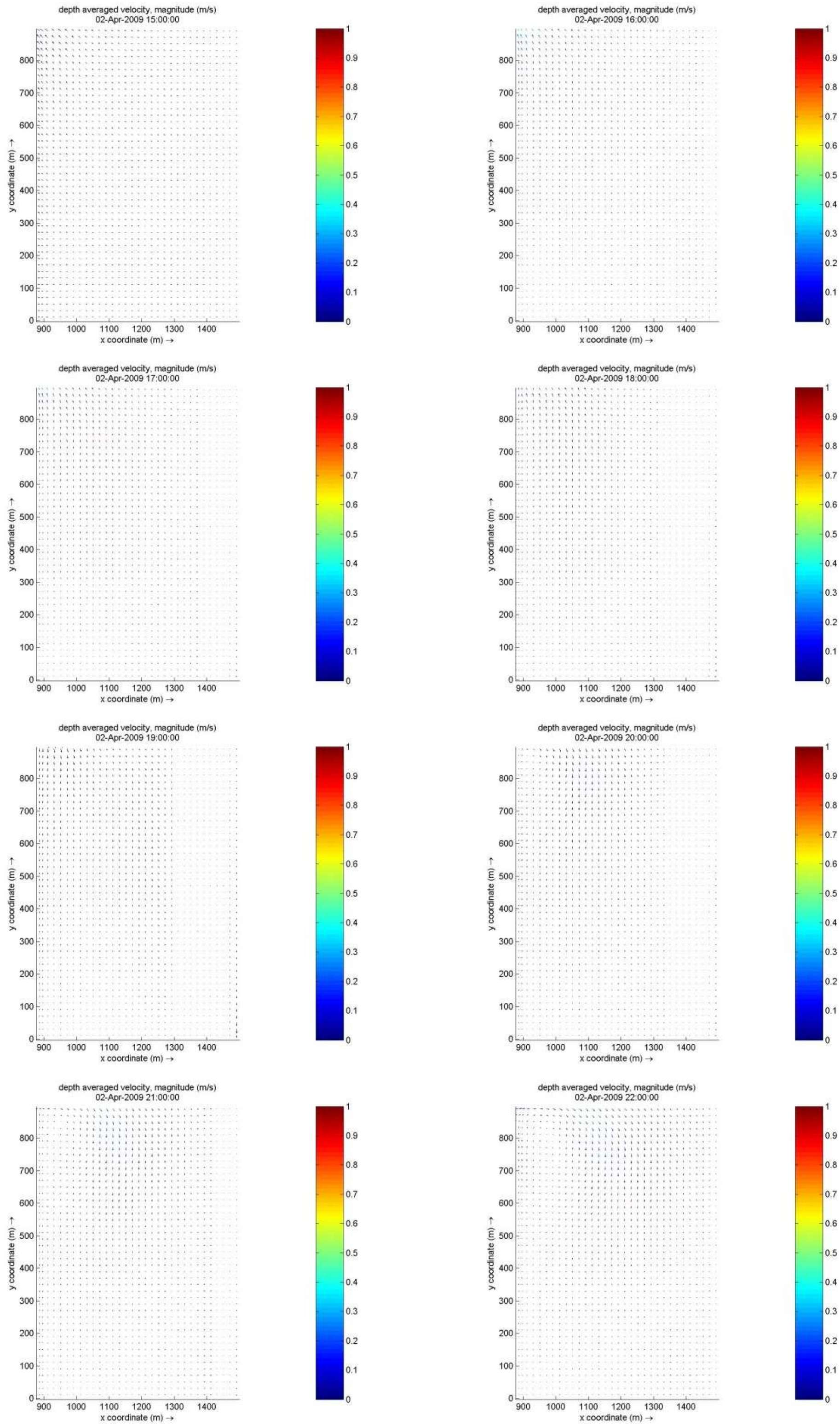
x coordinate (m) →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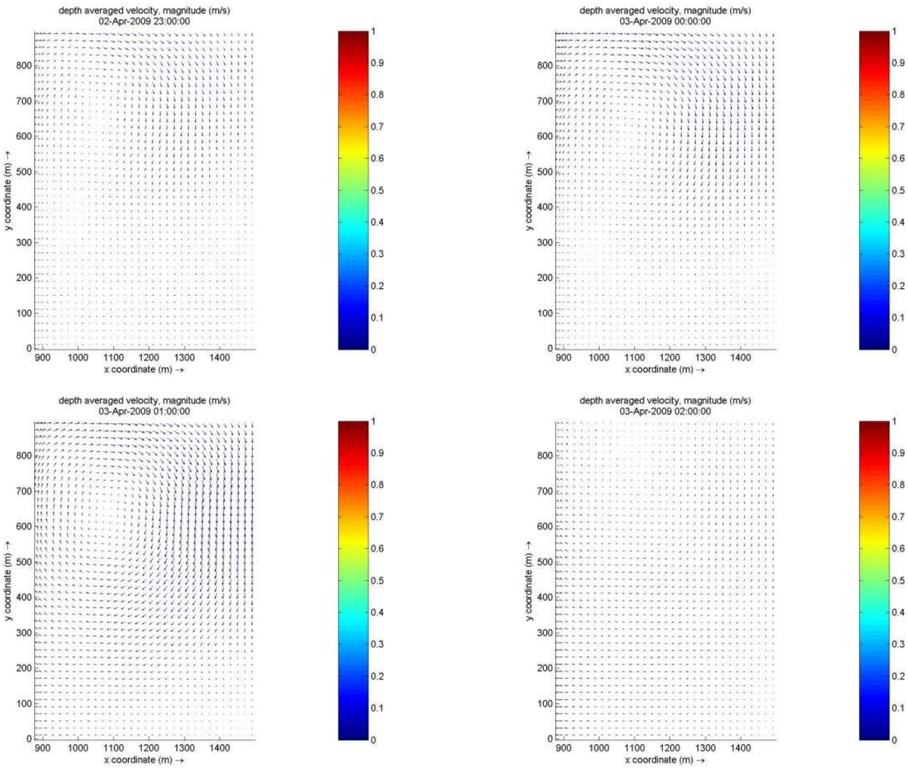
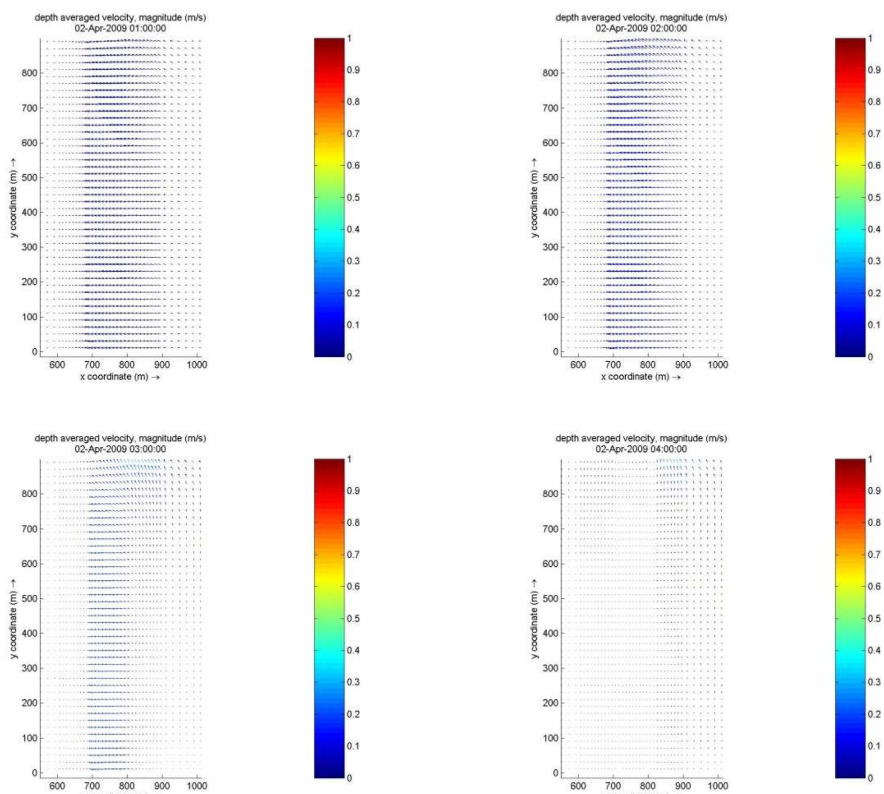
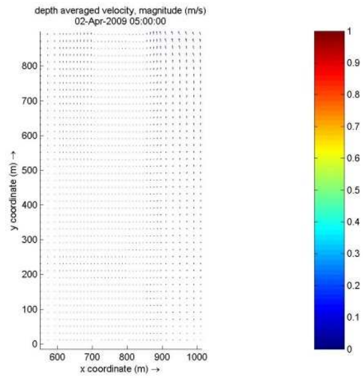


3. Coral Reef Crest

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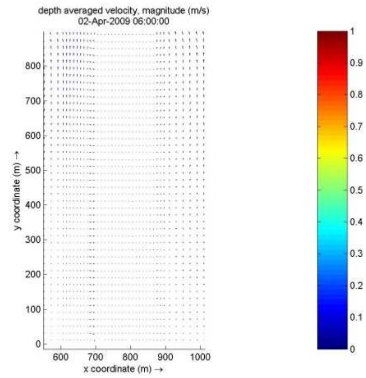
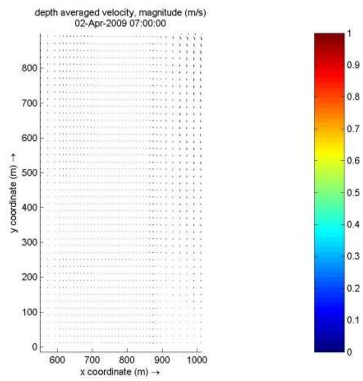
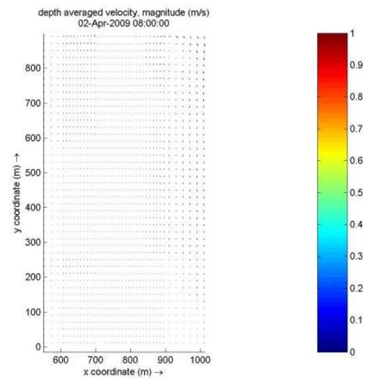
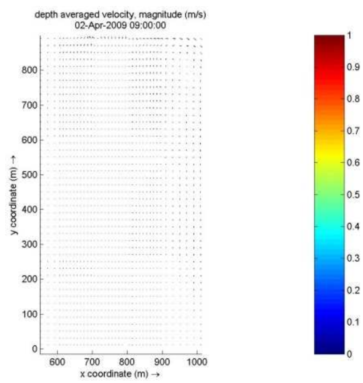
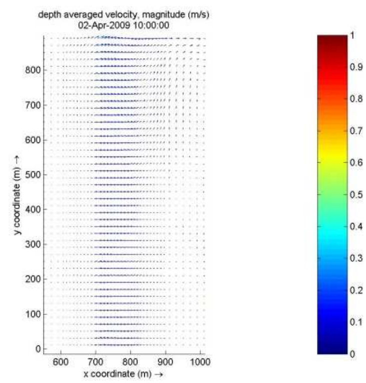
y coordinate (m) →
x coordinate (m) →

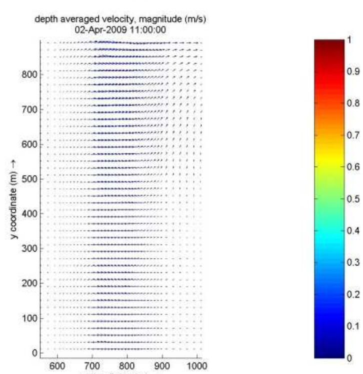

depth averaged velocity, magnitude (m/s)
02-Apr-2009 06:00:00
y coordinate (m) →
x coordinate (m) →

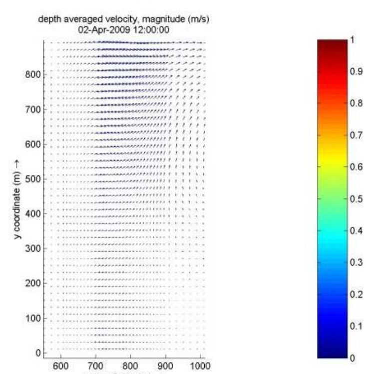

depth averaged velocity, magnitude (m/s)
02-Apr-2009 07:00:00
y coordinate (m) →
x coordinate (m) →

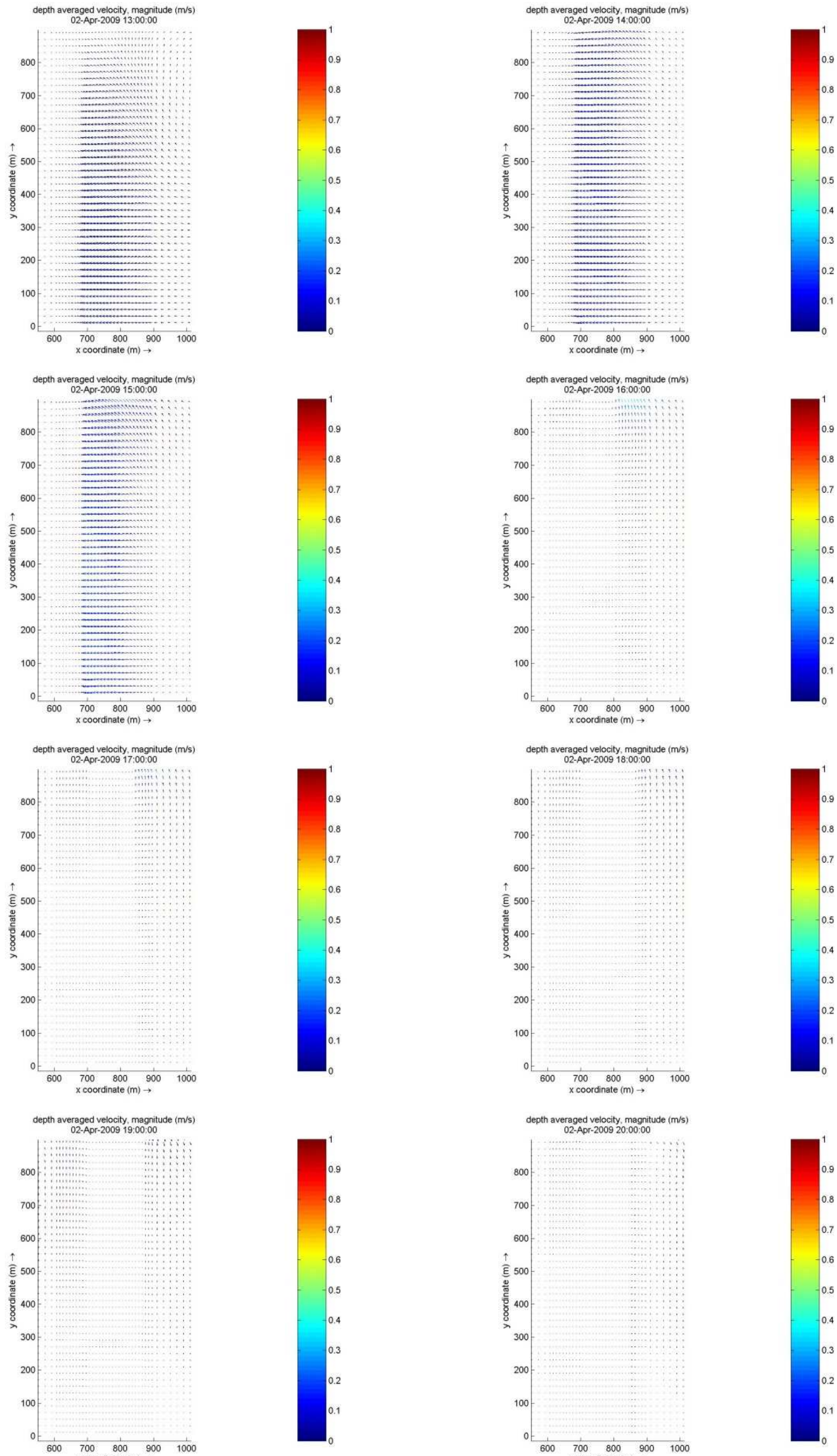

depth averaged velocity, magnitude (m/s)
02-Apr-2009 08:00:00
y coordinate (m) →
x coordinate (m) →

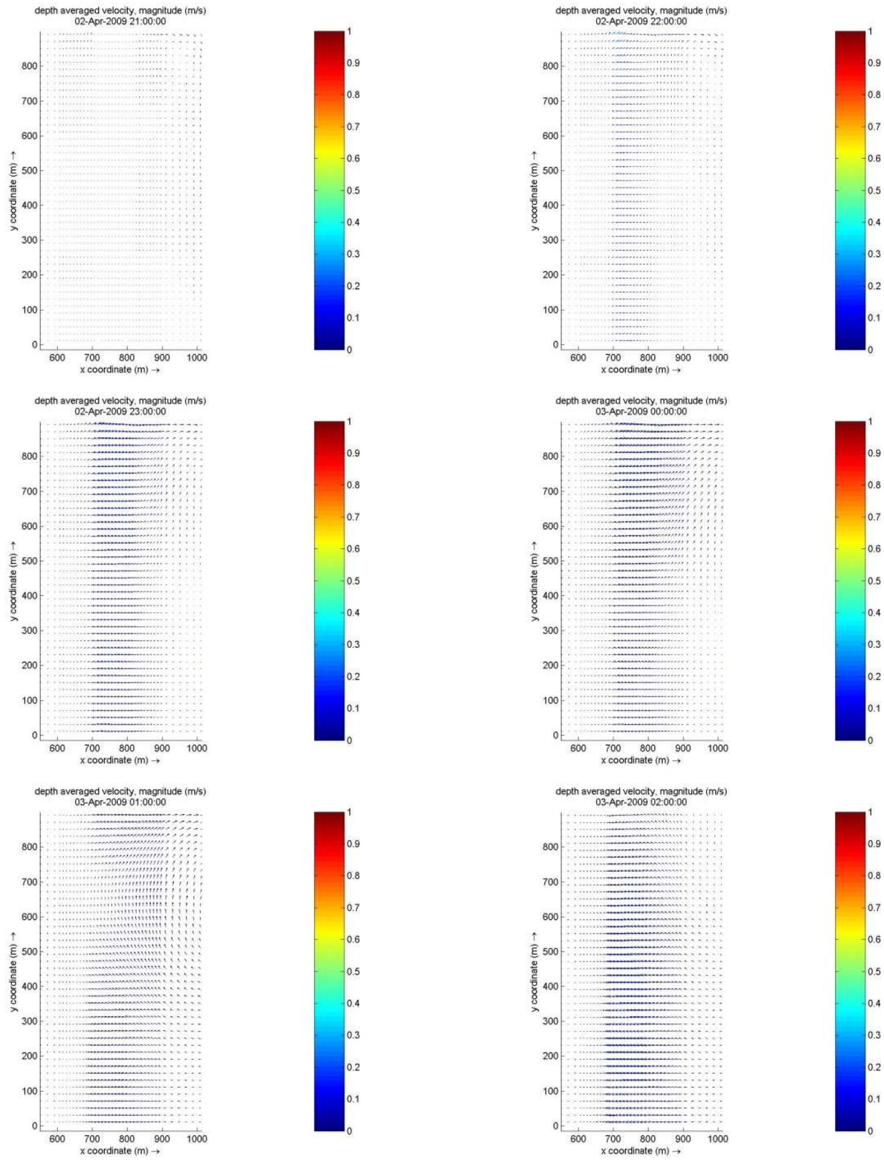

depth averaged velocity, magnitude (m/s)
02-Apr-2009 09:00:00
y coordinate (m) →
x coordinate (m) →


depth averaged velocity, magnitude (m/s)
02-Apr-2009 10:00:00
y coordinate (m) →
x coordinate (m) →


depth averaged velocity, magnitude (m/s)
02-Apr-2009 11:00:00
y coordinate (m) →
x coordinate (m) →


depth averaged velocity, magnitude (m/s)
02-Apr-2009 12:00:00
y coordinate (m) →
x coordinate (m) →


depth averaged velocity, magnitude (m/s)
02-Apr-2009 13:00:00
depth averaged velocity, magnitude (m/s)
02-Apr-2009 14:00:00
depth averaged velocity, magnitude (m/s)
02-Apr-2009 15:00:00
depth averaged velocity, magnitude (m/s)
02-Apr-2009 16:00:00
depth averaged velocity, magnitude (m/s)
02-Apr-2009 17:00:00
depth averaged velocity, magnitude (m/s)
02-Apr-2009 18:00:00
depth averaged velocity, magnitude (m/s)
02-Apr-2009 19:00:00
depth averaged velocity, magnitude (m/s)
02-Apr-2009 20:00:00
x coordinate (m) →
y coordinate (m) →


depth averaged velocity, magnitude (m/s)
02-Apr-2009 21:00:00
depth averaged velocity, magnitude (m/s)
02-Apr-2009 22:00:00
depth averaged velocity, magnitude (m/s)
02-Apr-2009 23:00:00
depth averaged velocity, magnitude (m/s)
03-Apr-2009 00:00:00
depth averaged velocity, magnitude (m/s)
03-Apr-2009 01:00:00
depth averaged velocity, magnitude (m/s)
03-Apr-2009 02:00:00
y coordinate (m) →
x coordinate (m) →