

POLLUTANTS IN MANGROVE ECOSYSTEMS: A CONCEPTUAL MODEL FOR EVALUATING RESIDENCE TIME

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ABSTRACT

Mangroves are extremely important from the ecological and socio-economic perspectives, but are degrading at an alarming rate nowadays. Besides direct clearance, hydrological alterations or climatic changes, chemical pollution could be a significant contributor of mangrove degradation. To understand chemical pollution in mangroves, the input and output (mass balance) of pollutants within a region need to be assessed. To identify critical situations that cause high concentrations of contaminants in the mangrove wetland, residence time was defined as the time required for flushing out pollutants from a determined region, and evaluated through numerical modeling. This concept was applied to a pollutant mass balance in the Sungei Buloh mangrove system in Singapore, using actual measured inflow concentrations and hydrodynamic modelling of tide in- and outflows. Delft3D was used to model the hydrodynamics and pollutants (as conservative substance) transport. The model was forced at its offshore boundaries by harmonic constituents and residual flows and also by multiple canal discharges at the landward boundaries. The pollutant transport model provided comprehensive data to analyse the behaviour of flow dynamics with pollutants. Several scenarios (i.e. high and low tides, spring and neap conditions) were assessed for their influence on pollutant dynamics. Residence time was confirmed low during high tide and spring period, and high during low tide and neap period. This study provides a better understanding on the residence time and transport of pollutants due to tidal variation within the mangrove.

Keywords: Residence time, Conservative pollutant, Tidal variation, Delft3D, Sungei Buloh Wetlands Reserve

1. INTRODUCTION

Mangroves are densely vegetated ecosystems at the interface of marine and terrestrial environments. Mangroves play a special role in supporting fisheries, stabilizing the coastal zone and the livelihood of nearby local communities. In the recent years, the pressure of increasing coastal population and associated agricultural, industrial and urban developments have caused a reduction in the global mangrove resource. In addition, chemical contamination could contribute

to mangrove degradation (Bayen, 2012), but further assessment are required to properly characterize this pressure. To better understand the impact of chemical pollution in mangroves, the inputs and outputs of chemical contaminants were studied in a model mangrove system, the Sungei Buloh Wetland Reserve (SBWR) in Singapore. Figure 1 shows the characteristic of the SBWR mangrove system. The present study focused on the definition and assessment of the residence time of pollutants in mangrove ecosystems. Information on the residence time of contaminants is essential to identify situations at risk for the mangrove ecosystems. Detailed discussion and theory related to the residence time can be found in Zimmerman (1976, 1988) and Takeoka (1984). Present study adopts definition of the residence time which is similar to Zimmerman (1976), i.e. the time it takes for 95% of the mass input to leave the control region without returning at a later phase of the tide.

With the advancement of sophisticated numerical models, numerical simulations are able to provide spatially and temporally extensive flow-field information (e.g. temperature, salinity and velocity distributions). High-resolution hydrodynamic models can be used to achieve refined estimates of residence time for the computational regions of application and also to determine the physical factors affecting their values and spatial distributions (Wan, 2013). The present study used the Delft3D software suite to model the hydrodynamics and pollutant transport. The hydrodynamics model was forced at its offshore boundaries by harmonic constituents and residual flows and also by multiple canal discharges at the landward boundaries. Subsequently, the pollutant transport model provided comprehensive data to analyse the behaviour of flow dynamics with pollutants.

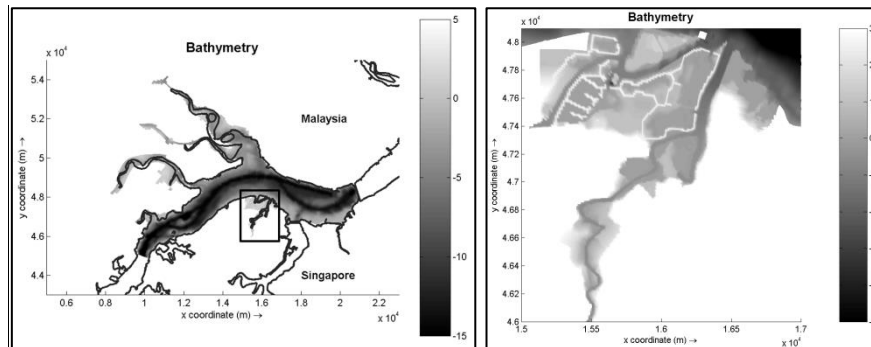


Figure 1: Model domain and its bathymetry showing for overall (left) and in more detail at Sungei Buloh Wetlands Reserve (right).

2. METHODOLOGY

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 use Delft3D-FLOW and Delft3D-WAQ (Deltares, 2011). Delft3D-FLOW is a hydrodynamic and transport simulation program which calculates non-steady flow and transport phenomena that results from tidal and meteorological forcing on a rectilinear or curvilinear boundary fitted grid. Subsequently, the result of the Delft3D-FLOW (i.e. hydrodynamic) was used as input for Delft3D-WAQ to evaluate the residence time of the pollutants (as conservative substance) transport. Since Sungei Buloh Wetland Reserve is not a stratified system and the flow of the substance used (see section 2.2.1) does not depend on vertical

variation, a 2D-model was sufficient. The use of a (2D) depth-averaged model delivers the same information with less requirements in terms of computational resources.

2.1 Hydrodynamic Information

The first attempt to understand the hydrodynamic flow characteristics in a model mangrove ecosystem in Singapore has been done by Kurniawan et al. (2014). In the previous study, the effect of vegetation and more specifically mangrove roots, on hydrodynamics was incorporated by increasing Manning's coefficients. In the present study, the influence of vegetation on flow was further modelled using a vegetation module in Delft3D-FLOW developed by Uittenboogaard (2003). This vegetation module is called the directional point model (DPM) and models vegetation as a number of rigid cylindrical rods, which influence the momentum and turbulence equations by adding extra source terms for drag and friction. This model has been tested and successfully implemented by Horstman et al. (2013).

2.2 Water Quality Information

2.2.1 Model Setup

The purpose of the present study was to develop the concept of residence time of contaminants in mangroves. The physicochemistry of the contaminant was therefore simplified to allow for a clear assessment of the present methodology. A simple, conservative tracer (CTR) which is not affected by sedimentation, degradation or other natural processes of decay, was defined for this purpose. This conservative tracer is only subject to the pollutant transport and would represent a chemical substance that is completely soluble and non-degradable. Future studies will integrate more complex physicochemical behaviour.

On top of this contaminant, the model also featured a special conservative tracer, labelled "Continuity". This parameter has no physical or chemical meaning, but was used to establish the numerical correctness and stability of the simulation. Any loss of the "continuity" tracer would indicate a local numerical error. In other words, it functioned as a check on the mass balance in the water quality module.

The time frame of the water quality calculation can be set independently of the coupled hydrodynamics, allowing for effective use of the available hard disk storage and computational power. In this study, the hydrodynamics were run for 22 days (nearly two full spring-neap cycles), while the pollutant transport scenarios are all based on smaller time frames of 13 days (one spring-neap tidal cycle). The pollutant (as a CTR) was released at different locations (i.e. SBB and SBK) and different tidal cycle during highest high water (HHW) and lowest low water (LLW). Table 1 summarises the precise time frames.

Table 1: Model scenarios based on tidal cycle

Scenarios	#1	#2	#5	#7
Tide Cycle	Spring (HHW)	Neap (HHW)	Spring (LLW)	Neap (LLW)
Release time	17-10-2012 12:00	24-10-2012 16:40	17-10-2012 20:00	23-10-2012 00:00

In the present study, point discharges were considered as the only source of tracers as it best related to an actual specific issue of interest to environmental managers. According to Oliveira and

Baptista (2004), integral formulations of residence time cannot take the space and time variability into account. Therefore, this study features multiple discharge locations and a discontinuous discharge (one hour only), in order to be able to capture the temporal and spatial effects. The two discharge locations corresponded to catchment discharges entering the wetlands reserve through Sungei Buloh Besar (SBB) and Sungei Buloh Kechil (SBK) (Figure 2, left panel). Both discharges were labelled with a different tracer (CTR1 for SBB and CTR2 for SBK), in order to identify the residence time of contaminants originating from each discharge individually. A base flow of $0.01\text{m}^3/\text{s}$ was applied from an earlier field assessment. The concentration of the pollutant was set to $200\text{mg}/\text{m}^3$. As the conservative tracer was not subject to any non-linear decay, the superposition could be applied and the residence time was defined relative to the total mass input. In addition, advection and diffusion of pollutant concentration were analysed at the six given observation locations (Figure 2, right panel).

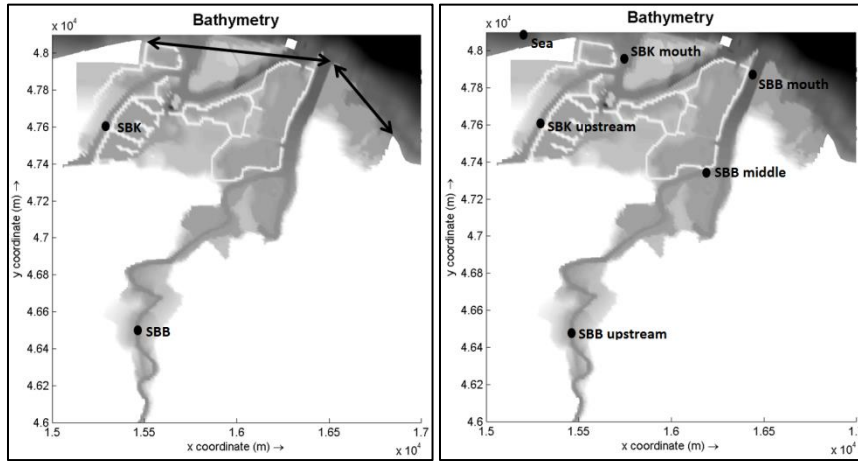


Figure 2: Discharges location and control region (left) and observation points for pollutant transport modelling (right)

2.2.2 Calculating the Residence Time

The definition of residence time (i.e. the time it takes for 95% of the mass input to leave the control region without returning at a later phase of the tide) was based on the available data sets: the Delft3D-FLOW module outputs data on water level and flow velocity and the water quality module provided contaminant concentration data. Since the total mass input was also a known parameter, the only step to take was the determination of the total mass in the control region (i.e. the geographical region of interest). With the concentration known in every grid cell, as well as the surface area of each grid cell and the water depth in each grid cell, the mass per grid cell and the total mass in the control region could be calculated using Equations (1) and (2).

$$m_{ij} = A_{ij} \cdot d_{ij} \cdot c_{ij} \quad (1)$$

$$M = \sum_{j=r}^s \sum_{i=p}^q m_{ij} \quad (2)$$

m_{ij} is the mass located in grid cell (i, j) , A_{ij} is the surface area, d_{ij} is the water depth in the centre of grid cell and c_{ij} is the concentration in the centre of grid cell. M is the total mass in the grid cells

restricted by p , q , r and s , p , q mark the boundaries of the chosen control region (Figure 2, panel left, double arrows line). All plots of the Sungei Buloh Wetlands Reserve were demarcated at this line, which is a continuation of the land boundary west of the SBWR (Figure 3). The control region comprised of all wetland areas and rivers, except for a small sea-bordering part of the Pulau Buloh island and parts of the Johor Strait. Contaminants move in and out of the control region, but after some time, they would leave the control region definitely. The total mass fluctuates with time but overall decreases and eventually intersects with the (horizontal) limit line of 5% (see above 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. Finally, the total amount of mass in the control region over time can be calculated 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. By plotting the total mass vs time and identifying the point of intersection at the 5% limit would define the residence time. Should this happens more than once, the last point in time would be used.

3. RESULTS AND DISCUSSION

3.1 Pollutant transport modelling

Figure 3 shows the spatial distribution of the pollutant in the control region at four moments over a tidal cycle, after pollutant discharge at the SBB-start location during highest high water (HHW) / peak spring tide. The unit in Figure 3 is g/m^2 unit (and not g/m^3), this allows for the clear depiction of the effective mass per area, and therefore of the spread of the pollutant. Figure 4 shows temporal distribution of advection and diffusion of pollutant concentration in the water column.

As can be seen in the upper left panel of the Figure 3, the concentration reached its peak in the first time step after the contaminants had been released. In the upper right panel, the mass plume had started moving seawards. The lower left panel already showed a large spread. Then, in the lower right panel, nearly all mass had flowed out of the control region. Temporal distribution in the left panel of Figure 4 supports the finding in which 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. In all situations, the conservation of mass was verified.

Spatial distribution maps for the release scenarios at Sungei Buloh Kechil (SBK) are not presented in this paper, but the temporal distribution (depicted on the right panel of Figure 4) showed the overall identical advection-diffusion behaviour. The only notable difference could be made at the observation point at sea, where the peak was 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 resulted in a much bigger lateral spread compared to a confined channel.

3.2 Residence time

Figure 5 shows temporal distribution of the total amount of mass in the control region of SBWR. If all the “pollutant” mass had resided in the control region, the diagrams would show a straight horizontal line after the discharge has stopped. However, the graphs show oscillations, which indicates that “pollutant” mass flowed in and out of the control region. Overall, it is obvious 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 SBK decreased visibly

within one or two ebb flows, while it took more time for the equivalent mass to leave the control region when discharged in SBB.

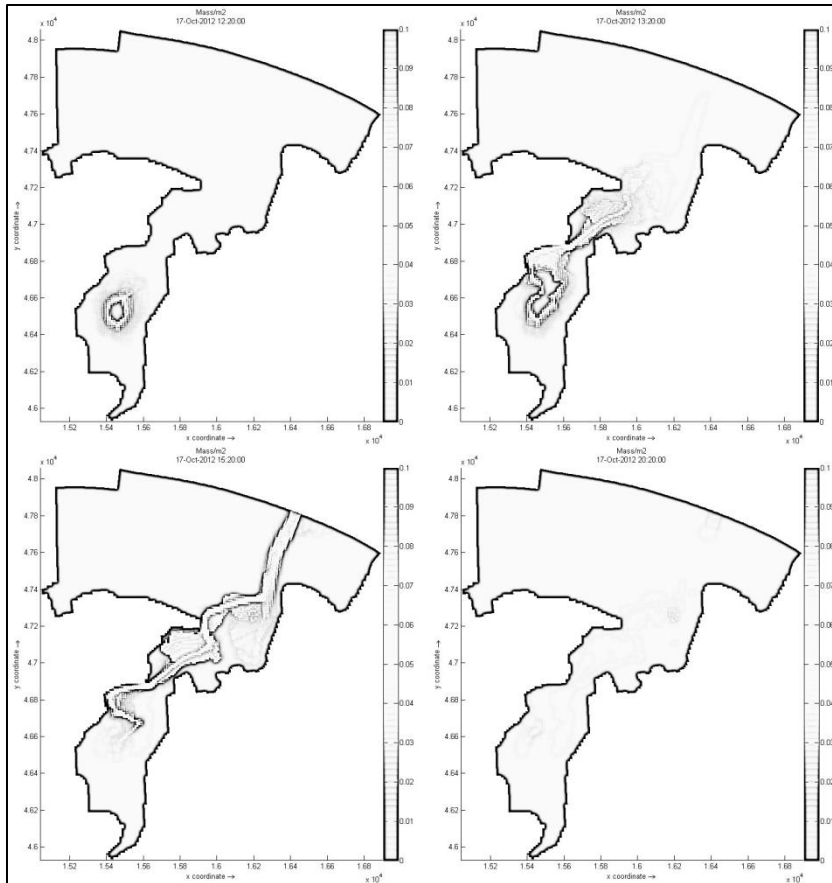


Figure 3: Spatial distribution of pollutant concentration (g/m^2) in the control region with the discharge at SBB, starting at highest high water (HHW) during at peak spring tide.

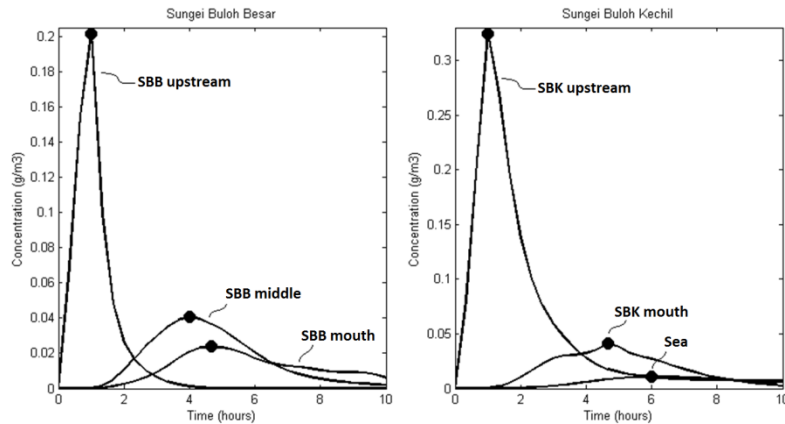


Figure 4: Temporal distribution of advection and diffusion of pollutant concentration (g/m^3) showing SBB (left) and SBK (right).

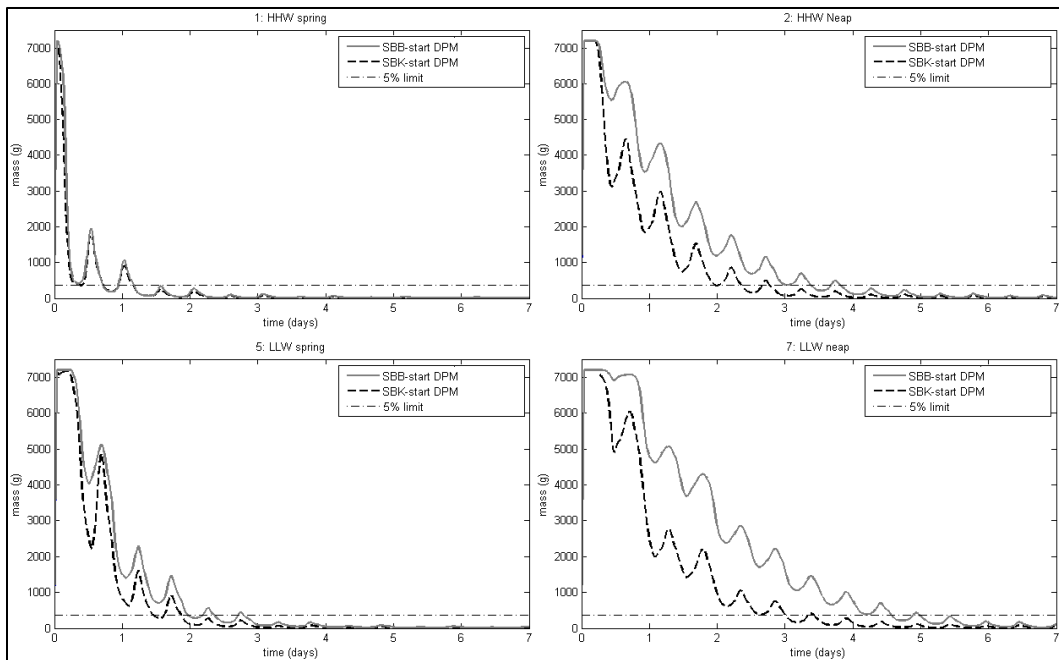


Figure 5: Temporal distribution of total mass in the control region of Sungei Buloh Wetland Reserve showing 4 scenarios during different tidal cycle (HLW: highest high water; LLW: lowest high water). The line represents 5% of the initial mass discharged in the system.

From Figure 5, it can be also noted that a discharge at neap tide (right panels) resulted in a significantly longer residence of mass than with a discharge at spring tide (left panels). The tidal range during the neap tide is smaller than during spring tide, as well as the amount of water flowing in and out of the Sungei Buloh Wetland Reserve. Since the cross-sections are overall similar for both situations, this means that the flow velocities in the reserve are lower with neap tide. As a result, since the conservative tracer is only influenced by advection, it can be concluded

that the modelled contaminant moves slower within the system during neap tide than during 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 discharged contaminant has initially the possibility to diffuse in the area, resulting in a slower seawards motion, thus lengthening the residence time. It was also noted that the total mass in the control region after one hour was equal to the total initial input (i.e. 7200 grams in this study); in contrast to the mass when discharged during highest high water (upper panels).

Figure 5 shows the 5% limit from the definition of residence time. As a tracer can re-enter the control region, the graph of the total amount of mass in the control region intersected this line multiple times. For example, in the upper right panel, the total mass from a discharge in the Sungei Buloh Besar intersected the 5% limit five times (starting after 4 days) before crossing it for the last time after 5.3 days. This means that, within the first four days, the total amount of contaminants was constantly higher than this limit and that for the subsequent 1.3 days, the total amount of contaminants could exceed this limit occasionally. The residence time in this scenario was therefore 5.3 days. A summary of all residence times is given in Table 2.

Table 2: Residence time in Sungei Buloh Wetlands Reserve

Scenarios	#1	#2	#5	#7
SBB	1.2 days	3.8 days	2.8 days	5.0 days
SBK	1.2 days	2.8 days	1.8 days	3.4 days

4. CONCLUSIONS

Since measurements in the field are often not possible due to either safety hazards or ecological implications, numerical models can provide comprehensive data on the behaviour of water flow and contaminants. The goal of the present study was to provide a workable definition of the residence time of contaminants in a model mangrove, the Sungei Buloh Wetland Reserve. The results showed the movement of a conservative tracer along this flow of water. After the discharge, the contaminants started to spread throughout the mangrove system. In the case of a discharge at low water, the contamination will be fairly contained to the upstream part of the area for a few hours. In case of a discharge at high water, much of the contamination flowed directly towards the sea. During neap tide, this effect was much lower than during spring tide. In addition, once the contamination has left Sungei Buloh Wetland Reserve, a reasonable fraction did not remain at sea, but re-entered the reserve. During this occurrence, the contaminant had spread to areas previously unreached, although the initial plume of contaminant had been diluted. In general, the residence time of contaminant was shorter when the discharge occurred during (highest) high water / spring tide, while it was longer during (lowest) low water / neap tide.

The definition of the residence time proved to be a useful tool to derive observations on the behaviour of contaminants. Such information will allow for the identification of situations at risk (e.g. mangrove area exposed to pollutant residues for a longer period). Future studies will also integrate more complex physicochemical behaviour, including sedimentation or (bio)degradation.

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