Water quality modelling of a mangrove system in Singapore
Defining residence time inside Sungei Buloh Wetland Reserve

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ACKNOWLEDGEMENTS

This report contains research carried out as a requirement in the MSc-program Hydraulic Engineering and Water Resources Management. This double degree MSc-program is a joint effort between Delft University of Technology and National University of Singapore. The research focused on defining the residence time of soluble contaminants and assess its influencing factors. This research was carried out within the framework of the QRAM project, which is an integrated risk assessment of chemical contaminants in mangrove ecosystems. This project is conducted by the SDWA (Sustainable Development and Water alliance, previously known as Singapore-Delft Water Alliance), and the Tropical Marine Science Institute.

Fortunately, I received help when I needed it, as well as fine supervision. Firstly, I would like to thank Stéphane Bayen, Senior Research Fellow at SDWA, for his general supervision and nuanced opinion. Secondly, I would like to thank Jahid Hasan and Alamsyah Kurniawan, both researchers at SDWA as well, for their most practical help and advice for the model details and input. They know a lot about modelling and I would like to thank them again for sharing their knowledge with me. Thirdly, I would like to thank Lee Wei Kit for his friendly guidance through Sungei Buloh Wetland Reserve, explaining a lot about mangroves, about the area and about how field work is conducted there. Lastly, I would like to thank Professor Henk-Jan Verhagen to be willing to be the supervisor for TU Delft. He gave the green light for the project and had trust in it.

During the project I had the pleasure of working together with Yorick Broekema, also a student in the Double Degree Programme. Together we made the initial model adjustments that we would both use for our research questions, though in a different way. During the remainder of the project, he helped making the report set up and at the end he had read the whole report, correcting the necessary and adding valuable comments; not forgetting the numerous brain storm sessions we had.
ABSTRACT

Modelling contaminants in the Sungei Buloh Wetland Reserve using Delft3D-WAQ results in useful data on residence times. Since measurements in the field are often not possible due to either safety hazards or ecological implications, the water quality model provides comprehensive data to analyse the behaviour of flow and contaminants and with that the residence time of these contaminants.

The goal of this research was to define a workable definition of the residence time for contaminants in Sungei Buloh Wetland Reserve and to use Delft3D to identify several situations in which concentration would become dangerously high or remain high for an extended period of time, to start with a simple conservative substance.

The residence time is the time it takes for 95% of the mass input to leave the control region without returning at a later phase of the tide. The control region is defined as the Sungei Buloh Wetland Reserve, covering the wetland areas and channels and leaving out the sea.

In order to identify critical situations, several scenarios were set up and assessed for their influence on the flow of the contaminants. A conservative contaminant was modelled. The scenarios comprised several possible important tidal factors – release during high or lower water, spring or neap tide – and the importance of the entrance location of the contamination. In addition, the model representation of the vegetation was changed from the use of a higher Manning roughness value to the use of a directional point model.

The results show that in general, the residence time of contaminants is lower when the discharge happens with high water and during spring tide, while a discharge of contamination with low water and during neap tide increases the residence time. The use of the directional point model instead of an adapted Manning’s roughness representation generally decreases the residence times.

Although only a conservative tracer was modelled, it is possible to say something about other tracers by superposition of properties; interest in detailed behaviour of specific substances could demand further exploration of these substances though. The water quality model used in this research can be used for that.
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INTRODUCTION

1.1 CONTEXT

Recent importance has been placed on the ecological and socio-economic importance of mangroves for adjacent populations, in terms of food resources, employment and generation of income (e.g. tourism, fisheries). Besides direct clearance, hydrological alterations, climatic changes or insect infestations, chemical pollution could be a significant contributor of mangrove degradation. However, in Singapore, the pressure of chemical pollution on mangrove ecosystems is presently unknown. In March 2012, the National Parks Board and the National University of Singapore started a collaboration to conduct an ecological risk assessment with regards to both conventional an emerging contaminants. This study will support environmental policy makers and managers in their decision-making regarding mangrove ecosystems, and nearby coastal waters. The first results are conclusive, and regretfully, both conventional and new pollutants were detected in the mangrove environment of Singapore.

To understand chemical pollution in mangroves, the inputs and outputs of chemical contaminants in a model mangrove system (Sungei Buloh) are currently assessed. During a workshop recently organised, the question of residence time was raised by NParks. The question is how long a substance (considered mostly soluble) would remain in a specific part of the park before being flushed to the sea.

A pollutant mass balance was completed to estimate total pollutant loads entering and being retained in the Sungei Buloh mangrove system based on measured inflow concentrations and hydrodynamic modelling of tidal in- and outflows.

1.2 GOAL

This project comprises coming up with a workable definition for the residence time, working with Delft3D, amending the existing model to improve the model results and running wide-ranging scenarios. The goal is to gain a better understanding of residence time in order to identify critical situations that cause high concentrations of contaminants. Several parameters will be assessed and judged on their influence and an estimation of residence times of contaminants in Sungei Buloh Wetland Reserve will be made.

1.3 HYPOTHESIS

The residence time of water in a mangrove ecosystem, and indirectly a soluble chemical substance, depends on multiple factors, like tide, rainfall, season and numerical factors. Its definition needs to contain a time constraint.

1.4 SIGNIFICANCE

The park managers are very interested in the concept of residence time and want to know how they can use this to identify high risks. Chemical contamination could be a significant contributor of mangrove degradation. The pressure of chemical contamination simply does not depend on the average residence time though. For example, areas with low flow velocities are prone to sedimentation, hampering the leave of contaminants from the area. Puddles can warm up a lot and become a hotbed of undesired biological growth. And some areas are simply further away from the sea than others are. The complete picture is rather complex and covers the fields of chemistry, biology, water management and hydraulic engineering. This research will start with a simplified idea of that. The results can benefit park managers and policy makers and help them making the right decisions to protect valuable sources of life.
2 THEORETICAL BACKGROUND

A literature study on residence time has been performed. In this section, an overview of the most important aspects relevant for this report is given. These are the general definition, as well a more applicable definition for this research.

2.1 GENERAL DEFINITION

According to Merriam-Webster, residence time is the duration of persistence of a mass or substance in a medium or place. In science, there no uniform definition of residence time. Bolin (1972) said that the average transit time or residence time is the expected lifetime for newly incorporated particles. Zimmerman (1976) defined residence time as the time for each material element to reach the outlet and with that, it is the complement of the age (the time a material element has been in the system).

Basically, the chosen method dictates a certain type of definition. A traditional approach to residence times is to take a single value – usually an average – to characterise the complete system. A common definition of residence time is:

$$\tau = \frac{V}{Q}$$

In which $\tau$ is the residence time, $V$ the volume of the system and $Q$ the net discharge into the system. This method is fast for closed systems, but for open system like estuaries, it becomes less straightforward to define $V$ and $Q$. Also, the simplicity of the equation neglects all variability in space and time.

2.2 RE-ENTRANT TRACERS

Therefore, a workable definition of residence time is crucial in order to be able to calculate local residence times. In 1997, Oliveira and Baptista (1997) made a distinction between re-entrant tracers (particles are allowed to move in and out of the control region with the tidal forcing) and once-trough tracers (representing materials whose properties considerably change when outside the control region). They applied the following definitions:

Re-entrant tracers: *Individual residence times are defined as the time taken for the particle to leave the control region without returning at a later phase of the tide or at a later tidal cycle.*

Once-through tracers: *Individual residence times are defined as the first time the particle leaves the control region.*

In this research, we use the definition of Oliveira and Baptista for re-entrant tracers, adapted to a situation with continuous concentrations and mass:

*The residence time is defined as the time it takes for 95% of the mass input to leave the control region without returning at a later phase of the tide.*
3 HYDRODYNAMIC MODEL DESCRIPTION

The computational model used in this research is Delft3D. Delft3D is a modelling suite that is designed to simulate 2D or 3D flow, sediment transport and morphology, waves, water quality and ecology and is capable of handling interactions between these processes, either online or offline.

The modules used in this research are Delft3D-FLOW and Delft3D-WAQ. Delft3D-FLOW is a hydrodynamic and transport simulation program that calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a rectilinear or curvilinear boundary fitted grid. Delft3D-WAQ is a 3-dimensional water quality model framework that solves the advection-diffusion-reaction equation on a predefined computational grid and a wide range of model substances. Delft3D-WAQ is not a hydrodynamic model, so information on flow fields is derived from Delft3D-FLOW.

This research falls within a bigger research project, QRAM. This research started after the completion of QRAM Phase 1, the orientation phase. This means that the Sungei Buloh model that is run in Delft3D was already existent as a preliminary model. This model provided good results for the simulation of water levels in the Sungei Buloh area, but showed some instabilities on velocities. It is for this reason that first the QRAM Phase 1 model is updated with respect to grid and bathymetry to try to eliminate this unrealistic velocity patterns. After improving the QRAM Phase 1 model, vegetation is added using a separate vegetation module in Delft3D. Results of this runs are also used for the water quality module that is used to estimate residence times of contaminants.

This chapter contains the following sections:

- Properties of the QRAM Phase 1 model
- Adaptations to the QRAM Phase 1 model
- Hydrodynamic model summary
- Available data from measurements
- Water quality modelling: model input
- Water quality modelling: scenarios

3.1 PROPERTIES OF THE QRAM PHASE 1 MODEL

3.1.1 LOCATION

The Sungei Buloh Local Model (SBLM) that is used to provide hydrodynamic information to estimate the fluxes at the open sea boundary consists of the Sungei Buloh wetland area, channels and part of the Johor Strait. It extends from the Johor-Singapore causeway to the rivers in Johor and an open sea boundary next to Sarimbun Reservoir. See Figure 1 and Figure 2. Due to the limited size of the SBLM and the complicated tidal and seasonal interactions around Singapore, the model has been nested in a larger model. The model used for nesting is the Singapore Regional Model-A (SRMA), which was extensively validated during previous studies (for example Kurniawan, A., Ooi, S.K., Hummel, S., Gerritsen, H., 2011).
Figure 1 – Extent of the Sungei Buloh Local Model (in bright blue) embedded on a Google map. North is up.

Figure 2 – Area of interest embedded on a Google map: in white the (land) boundary of Sungei Buloh Wetland Reserve. North is up.
### 3.1.2 Model Set-Up

The grid used for SBLM consists of about 28100 grid cells, which range from sizes of 10 x 10 metres in the Sungei Buloh wetlands to 100 x 100 metres in the Johor Strait. A higher resolution is provided in the Sungei Buloh wetland to obtain detailed information of the hydrodynamics in this area.

The bathymetry of Johor Strait is taken from the SRMA. Bathymetry in the wetland is updated using data from a survey recently conducted by YJP Surveyor for NParks.

The SBLM has one open boundary, located on the west side of Johor Strait. This open boundary is a water level variation taken from the SRMA. The east side of Johor Strait is closed by the causeway.

Effect of (mangrove) vegetation in this model is taken into account by varying the roughness value. The roughness value is given by Manning’s coefficient and this varies from 0.03 in the channels to 0.06 in the (vegetated) wetlands.

To represent freshwater inflow from land, the model has four discharge points. The discharges are given as a time series, estimated from rainfall data. The location of the discharges is given in Figure 3. The model includes several observation points for monitoring and in order to estimate inflow and outflow rates for the mass balance, it also includes several cross-sections near the open water boundary of the Sungei Buloh Wetland Reserve. These are also depicted in Figure 3.

A summary of model parameters is given in Table 1.

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Number of grid cells</td>
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<tr>
<td>Grid cell size</td>
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<td>Time zone</td>
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<tr>
<td>Initial condition</td>
<td>Mean Sea Level at 0 m</td>
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<td>Boundaries</td>
<td>Water level time series from SRMA</td>
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<td>Gravity</td>
<td>9.81 m/s²</td>
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<td>Water density</td>
<td>1000 kg/m³</td>
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<td>Roughness</td>
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<td>Uniform horizontal eddy viscosity of 1 m²/s</td>
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<td>Advection scheme for momentum</td>
<td>Flood</td>
</tr>
<tr>
<td>Fresh water discharges</td>
<td>4 locations</td>
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3.2 ADAPTATIONS TO THE QRAM PHASE 1 MODEL

To improve model performance several adaptations have been made to the model as described in section 3.1. These adaptations are stated in this section. This section will be concluded by a table that summarizes the different parameters for the QRAM Phase 1 model and the improved model.

3.2.1 GRID

In an early run of the model, instabilities were observed in the velocity pattern. The first attempt to get rid of these instabilities, is improving the grid. Ideally, it should align with the flow directions in the Sungei Buloh Wetlands. In order to achieve this, the part of the grid representing the Sungei Buloh Wetland Reserve is cut from the SBLM grid, receiving a complete redesign and is pasted to the remaining part of the SBLM grid again.

However, because of the complex alignment of the channels this proved to be very difficult, especially because the part of the new grid that connected to the Johor Strait had to keep the same alignment for a smooth transition between the original part of the grid and the new part.

Figure 4 to Figure 8 show the grid and its properties for the QRAM Phase 1 grid on the left and for the new grid on the right. Only the part of the grid covering the Sungei Buloh Wetland Reserve area is depicted, since the other parts have not changed. From Figure 4, the design philosophy becomes clear: starting from the upper part, the grid should curve as soon as possible, so that the grid aligns with the channels in either M or N direction (the two directions in a curvilinear grid). Unfortunately, because the ratio between the channel curvature and the desired grid cell size was too large in the Sungei Buloh Kechil area (on the left side), this philosophy was only applied to the Sungei Buloh Besar (on the right side).
In order to reduce the computational time, we tried to keep the grid cell size the same in the entire Sungei Buloh Wetland Reserve area. The high density of grid cells on the right is necessary in order to be able to make a proper curve in the grid, see Figure 5.

Figure 6 shows the orthogonality of the grids. The values are the cosine values of grid corners. The cosine values should be close to zero. The error in the computed direction of the pressure term in Delft2D-FLOW is proportional to these values. In offshore areas, the orthogonality should be less than one fiftieth. Near closed boundaries, higher values are sometimes acceptable. Both grids have orthogonality values of less than one hundredth, with some exceptions near the edge.
The grid should be smooth to minimise truncation errors in the finite difference scheme. Adjacent grid cells should vary less than 20 percent, although locally exceptions may be acceptable. This applies for both directions in the grid. Figure 7 and Figure 8 show that both grids stay well below this limit and are fairly smooth.

The aspect ratio (not shown) must be in the range [1,2] unless the flow is predominantly along one the grid lines. Both grids comply with this condition.
3.2.2 BATHYMETRY

In order to overcome several high velocity instabilities in the channel in random directions, the bathymetry is adapted. The original bathymetry contains numerous sharp transitions between deep and shallow areas, as well as many narrow channels that are not represented very well on the grid, which results in unrealistic flow patterns. Hence, transitions are smoothed out and some of the channels widened and deepened in order to improve its representation of the channel in reality.

The biggest change, however, is the inclusion of the footpaths in the form of embankments. During a field visit, it was observed that footpaths on top of embankments run throughout the wetland reserve. The topographic maps provided by the YJP surveyor confirmed this. These embankments were not present in the original SBLM bathymetry, because the embankments and the grid cells are in the same order of magnitude and therefore left out during an automatic conversion of samples to a bathymetry file. The embankments, together with 14 inlets, are assumed to have a major impact on flow patterns in the area, and thus are included in the bathymetry. Because the embankments do not flood during regular high tides, the height is estimated to be 2.6 metres. A comparison of the old and new bathymetry is given in Figure 9.
Figure 9 – Sungei Buloh Wetland Reserve area: QRAM Phase 1 bathymetry (left) versus updated bathymetry (right). Scale: –1 - 2m.

3.2.3 VERIFICATION OF ADAPTED MODEL

The updated grid and bathymetry improve the result of the simulation to a much better degree, although some less severe instabilities are still observed. Figure 11, Figure 12 and Figure 13 show velocity vector plots at three locations in the wetlands reserve (see Figure 10). In Figure 11, high peak velocities are gone; in Figure 12, a zone with major instabilities and velocity vectors in every direction has been stabilised; and in Figure 13, major staircasing disappeared. Notice that updating the bathymetry (as described above) changed flow patterns as well; the 2DH model shows increased flows in channels and new outlets compared with the QRAM Phase 1 model, but this section focuses on instabilities in the flow pattern, not the flow pattern itself. That will be discussed in section 3.5.2.

Figure 10 – Flow velocity vector plots (overview). The rectangles are displaying the areas zoomed-in upon in the subsequent figures. QRAM Phase 1 bathymetry (left) versus updated bathymetry (right).
Figure 11 – Flow velocity vector plots (example 1). QRAM Phase 1 bathymetry (left) versus updated bathymetry (right).

Figure 12 – Flow velocity vector plots (example 2). QRAM Phase 1 bathymetry (left) versus updated bathymetry (right).
Figure 13 – Flow velocity vector plots (example 3). QRAM Phase 1 bathymetry (left) versus updated bathymetry (right).
3.3 HYDRODYNAMIC MODEL SUMMARY

In Table 2, an overview is provided of the parameters of the QRAM Phase 1 model, the adapted 2D depth averaged model and the full 3D model.

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<th>3D model</th>
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<td>10 – 100 meter</td>
<td>10 – 100 meter</td>
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<td>9.81 m/s²</td>
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<td>Water density</td>
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<td>1000 kg/m³</td>
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<td>Roughness</td>
<td>Manning, 0.03 in coastal area and 0.06 in wetland</td>
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<td>Manning, 0.03 in coastal area; adapted in wetland</td>
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<td>Uniform horizontal eddy viscosity of 1 m²/s</td>
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<tr>
<td>Fresh water discharges</td>
<td>4 locations</td>
<td>4 locations</td>
<td>4 locations</td>
</tr>
</tbody>
</table>

3.4 AVAILABLE DATA FROM MEASUREMENTS

The available data sets are a time series of water levels taken at the bridge over the Sungei Buloh Besar, which coincides with observation point S806, and some single point measurements of velocity taken from a boat.

The location of the water level measurements is highlighted in Figure 14 in yellow. The measurement covers one spring-neap cycle and starts at 15-10-2012 16:18 and ends at 07-11-2012 14:08. The measurement interval does not concur with the history file time interval of the computations (which is more regular, a water level is outputted every 10 minutes) so to compute correlation and root mean squared error the vector containing
field data is stretched out to match the size of the computed values and interpolated to account for the missing values.

The locations where the velocity measurements were taken are highlighted in Figure 15. The measurements consist of multiple single point measurements at several locations, covering a short time interval on 28-11-2012 from 08:44 till 08:47. The general simulation stop-time in our 2D and 3D models is 08-11-2012 00:00 though, causing these measurements to be out of the model’s time range. A comparable situation is sought using a filter in Matlab that assigns several characteristics to the situation at 28-11-2012 08:44 and searches for other points in the data set that contain the same characteristics, see Figure 16. The measurements’ conditions from 28-11-2012 08:44 are represented the best on 03-11-2012 11:00.

The velocity data series is extremely noisy, so a filter is used on the data in order in order to be able to check the computed velocity with the measurements properly, resulting in only 4 usable velocity points.

![Observation points in the SBLM. The red circles indicates the observation point in the mouth of the Sungei Buloh Besar (SB05), the yellow circle indicates the observation point at the bridge over the Sungei Buloh Besar (SB06).](image1)

![Locations (path) where the boat collected velocity data](image2)

![Results of filter to search for a similar situation. Rightmost point is the date of the original measurement, where the water level is illustrated with the red line. The cloud left are all points with a similar water level in the time span of the vegetation simulations.](image3)
3.5 HYDRODYNAMIC RESULTS OF THE SUNGEI BULOH LOCAL MODEL

To assess the effect of mangroves on the hydrodynamics in Sungei Buloh and the performance of different modelling representations of vegetation a number of simulations are performed. For reference also a simulation without added vegetation is performed, the result of this simulation is added in every figure to see the effect of the vegetation.

There is a little field data available of the Sungei Buloh Wetland Reserve, which makes validation of the model hard. As described in section 3.4, a water level time series of a full spring-neap tidal cycle is available near the mouth of the Sungei Buloh area, as well as some single point values of velocity obtained from boat measurements.

First, it will be checked whether the water level near the entrance of the Sungei Buloh Wetland Reserve agrees with the field data. This performance will be checked with statistical parameters: correlation coefficient and root mean squared error.

Then the computed velocity field will be checked against the single point measurements. These measurements were taken just outside of the Sungei Buloh Wetland Reserve. It is difficult to say something about the performance of the model inside the wetland reserve, since there is no data available on water levels, flow patterns or velocity profiles in the wetlands.

3.5.1 MODEL PERFORMANCE: WATER LEVEL

As mentioned before, a time series of water levels during one full spring-neap tidal cycle is available. Model computations are checked against this data set. Although the data was acquired at the bridge over the Sungei Buloh Besar (observation point SB06, see yellow circle in Figure 14), the comparison is made with model results from the mouth of the Sungei Buloh Besar (observation point SB05, see red circle in Figure 14). This point does not have a limited depth in the model and is able to show the full tidal range. The observation points SB05 and SB06 are only 360 metres away from each other, which is a very small distance compared to the tidal wave length; so besides the lowest possible water level, they show the same water level series. Section 5.6.1 elaborates on this.

In Table 3, the performance of two different roughness representations, Adapted Manning and the DPM (see section 4.3), is summarised in terms of correlations and root mean squared error. Both models seem to perform well on representing water level, and the root mean squared error is in the order of 5%. During higher tides, the model seems to compute too high water levels, whereas around lower tides the water levels agree very well. This is illustrated in Figure 17.

On the basis of the computed water levels compared to field data, it is not possible to say that one model works better than another model, correlation and root mean squared error differences are in the order of 0.1%.

<table>
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<th>Run</th>
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<th>Root mean squared error [m]</th>
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<tr>
<td>2D – MAN</td>
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<td>0.2163</td>
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</table>
3.5.2 MODEL PERFORMANCE: VELOCITY

A number of single point measurements are available as velocity data. The data is very noisy which results in only 4 usable velocity measurement points. A vector plot is made to compare direction and magnitude of the observations with the model computations. All models agree well with the observations. Keep in mind that there is not much difference in the velocity field at that location between the different simulations: The location where the data was collected is on open sea outside Sungei Buloh Wetland Reserve. The different vegetation representations mainly affect the flow inside the wetland, since that is where the vegetation is added to the model. The velocity field figure is just to verify that the model computations agree with field observations, which makes it very reasonable that inside Sungei Buloh Wetland Reserve the computed velocities also agree with reality. A correct flow representation is dependent on much more factors, e.g. a correct representation of bathymetry, correct implementation of vegetation and a good numerical grid are some aspects that can affect the velocity. However, an assessment on performance of different vegetation representations can be made by comparing the results of the simulations with one another.

In Figure 18, the velocity field of 03-11-2012 11:00 is plotted with 4 measurements for the 2D horizontal simulation without vegetation.
Figure 18 – Velocity vector field on 03-11-2012 11:00 for the 2D horizontal simulation without vegetation. Velocity observations are added as purple arrows (in the centre of the figure).
4 WATER QUALITY MODELLING

The residence time of contaminants is modelled using the Water Quality module in Delft3D (general configuration (WAQ)). It needs the hydrodynamic and grid data from the Flow module and an input of substances from the Processes Library Configuration Tool (PLCT). The next section discusses important choices for the water quality model and provides the modelling approach and the details of the scenarios.

4.1 MODEL SET UP

4.1.1 HYDRODYNAMICS

The hydrodynamic and grid data are derived from the 2DH model (see section 3.3). Using a 2D model will be sufficient since Sungei Buloh Wetland Reserve is not a stratified system and the flow of the substance used (see below) does not depend on vertical variation. The use a depth-averaged model therefore delivers the same results with less computational resources needed. We used a direct output from the Flow module to create the input files for the Water Quality module, using the additional parameter flwq, as described in the Delft3D-FLOW user manual. All scenarios use a time interval of 20 minutes. Section 4.3 gives an overview of the various start and stop values. Grid aggregation is not applied, as the desired resolution is modelled already.

4.1.2 SUBSTANCES, INITIAL AND BOUNDARY CONDITIONS

The scope of this research is more qualitative of nature than quantitative and that is why we use a simple, conservative tracer (CTR) which is not affected by sedimentation, degradation or other natural processes of decay; a conservative tracer is only subject to transport. This could be a chemical substance that is completely soluble and non-degradable.

Beside the above-mentioned conservative tracer, the model also features a special conservative tracer: Continuity. It has no physical or chemical meaning (Delft3D-WAQ user manual). Instead, it is used to establish the numerical correctness and stability of the simulation. By assigning a concentration of 1 g/m$^3$ to all water sources (the initial condition, the open boundary condition and the discharge concentrations), the Continuity concentration should remain 1 g/m$^3$ during the whole simulation, as there are no processes that dilute or concentrate it and all water has a concentration of 1 g/m$^3$. If it does not, it indicates the local numerical error: the deviation (in percentage) of Continuity indicates the deviation (in percentage) of the other tracers. So it functions as a check on the mass balance in the water quality module.

All other tracers have an initial value of 0 g/m$^3$. This way, the only source of these tracers are the discharges. This isolates the tracers to determine their residence time later on. The initial value could as well have been any other arbitrary value as a matter of fact. What drives the model is the difference in concentration, not the concentration itself.

4.1.3 TIME FRAME

The time frame of the water quality calculation can be set independently of the coupled hydrodynamics, allowing for clever use of the available hard disk storage and computational power. The hydrodynamics were run for 22 days (nearly two full spring-neap cycles), while the different scenarios in this research are all based on smaller time frames of 13 days (one spring-neap cycle). The 13-day time frames of all scenarios lie within the same 22 days. See section 4.3 for the precise time frames. All scenarios use the same 20 minutes time interval as outputted by the Flow module.
4.1.4 NUMERICAL OPTIONS

The numerical integration method that is used is scheme #16: implicit upwind scheme in horizontal, centrally discretised vertically, with an iterative solver. This method is an iterative solver, which uses the Generalised Minimal Residual method (GMRES), so convergence is always guaranteed (Delft3D-WAQ user manual). In order to reach convergence though, the maximum number of iterations needs to be higher than the standard value of 50; this value is changed to an arbitrarily higher value of 2000. The only implication of this change is that the computational time might increase in case of slow convergence.

4.1.5 DISCHARGES

According to Oliveira and Baptista (2004), integral formulations of residence time cannot take the space and time variability into account. Therefore, this research’s models feature multiple discharge locations and a discontinuous discharge (one hour only), in order to be able to capture the temporal and spatial effects. To keep it simple though, the two most obvious discharge location are analysed; namely, the localities of where the Sungei Buloh Besar and the Sungei Buloh Kechil enter the wetlands reserve (SBB-start and SBK-start), see Figure 19. The location of the discharge points do not resemble the entrance point exactly, so that the spreading of concentration maintains residence within the model area.

Both discharges discharge water with a different tracer in order to be able to identify the residence time of contaminants originating from every discharge individually. These are CTR1 for Sungei Buloh Besar and CTR2 for Sungei Buloh Kechil.

A base flow is modelled. This means that the flow rate is 0.01 m$^3$/s. In order to identify the temporal effect on residence times, only a one-hour block of base flow is discharged and the rest of the model time, the discharge is zero. See Figure 20. The concentration is chosen to be a constant 200 g/m$^3$ – a value that could be realistic for a contaminant. The actual concentration, however, does not matter in the end, because the conservative tracer is not subject to any non-linear decay, so superposition can be applied. In addition, the residence time is defined relative to the total mass input and thus concentration.
4.2 WATER QUALITY MODEL SUMMARY

Table 4 shows an overview of the parameters that apply to all scenarios in the water quality model. An overview of the runs is given in section 4.3.

Table 4 – Summary of water quality model parameters

<table>
<thead>
<tr>
<th>Input tab</th>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrodynamics</strong></td>
<td>Grid aggregation</td>
<td>No grid aggregation</td>
</tr>
<tr>
<td><strong>Dispersion</strong></td>
<td>First direction</td>
<td>$1 \text{ m}^2/\text{s}$</td>
</tr>
<tr>
<td></td>
<td>Second direction</td>
<td>$1 \text{ m}^2/\text{s}$</td>
</tr>
<tr>
<td><strong>Substances</strong></td>
<td>Conservative tracers</td>
<td>‘CTR1’, ‘CTR2’ and ‘Continuity’</td>
</tr>
<tr>
<td><strong>Initial conditions</strong></td>
<td>CTR1</td>
<td>$0 \text{ g/m}^3$</td>
</tr>
<tr>
<td></td>
<td>CTR2</td>
<td>$0 \text{ g/m}^3$</td>
</tr>
<tr>
<td></td>
<td>Continuity</td>
<td>$1 \text{ g/m}^3$</td>
</tr>
<tr>
<td><strong>Boundary conditions</strong></td>
<td>CTR1</td>
<td>$0 \text{ g/m}^3$</td>
</tr>
<tr>
<td></td>
<td>CTR2</td>
<td>$0 \text{ g/m}^3$</td>
</tr>
<tr>
<td></td>
<td>Continuity</td>
<td>$1 \text{ g/m}^3$</td>
</tr>
<tr>
<td><strong>Time frame</strong></td>
<td>Time period</td>
<td>13 days</td>
</tr>
<tr>
<td></td>
<td>Time interval</td>
<td>20 minutes</td>
</tr>
<tr>
<td><strong>Numerical options</strong></td>
<td>Integration method</td>
<td>#16</td>
</tr>
<tr>
<td></td>
<td>Max number of iterations</td>
<td>2000</td>
</tr>
<tr>
<td><strong>Discharges</strong></td>
<td>SBB-start and SBK-start</td>
<td>$0 \leq t \leq 1\text{h}: \quad Q = 0.01 \text{ m}^3/\text{s}, \quad c = 200 \text{ g/m}^3$.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t &gt; 1\text{h}: \quad Q = 0 \text{ m}^3/\text{s}$</td>
</tr>
</tbody>
</table>


4.3 MODELLING APPROACH AND SCENARIOS

In this section, the research objectives will be set out and an overview of all the simulations to reach these objectives will be described.

4.3.1 RESEARCH OBJECTIVES

The research objectives are derived from the goal, as described in section 1.2. It is desired to reach an answer to the following questions:

- Which parameters have an effect on the residence time?
- What is the influence of these parameters?
- What is the residence time for contaminants discharge into Sungei Buloh Wetland Reserve?

4.3.2 OVERVIEW SIMULATIONS

As described in section 1.3, parameters of influence are the tidal cycle and the discharge location. Also, numerical aspects can play an important role. In Table 5, the various scenario runs are first ordered by discharge location and used vegetation model, followed by Table 6 with four scenarios that have different starting points in the tidal cycle. Hence, the total amount of scenarios is 16. These scenarios will provide the answers to the questions above.

During an early stage, this research included four extra scenarios in order to test the influence of the daily inequality and the influence of release at mean water level instead of high or low water (the scenarios #3, #4, #6 and #8), but from early model results, these scenarios turned out not to be significantly different.

Table 5 – Model scenarios 1, discharge location and vegetation model

<table>
<thead>
<tr>
<th>Discharge location</th>
<th>Vegetation model</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBB-start</td>
<td>Manning, 0.03 in coastal area; adapted in wetland</td>
</tr>
<tr>
<td>SBK-start</td>
<td>Manning, 0.03 in coastal area; adapted in wetland</td>
</tr>
<tr>
<td>SBB</td>
<td>DPM</td>
</tr>
<tr>
<td>SBK</td>
<td>DPM</td>
</tr>
</tbody>
</table>

Table 6 – Model scenarios 2, tidal cycle

<table>
<thead>
<tr>
<th></th>
<th>#2</th>
<th>#5</th>
<th>#7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily cycle</td>
<td>HHW</td>
<td>HHW</td>
<td>LLW</td>
</tr>
<tr>
<td>Semimonthly cycle</td>
<td>Spring tide</td>
<td>Neap tide</td>
<td>Spring tide</td>
</tr>
<tr>
<td>Date time start</td>
<td>17-10-2012 12:00:00</td>
<td>24-10-2012 16:40:00</td>
<td>17-10-2012 20:00:00</td>
</tr>
<tr>
<td>Date time stop</td>
<td>31-10-2012 11:40:00</td>
<td>07-11-2012 16:20:00</td>
<td>31-10-2012 19:40:00</td>
</tr>
</tbody>
</table>
5 RESULTS AND ANALYSIS

To arrive at an answer to the research objectives as stated in section 4.3, several simulations have been performed. This section provides the results of these simulations by showing the flow of mass, defining the residence time and showing the residence times based on these simulations.

This chapter contains the following sections:

- Flow of mass
- From hydrodynamic and water quality modelling to residence time
- Residence times
- Summary of residence times
- Model limitations

5.1 FLOW OF MASS

Knowing the flow of water and with that the flow of the contaminant will contribute to a better understanding of residence time. Figure 21 shows the contaminant concentration in the control region at six moments in a tidal cycle. The figure’s scenario is the one with the discharge at SBB-start, starting at highest high water during at peak spring tide and DPM vegetation. Notice that the concentration has the unit g/m² instead of the standard g/m³. This has the effect that the data set shown in the map plots is not influenced by the highly varying depth and thus the plots show the effective amount of mass per area.

Panel one of Figure 21 shows the concentration peak in the first time step after the contaminants have been released. In panel two, more mass has been added and the mass plume has started moving seawards. The third panel already shows a big spreading. Then, in the fourth panel, nearly all mass has flowed out of the control region. The mass resides in the Johor Strait at this moment, mostly just outside the wetlands reserve. The fifth panel shows the re-entering of the contamination. The last panel demonstrates that the contamination moves all the way back upstream and also enters the other river arms, though much diluted.

For the same scenario, Figure 22 shows the concentration in three observation points. These locations are marked in Figure 23. The advection of the mass plume is clearly visible in the different locations of the concentration peaks. Also, the height of the concentration peak decreased as the mass plume moves in space, indicating diffusion, which means that the width of concentration peak increases. After all, the mass is a conservative tracer with mass conservation.

The Sungei Buloh Kechil shows the same advection-diffusion behaviour. In the right panel of Figure 22 are the results of an observation point at sea. This concentration peak is rather low compared to the concentration peak in SBB-mouth in the left panel. This is a logical result from the fact that the plume at sea knows a much bigger lateral spreading than in a confined channel.
Figure 21 – Map plots of concentration (in [g/m²]). The six panels depict a small movie of the mass transport in time. View them from left to right first, then from top to bottom. The colours indicate the amount of mass per square metre, ranging from nought (blue) to 0.1 g/m² (red). The first picture is taken right after the discharge start. The others are taken after one, three, eight, eleven and thirteen hours; showing one complete high to low to high water cycle.
Figure 22 – Advection and diffusion of mass in time. The peak concentration is marked.

Figure 23 – Locations of the observation points for water quality modelling.
5.2 FROM HYDRODYNAMIC AND WATER QUALITY MODELLING TO RESIDENCE TIME

The definition of residence time (the time it takes for 95% of the mass input to leave the control region without returning at a later phase of the tide) is based on the available data sets: the Delft3D-FLOW module outputs data on water level and flow velocity and the water quality module provides contaminant concentration data.

Because the total mass input also is a known parameter, the only step to take is the determination of the total mass in the control region. With the concentration known in every grid cell (Delft3D-WAQ output), as well as the surface area of each grid cell (grid property) and the water depth in each grid cell (Delft3D-FLOW output), the mass per grid cell and the total mass in the control region can be calculated using the formulas (2) and (3).

\[ m_{ij} = A_{ij} \cdot d_{ij} \cdot c_{ij} \]  
\[ M = \sum_{p=r}^{q} \sum_{r=s}^{p} m_{ij} \]

In this formula, the indices \( i \) and \( j \) indicate the location of a grid cell in \( m \) and \( n \) direction (\( m \) and \( n \) are the two directions of the curvilinear grid), \( m_{ij} \) is the mass located in grid cell \((i,j)\), \( A_{ij} \) the surface area of grid cell \((i,j)\), \( d_{ij} \) the water depth in the centre of grid cell \((i,j)\) and \( c_{ij} \) is the concentration in the centre of grid cell \((i,j)\).

The control region is the Sungei Buloh Wetlands Reserve, defined by grid line \( m=72 \). All plots of the Sungei Buloh Wetlands Reserve in this report were cut at this line, which is a continuation of the land boundary west of the Sungei Buloh Wetlands Reserve. The control region comprises all wetland areas and rivers, except for a small sea-bordering part of the Pulau Buloh island and does not include parts of the Johor Strait.

Contaminants move in and out of the control region, but after some time, they will have left the control region for good. The graph of the total mass in time is fluctuating but decreasing and it intersects with the (horizontal) limit line of 5% (see the definition of residence time). The last intersection in time is the moment the total mass in the control region will never increase to values above the limit, indicating the residence time of this contaminant.

Summarising, by multiplying the available data of the surface area, depth and concentration per grid cell and adding these for all cells in the control region, a graph showing the course of the total amount of mass in the control region over time can be constructed. The point in time this graph intersects the 5% limit is the residence time; in case this happens more than once, the last point in time is determinative (following the definition of a re-entrant tracer, see section 2.2).
5.3 RESIDENCE TIMES

5.3.1 COMPARISON DISCHARGE LOCATION

Figure 24 shows plots of the total amount of mass in the control region for roughness modelled with Adapted Manning. With all the mass residing in the control region, the graphs would show a horizontal line when the discharge has stopped. However, the graphs show oscillations, which indicate that mass flows in and out of the control region.

Overall, it is clear that the residence time of the shorter Sungei Buloh Kechil is smaller than the residence time of the Sungei Buloh Besar. The total amount of mass when discharged in the Kechil strongly reduces within one or two ebb flows, while the total amount of mass remains higher with discharges in the Besar.

A discharge with neap tide (right panels) results in a significantly longer residence of mass than with a discharge with spring tide (left panels). The tidal range with neap tide is smaller than the tidal range with spring tide, so also the amount of water flowing in and out of the Sungei Buloh Wetland Reserve is smaller with neap tide. Since the cross-sections do not differ too much, this means that the flow velocities in the reserve are lower with neap tide. And because the conservative tracer is only influenced by advection, the modelled contaminant moves slower through the reserve with neap tide than with spring tide.

At the moment of release, the graphs for discharges during lowest low water (lower panels) are horizontal for a few hours: the plume does not move seawards at first, but only with ebb tide. This means that the contaminant in the discharge first has the possibility to diffuse in the area, resulting in a slower seawards motion, thus lengthening the residence time. Also, the total amount of mass in the control region after one hour is equal to the total mass input (7200 grams); in contrast to the mass when discharged during highest high water (upper panels).

Figure 24 also shows the 5% limit from the definition of residence time (section 2.2). Because a tracer can re-enter the control region, the graph of the total amount of mass in the control region generally intersects this line multiple times. For example, in the upper right panel, the total amount of mass from a discharge in the Sungei Buloh Besar intersects the 5% limit five times (starting after 4 days) before it touches it for the last time after 5.3 days. This means that in the first four days, the total amount of contaminants is constantly higher than the limit and that for another 1.3 days the total amount of contaminants can occur to be high. The residence time in this scenario is 5.3 days.

A summary of all residence times is given in section 5.4.
Figure 24 – Total amount of mass in Sungei Buloh Wetland Reserve. Check on the influence of discharge location: SBB-start versus SBK-start for all tidal scenarios, with Adapted Manning vegetation model.

Figure 25 – Total amount of mass in Sungei Buloh Wetland Reserve. Check on the influence of the vegetation model: Adapted Manning versus DPM for all tidal scenarios, with discharge at SBB-start.
5.3.2 COMPARISON VEGETATION REPRESENTATIONS

In Figure 25, lines with the same pattern and colour represent the same data set as in the other figures in this section. The figure depicts the difference between the total amount of mass in the control region for vegetation represented by Adapted Manning and by the directional point model, in the case of a discharge in the Sungei Buloh Besar. The results are visibly different.

Firstly, the initial mass peak neatly touches the total mass input of 7200 grams in all four scenarios modelled with the DPM. The scenarios modelled with Adapted Manning Hereafter, the graphs are horizontal, indicating no mass leaving the control region. The amount of time the graphs are horizontal is increased by the time till ebb tide (lower panels) and the lower flow velocities during neap tide (right panels). These effects are addable: the lower right panel shows the longest time of no outflow of mass out of the control region, while the upper left panel shows swift outflow.

Secondly, while initially the total amount of mass in the control region remains higher in the DPM scenarios, it decreases more rapidly afterwards and intersects the graph of the scenario with Adapted Manning. The explanation follows from Figure 27, which illustrates the effect of vegetation using the DPM by showing the velocity differences between a model run with no vegetation and one with the DPM, and Figure 28, which shows velocity differences between a no vegetation run and one with DPM. Both figures represent the flow differences at the maximum of the ebb flow, which means that the flow is directed seawards. Figure 28 shows that the outflow in the Sungei Buloh Besar in the model using Manning for vegetation is lower indeed and that adds to the residence time.
Figure 27 – Velocity difference of the base run (no vegetation) compared with the added vegetation using the DPM. The difference is found in the northern part of the Sungei Buloh wetland reserve. This implies that the vegetation effects the flow velocity in the north, though barely in the south. Taken from *Hydrodynamic modelling of a mangrove system in Singapore* by Y. Broekema.
Figure 28 – Velocity difference of a simulation without vegetation and a simulation with added vegetation using an increased Manning’s roughness value. The biggest difference is found in the southern part of the model area. In the north the result is similar (though not equal to) the DPM representation. That the result is not equal in depth averaged sense is a matter of calibrating the Manning’s coefficient better, which is not done in this project due to time limitations. The big differences in the south could also be calibration problems, though later on it will be explained why that is not the case. Taken from Hydrodynamic modelling of a mangrove system in Singapore by Y. Broekema.

About the same explanation applies for the Sungei Buloh Kechil. Here, the higher flow with Adapted Manning is in sharp contrast with the lower flow in the Sungei Buloh Besar. The more rapid decrease of the total mass in the control region when using the DPM is not clearly present here, see Figure 26.

5.3.3 Daily Inequality

Figure 24 also shows the phenomenon of daily inequality. While it remains hidden in the scenarios in which the discharge start at highest high water, the scenarios starting at lowest low water do make it visible. Mass peaks seem to group in groups of two.

Daily inequality means that from the two high waters every day, one is higher than the other; and the same applies to the low waters. In general, a lower water level means more water with dissolved substances flowing out of the control region, hence decreasing the amount of mass in the control region. So, a lower low water than the previous one exports more mass out of the control region, but with a higher low water, less mass is exported. This effect is increased by the fact that after every highest low water follows the highest high water. This overrules the general rule of thumb that with every tidal cycle the total amount of mass in the control
region decreases because of advection and diffusion to and at sea. The lower right panel of Figure 24 shows this precisely: the peak at 2 days is higher than the one before. The reason for the fact that the scenarios with discharge at highest high water do not show this behaviour is timing; the determining follow up of highest high water after lowest high water is half a tidal cycle later. Meanwhile, the diffusion processes, which are much stronger with the high concentration differences initially, mask the effect of daily inequality.

5.4 SUMMARY OF RESIDENCE TIMES

The residence times as calculated in the different scenarios are summarised in Table 7.

Table 7 – Residence times in Sungei Buloh

<table>
<thead>
<tr>
<th></th>
<th>#1: HHW spring</th>
<th>#2: HHW neap</th>
<th>#5: LLW spring</th>
<th>#7: LLW neap</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBB-start</td>
<td>2.2 days</td>
<td>5.3 days</td>
<td>3.9 days</td>
<td>6.5 days</td>
</tr>
<tr>
<td>SBK-start</td>
<td>1.6 days</td>
<td>2.8 days</td>
<td>2.7 days</td>
<td>3.4 days</td>
</tr>
<tr>
<td>SBB-start</td>
<td>1.2 days</td>
<td>3.8 days</td>
<td>2.8 days</td>
<td>5.0 days</td>
</tr>
<tr>
<td>SBK-start</td>
<td>1.2 days</td>
<td>2.8 days</td>
<td>1.8 days</td>
<td>3.4 days</td>
</tr>
</tbody>
</table>

5.5 RESULTS FOR THE STRAIT OF JOHOR

The previous sections of the results focused on Sungei Buloh Wetlands Reserve. Future research on a wider area, e.g. the water quality around fish farms, is possible as well. Reviewing Figure 21, it is obvious that the contamination leaving Sungei Buloh Wetland Reserve does not disappear, but enters the Johor Strait, via which it eventually will reach the open sea. The model used in this research already shows results of the plume of contaminants in the Johor Strait. The results of that are shown in Figure 29.

The first panel shows the initial mass plume leaving Sungei Buloh Wetland Reserve. The second panel shows that the plume moves towards the west, the way in which the water is flowing during ebb tide. Then, in the third panel, the plume returns to the mouth of the Sungei Buloh Besar in a diffused form. After re-entering the reserve in panel number four, the plume enters the Johor Strait in panel number five. Here, the spreading of the plume is already much bigger than before. The sixth panel shows a very diluted plume moving westwards again.
Figure 29 – Map plots of concentration (in [g/m$^2$]). The six panels depict a small movie of the mass transport in time. View them from left to right first, then from top to bottom. The colours indicate the amount of mass per square metre, ranging from nought (blue) to 0.01. Notice that this scale is only a tenth of the scale in figure 21; because of the bigger spreading and lower concentrations, this is needed to make the plume properly visible.

5.6 MODEL LIMITATIONS

Continuing on the results as provided in the previous sections, in this section, limitations of the hydrodynamic model and the water quality model are presented.

5.6.1 HYDRODYNAMIC MODEL LIMITATIONS

During the course of this project assumptions have been made that may limit the results and validity of the hydrodynamic model. This section elaborates on the grid and bathymetry.

To keep computational time within reasonable limits the smallest grid size in the SBLM in the area of interest is about 10 x 10 metres. Bathymetry was added to the model using topographic maps created by YJP Surveyor for Nparks. Using GIS, the bottom data from this maps were transferred to samples for the Sungei Buloh Wetland Reserve. Then, the depth file was generated in Delft3D-QUICKIN using these samples. It turned out that the grid-resolution was not high enough to capture all these bottom data points well. This resulted in a bathymetry where all the footpaths on embankments were absent, where channels were not deep enough, and transitions very sharp.
So in the adapted model used for this project, bathymetry was drastically improved by including the embankments (as described in section 3.2.2). In addition, the channels were slightly widened and deepened. With a grid cell size of 10 metres, though, this may quickly lead to an over estimation of the width of the channel. The depth of the channel were also subject to discussion: when validating water level (see section 3.5.1), it became clear that the water level in the adapted model still cannot reach the lowest value as observed in the field (see Figure 30).

![Water level observations vs model computations](image)

**Figure 30** – The bathymetry of the Sungei Buloh Besar is adapted and the water level is now represented very well except for the lowest low waters.

### 5.6.2 WATER QUALITY MODEL LIMITATIONS

#### 5.6.2.1 TOTAL MASS BALANCE: FLOODING AND DRYING

As shown in Figure 21 in the section 5.1, nearly all discharged contamination moves seawards in this scenario. The fourth panel, however, shows besides a small mass plume in the river mouth, also some vague ‘contours’ around the more upstream part of the river. Checking the local water levels, it turns out that these areas are dry. The concentration map still shows mass, so the drying-flooding algorithm of Delft3D will be investigated.

Section 3.1 already mentions the use of the Flooding scheme for advection in the momentum equation. This makes Delft3D’s drying and flooding algorithm effective and accurate for rapidly varying flows. According to the Delft3D-Flow manual, crucial items in a wetting and drying algorithm are the way in which the bottom depth is defined at a water level point, the way in which the water level is defined at velocity points and the criteria for setting a velocity and/or water level points wet or dry.

The latter is user specified and is set to 10 centimetres. Delft3D’s drying check sets points dry when the water level is less than half of this parameter. This means that every dry grid cell that once was wet, could contain up to 5 centimetres of water, which is contained in this grid cell and does not move anywhere until it floods again.

In the case of modelling a substance that is in the water at the moment a grid cell is set as dry, e.g. because the ebb tide causes the water level to decrease like in Figure 21, this substance is captured in that cell until the tide comes in again, floods the cell and takes the substance along with it. This explains light blue contours of the fourth panel of Figure 21.

In addition, this effect is traceable in the upper left panel of Figure 24. Here, the magnitude of this error also becomes clear. The first trough in the graphs indicates that 0.5 kg (6.9%) of the amount of mass still resides in the control region for mass released in the Sungei Buloh Besar; for mass released in the Sungei Buloh Kechil this is 0.25 kg (3.5%). For the Sungei Buloh Besar, about 0.05 kg truly has not flowed out of the control region and is still in the river, but the remaining 0.45 kg (6.3%) is the magnitude of the error made by flooding and
drying. For the Sungei Buloh Kechil, there is no mass in the river, so the magnitude of the flooding and drying error is 3.5%. But in the next tidal cycle, the mass is taken by the water that floods the cells again and therefore, it does not influence the residence time significantly in the end.

### 5.6.2.2 TOTAL MASS BALANCE: NUMERICAL DEVIATIONS

In Figure 24, Figure 25 and Figure 26 from section 5.3, not all graphs touch the total mass input of 7200 g. The maximum of some graphs is lower, while others are higher. There are several factors influencing the features of these graphs, some can be explained physically while others are a result of numerical approximations. Looking at the physical situation in Sungei Buloh, the mass input takes one hour and some mass may already flow out of the control region during the discharging period, lowering the total amount of mass in the control region. The results are also influenced by the numerics of Delft3D. Figure 31 shows a concentration map of the Continuity tracer. As described in section 4.1.2, this tracer has a uniform initial concentration of 1 g/m$^3$ and all inputs into the system have the same concentration. Therefore, the concentration should not change, except when numerical errors occur. The Continuity tracer identifies the magnitude of these errors; a value of 1.1 means that it is 10% too high and any substance in the same grid cell also has a concentration that is 10% too high. As visible in Figure 31, numerical errors do increase and decrease the concentration of substances in the scenarios.

![Figure 31 - Concentration of the Continuity tracer](image_url)

Figure 31 – Concentration of the Continuity tracer (see section 3.3.3) one hour after the discharge start, for the scenario ‘Adapted Manning, discharge start at lowest low water with neap tide’. A green colour (1 g/m$^3$) shows that there is no numerical error. A concentration of 1.1 g/m$^3$ informs about an overestimation of the other modelled tracers of 10%.
6 CONCLUSION

Modelling contaminants in the Sungei Buloh Wetland Reserve using Delft3D-WAQ results in useful data on residence times. Since measurements in the field are often not possible due to either safety hazards or ecological implications, the water quality model provides comprehensive data to analyse the behaviour of flow and contaminants and with that the residence time of these contaminants.

The goal of this research was to define a workable definition of the residence time in Sungei Buloh Wetland Reserve and to use Delft3D to identify several situations in which concentration would become dangerously high or remain high for an extended period of time, to start with a simple conservative substance.

The residence time is the time it takes for 95% of the mass input to leave the control region without returning at a later phase of the tide. The control region is defined as the Sungei Buloh Wetland Reserve, covering the wetland areas and channels and leaving out the sea.

In order to identify critical situations, several scenarios were set up and assessed for their influence on the flow of the contaminants. A conservative contaminant was modelled. The scenarios comprised several possible important tidal factors – release during high or lower water, spring or neap tide – and the importance of the entrance location of the contamination. In addition, the model representation of the vegetation was changed from the use of a higher Manning roughness value to the use of a directional point model, since the mangrove vegetation is believed to have a significant influence and therefore should be modelled as accurate as possible.

The results show that – as expected for a conservative tracer – the substance moves along with the flow of water. After the discharge, the contaminants start to spread through the reserve. In the case of a discharge with low water, the contamination will be fairly contained to the upstream part of the area for a few hours, though in case of a discharge with high water, much of the contamination flows directly towards the sea. With neap tide, this effect is much lower than with spring tide, when there is much more flow.

Also, once the contamination has left Sungei Buloh Nature Reserve, a reasonable share does not stay at sea, but re-enters the reserve. This time, it also reaches areas previously unreached, although the initial plume of contaminants has been diluted greatly.

Altering the model representation of vegetation to the directional point model, delivers different flow patterns (as described in Hydrodynamic modelling of a mangrove system in Singapore by Y. Broekema) which has a its impact on the behaviour of the contaminants and the residence time.

In general, the residence time of contaminants is lower when the discharge happens with (highest) high water and during spring tide, while a discharge of contamination with (lowest) low water and during neap tide increases the residence time. The use of the directional point model instead of an adapted Manning’s roughness representation generally decreases the residence times.

A relevant question would be whether this model with a simple, conservative tracer can tell something about more complicated behaviour of various other contaminants; as touched upon in the section 1.4. One could think of many examples in which the residence time would be either considerably lengthened or decreased. Although these have not been modelled, it is possible to say something about them by superposition of properties. E.g. from the flow results it is known that the flow in the channels is up to one order of magnitude higher than the flow on the tidal flats. Specific behaviour of contamination influenced by low flows, like (contaminated) sediment, can cause a longer residence time because of (temporary) settling. Also, some contamination will show chemical activity because of which the concentration can decrease. Based on a decay rate, one could already make an estimation of the decrease of residence time compared to a conservative tracer. Interest in detailed behaviour of specific substances could demand further exploration of these substances and the model used in this research can be used to do so.
Finally, the model allows for use for modelling substances outside Sungei Buloh Wetland Reserve. These could either be substances coming from the reserve and influencing the Johor Strait water quality or substances originating from a place in the Johor Strait also influencing the wetlands reserve.
7 REFERENCES

Reports

Delft3D-FLOW user manual, version 3.15, revision 18392, 7 September 2011.


Articles

