Numerical Simulation of Wetland Hydrodynamics

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Summary Wetlands are increasingly forming an important link in the treatment train used in urban catchments to improve stormwater quality, retard flows, and provide public amenity. The hydrodynamic behaviour of constructed wetlands have a direct influence on the effectiveness of these wetlands in water pollution control and the overall sustainability of wetlands as stormwater treatment facilities. This paper describes the numerical simulation of flow hydrodynamics within a wetland. Using data collected from a field-based investigation of wetland hydrodynamics in the Monash University Research Wetland, a two dimensional model was developed and calibrated. Mike 21, a 2 dimensional depth averaged model, developed by the Danish Hydraulic Institute was used to undertake the simulations. Field observation found that hydraulic roughness, as reflected in the different zones of vegetation and the relationship between water depth and vegetation, were the factors that controlled flow within the wetland. However, calibration of the model found eddy viscosity was the key calibration parameter due to the flow within the wetland being dominated by inertia rather than friction.

1. INTRODUCTION

Wetlands are increasingly forming an important link in the treatment train used in urban catchments to improve stormwater quality, retard flows, and provide public amenity. To achieve these benefits the design must take into account the catchment hydrology, the pollutants to be removed, wetland ecology and the hydrodynamic behaviour of the system.

The design of stormwater wetlands requires consideration of the following elements, hydrologic performance, hydraulics performance and the creation of conditions to optimize treatment processes (Wong & Somes, 1995). Hydrologic design takes into account the inherent variability of urban runoff to size the basin volume and outlet structures to retain the appropriate proportion of runoff and ensure that the ecology of the system is maintained (Somes et. al., 1996). The hydraulic design of the wetland ensures that flows within the basin have the following characteristics; uniform distribution of flow velocity throughout the wetland, uniform vertical velocity profile and protection against scour (Wong, 1997). The third stage of the design is the creation of conditions to enhance the treatment of the stormwater retained. The design process is iterative often requiring several preliminary designs to achieve an optimal design.

A review of current design guidelines by Somes and Wong (1994) identified that most design guidelines were ad hoc and based on either wastewater treatment or overseas experience. Design aspects relating to wetland hydrodynamics in particular were either very simplistic or not considered in design guidelines.

Wetland hydrodynamics is influenced by both internal and external factors. Internal factors include basin bathymetry, spatial variability of vegetation and inlet and outlet conditions and external factors including wind shear and hydraulic loading rate. The imperfect flow patterns result in short-circuit flow paths and stagnant zones in constructed wetlands, which causes the inflow to be retained for varying periods of time.

Wong (1997) identified that current inadequacies in wetland performance can be attributed to poor hydrodynamic design. This reflects the lack of understanding of wetland hydrodynamics amongst many practitioners. To improve the understanding of hydrodynamics of wetland flow behaviour requires visualization of flow patterns within wetlands. This can be achieved by field observation (using a tracer) or the use of computer models. Numerical modeling can aid the understanding of hydrodynamics and facilitate good design by allowing the flexibility for designers to try different wetland configurations in relation to location of inlets and outlets, the hydraulic characteristics of these inlets and outlets, wetland morphology and botanical layout. Development of the numerical simulation will allow the investigation of the effects variations to bathymetry, vegetation distribution, inlet and outlet design on wetland hydrodynamics. These models provide the necessary tool for assessment of preliminary designs involving a range of works directed at improving flow patterns within the wetland.

This paper investigates the use of a numerical model to simulate the hydrodynamics behaviour within a real wetland. The investigation involves the calibration of the MIKE 21 two-dimensional hydrodynamic model to field data collected at the Monash University Research Wetland.

2. HYDRAULIC RESIDENCE TIME DISTRIBUTION FUNCTION

Two common methods used to assess wetland hydrodynamics are the plotting of flow vectors and the analysis of detention times of the outflow. Analysis of flow vectors involves the plotting of vectors representing the direction and magnitude of flow vectors within the wetland. This method of presentation allows visual assessment of flow patterns within the wetland.
Hydraulic Residence Time (HRT) is a measure of variation of detention time for water entering a wetland. Figure 1 shows a schematic representation of the use of

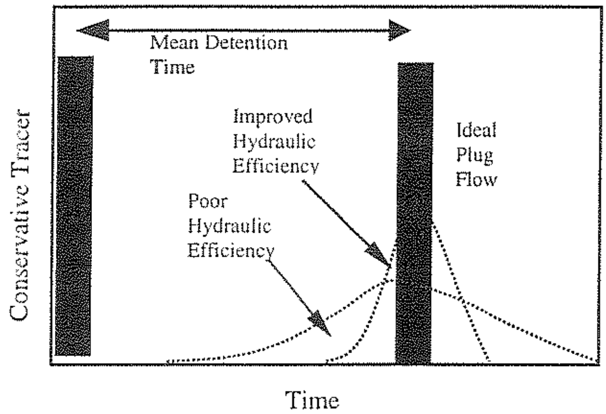

Figure 1. Residence Time Distributions for two Theoretical Wetlands

the distribution of hydraulic residence times (RTD) of a conservative tracer travelling through a system to reflect the effectiveness of its hydrodynamics. For wetlands with poor hydrodynamic characteristics, the RTD will typically have a low kurtosis value. This reflects the presence of stagnant zones in sections of the wetland resulting in low residence time for some portion of the inflow pollutants and the presence of short-circuit flow paths resulting in short residence times for some portion of the inflow pollutants. The tracer concentration at the outlet from a wetland operating under ideal flow conditions would be same shape as the pulse of tracer entered at the inlet (refer Figure 1) and hydrodynamic design considerations are directed at achieving as close to this ideal condition as possible

The RTD provides a useful tool to determine the relative hydrodynamic performance of different wetland designs. In assessing the performance of wetlands, the use of RTD curves allows the comparison of the hydrodynamic performance of different wetlands or the same wetland under different conditions.

The determination of the RTD of a stormwater wetland by field observation is not a trivial matter, as the flow must be kept constant throughout the measurement process. Simulations using calibrated numerical models to determine the RTD provide an alternative to field investigations. By varying parameters within the model, changes to wetlands can be simulated to investigate their relative effect on hydrodynamic performance. To successfully undertake these investigations a correctly calibrated numerical model of the real system is required.

3. NUMERICAL MODELLING

3.1 Boundary Conditions

Two dimension hydrodynamic models were developed to simulate surface flows in estuaries, coastal regions and flood plains. In a typical two-dimensional free-surface model, open boundary conditions are required to compute flow through the model domain. For a typical wetland model, open boundaries are not required as the inlet and outlet positions and characteristics are fixed. To simulate the inlet and outlet conditions of wetlands, isolated sources and sinks can be used in the model. This is implemented by either adding or removing mass at each time step from the computational node to which the source or sink is specified. For point sources such as the outlet of a pipe, a directional velocity can be assigned hence providing the appropriate directional momentum to the flow computation. This approach is satisfactory for steady state conditions while for dynamic flow regimes, the application of appropriate head discharge relationships is desirable to describe the inflow and outflow.

3.2 Model Description

The numerical model used in this analysis of wetland hydrodynamics was the Danish Hydraulic Institute's (DHI) depth averaged, two-dimensional modeling system MIKE 21 (DHI, 1996). MIKE 21 simulates the variation of water levels and flows (depth and flux) in response to a variety of forcing functions. The water levels and flows are resolved on a square or rectangular grid covering the area of interest. The main inputs to the model are, topography of the area to be modelled (bathymetry), bed resistance coefficients, eddy viscosity coefficients, wind fields and water level and/or discharge boundary conditions. The model has routines to allow flooding and drying over the computational grid during the model simulation. This enables the analysis of dynamic flood situations such as tidal flooding and floodplain inundation resulting from bank overtopping in rivers.

MIKE 21 solves the vertically integrated equations of continuity and momentum in two horizontal dimensions. The equations are solved by implicit finite difference techniques with the variables defined on a space staggered grid. A 'fractioned-step' technique combined with an Alternating Direction Implicit (ADI) algorithm is used in the solution to avoid the necessity for iteration. Second order accuracy is ensured through the centering in time and space of all derivatives and coefficients.

4. FIELD CALIBRATION DATA

Field data on flow hydrodynamics were collected to enable establishment and calibration of the MIKE21 model. The Monash University Research Wetland (MURW) was established to facilitate research in wetland processes. The facility is located in the Strezlecki ranges south east of Melbourne and consists of four cells in series. The MURW was constructed and planted in 1994, the design and construction is described in Somes and Wong (1994). The fringes of the wetland were planted with emergent macrophytes during spring of 1994 (Somes et al. 1996). The second cell of the MURW was used in the present investigation. The data gathered included data describing vegetation distribution, basin bathymetry and measurement of flow velocities. The fieldwork was conducted over a period of six months during 1996.

The data collection involved collection of 3 dimensional velocity data. Tracer studies to develop the RTD for the wetland could not be undertaken as the flow regime was maintained by water pumped into the wetland from the outlet. This re-circulation of water from the outflow would have made a mass balance of tracer impossible as tracer would have been re-introduced at the inlet.

Measurements of flow velocities within the wetland were made while the flow was maintained at a constant flow rate of 50 l/s, equivalent to the maximum flow that would pass through the wetland during a storm event. During the velocity measurement phase of the field investigation, runoff from the catchment was bypassed around the wetland.

The velocity measurements were taken from a series of purpose built platforms. The platforms were designed to move on a timber frame that was constructed over the wetland. The use of platforms allowed velocity readings to be taken without the need to wade in the wetland. This minimized disturbance of either flows or vegetation within the wetland. The cell in which the measurements were taken was 44 m by 20 m and had a volume of 770 m^3. At the inlet and around the outlets measurements were taken on a 2m by 2m grid. At other sections of the wetland measurements were taken on a 4m by 2m grid. The coarser grid reduced the number of points where velocity measurements were taken but still provided sufficient detail to describe the flow patterns within the wetland.

The probe used to measure the velocities was an Acoustic Doppler Velocimeter (ADV) manufactured by SonTek. The ADV measures velocities along three axes to a resolution of 0.1 mm/s. The high resolution of the ADV probe and the low magnitude of velocities within the wetland made the readings very sensitive to any outside movement. The probe required a rigid support and accurate location system that would allow the probe to be held free of movement and to be orientated to an established co-ordinate system.

4.2 Monitoring Results

Figure 2 is a plot of the field data used to calibrate the numerical model. The plot consists of vectors showing the relative magnitude and direction of the mean velocity at points within the wetland and the general direction of flow in three stagnant zones with very low velocities. Included on Figure 2 is the distribution of hydraulic roughness as represented by Manning's "n" values.

The direction and magnitude of flow vectors shows a major flow path through the open water area of the wetland. This open water area generally follows the path of the old creek bed within the wetland. The combination of deep water and absence of emergent vegetation produces an area with the lowest hydraulic resistance within the wetland. The emergent vegetation in the shallower areas has a significantly higher hydraulic resistance. The difference in hydraulic roughness between vegetated and open water areas of similar depth is shown on Figure 2. The values of hydraulic roughness used are based on recommended values by Kadlec and Knight (1996) who combined results from several field studies. It can be clearly seen that the difference of hydraulic roughness between open areas and vegetated areas is up to 2 orders of magnitude. The low level of hydraulic resistance in the open water area allows the preferential flow path to form.

The results of the field study show that hydraulic roughness, and the inter-relationship between water depth and vegetation, strongly influence flow patterns within wetlands. The flow is conveyed through the area with the lowest hydraulic roughness. Walker et al. (1994) used tracers and numerical modeling to establish the flow pattern within the Happy Valley Wetland in Adelaide, South Australia, had similar findings. The results of Walker et al. (1994) showed that once the wetland reached steady state the main flow path was from the inlet through the deepest part of the pond to the outlet. The central region of the wetland investigated by Walker et al. (1994) was not vegetated and would have similar values of hydraulic conveyance to the MURW.

MODELLING RESULTS

4.1 Model Setup

A grid size of 1m was chosen for the numerical model, this provided a detailed description of the cell bathymetry and vegetation distribution. The model was run with a steady inflow of 50 l/s as applied during the field measurements. There was no allowance for wind shear effects in the model as the weather was calm during the measurement period and its effect on the wetland flows was considered to be minimal. A model time step of 1 second was used in the simulations. This time step in conjunction with the grid size gave a

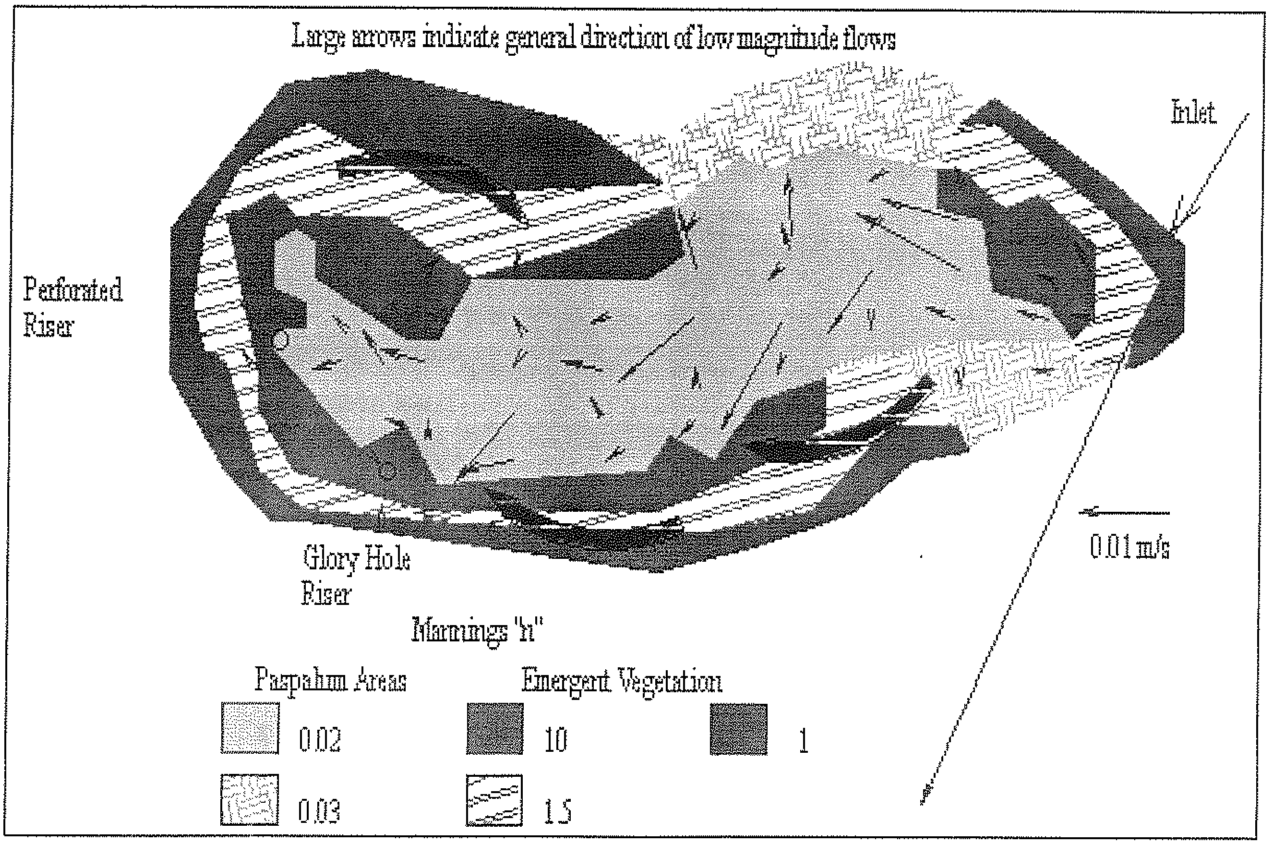

Figure 2. Velocity Measurements from Field Study of Monash University Research Wetland

maximum Courant number of approximately 4. This was considered acceptable considering the steady flow conditions modeled. Experience shows that a maximum Courant number of less than 5 is desirable, although values of between 10 and 20 can still give stable and sensible results (DHI, 1997). The model was found to be insensitive to variations of the time step and grid size. Analysis of the models sensitivity included a doubling of the grid size (2m) and halving the time step (0.5 second).

4.2 Model Calibration

The hydrodynamic model was calibrated against the recorded velocity data. This was performed by visually comparing the measured and recorded flow vectors and the flow patterns they formed. The purpose of this exercise was to establish whether the hydrodynamic model was capable of adequately reproducing the complex wetland cell flow pattern.

Two aspects of the hydraulic model adjusted during the calibration process were the hydraulic roughness term (Manning's "n") and the horizontal eddy viscosity term. The variation in hydraulic roughness is used to account for changes in roughness and hence energy losses across the wetland cell. The "eddy viscosity" term in MIKE 21 models the effect of sub-grid scale turbulent processes (small eddies) and viscous shear on the mean flow.

It was found during modeling that the directional source had a significant impact on the wetland flow patterns. This meant that the location and orientation of the inflow pipe needed to be accurately defined. The low overall velocities in the wetland cell amplify the importance of the added momentum from the source point and the impact of turbulent flow description via the eddy viscosity formulation described earlier.

Model Friction

The model friction was based on a vegetation map of the wetland produced from a spatial survey prior to the measurement program. Vegetation codes were digitized onto the same 1m grid as the model bathymetry. Uniform friction values were then assigned to each vegetation type according to the Manning's n values shown in Figure 2. During the calibration stage, the friction values were varied to gauge the effect on the cell flow patterns.

The values of friction used in the model are given in Table 1, and were distributed according to vegetation

Vegetation Type	Manning's "n"
Paspalum Areas	0.05
Emergent Vegetation 0 – 0.4 m	2.0
Emergent Vegetation 0.8 – 1.6 m	1.0

Table 1 Manning's "n" used in simulations

type. Testing of different friction values showed the model was relatively insensitive to changes in friction. This is due to the low velocities creating very small friction forces.

Eddy Viscosity

Walker et al (1994) found eddy viscosity to have little impact on wetland flow patterns in comparison to other factors whereas Wu and Tsanis (1994) found the eddy viscosity to have a significant impact on flow distributions.

MIKE 21 has two methods of applying eddy viscosity in the model. The simplest form is the application of an eddy viscosity coefficient, which can be varied across the computational domain. In the more complicated method, the eddy viscosity is described by a time varying function of the local gradients in the velocity field. This mixing length approach is a relatively simple but effective means of achieving turbulence closure (Rodi, 1980). Both methods of eddy viscosity distribution were tested in the model calibration.

The best results were computed using the mixing length eddy viscosity model. The results for this case showed the appropriate channeling of flow through the deeper and less thickly vegetated areas. The model simulations in which a constant eddy viscosity term was used gave velocities which were too high in the heavily vegetated areas. Figure 3 shows the computed velocity field for a model run using constant eddy viscosity. This shows that the velocity was more evenly distributed across the wetland than the findings of the field study indicated. Using the time varying eddy viscosity a better correlation between the simulation and field data was obtained. Figure 4 is a plot of the flow pattern from the calibrated model.

5.3 Applicability of Numerical Simulation to Wetland Systems

The results of the modeling show that a 2-dimensional numerical model is capable of reproducing the flow distributions within a wetland. The most significant calibration factor was found to be the eddy viscosity. The calibration process found that the numerical model was relatively insensitive to changes in friction due to the low velocities of the flow. The flow was inertia dominated hence the influence of eddy viscosity on the results. An eddy viscosity formulation based on the local velocity gradients provides a better description of the turbulent losses in a wetland cell than a constant value.

In addition to computing the flow vectors within the wetland, models such as MIKE 21 can be used to develop RTD functions for wetlands. By utilizing the advection and dispersion utilities in MIKE 21 conservative tracers can be routed through wetlands to develop their RTD function.

6. CONCLUSIONS

The collection of detailed velocity data from wetlands requires a considerable amount of time and effort. To collect useful data particular attention must be made to the flow regime, weather conditions and data collection method to ensure that all readings are consistent. The platforms constructed for this study proved very

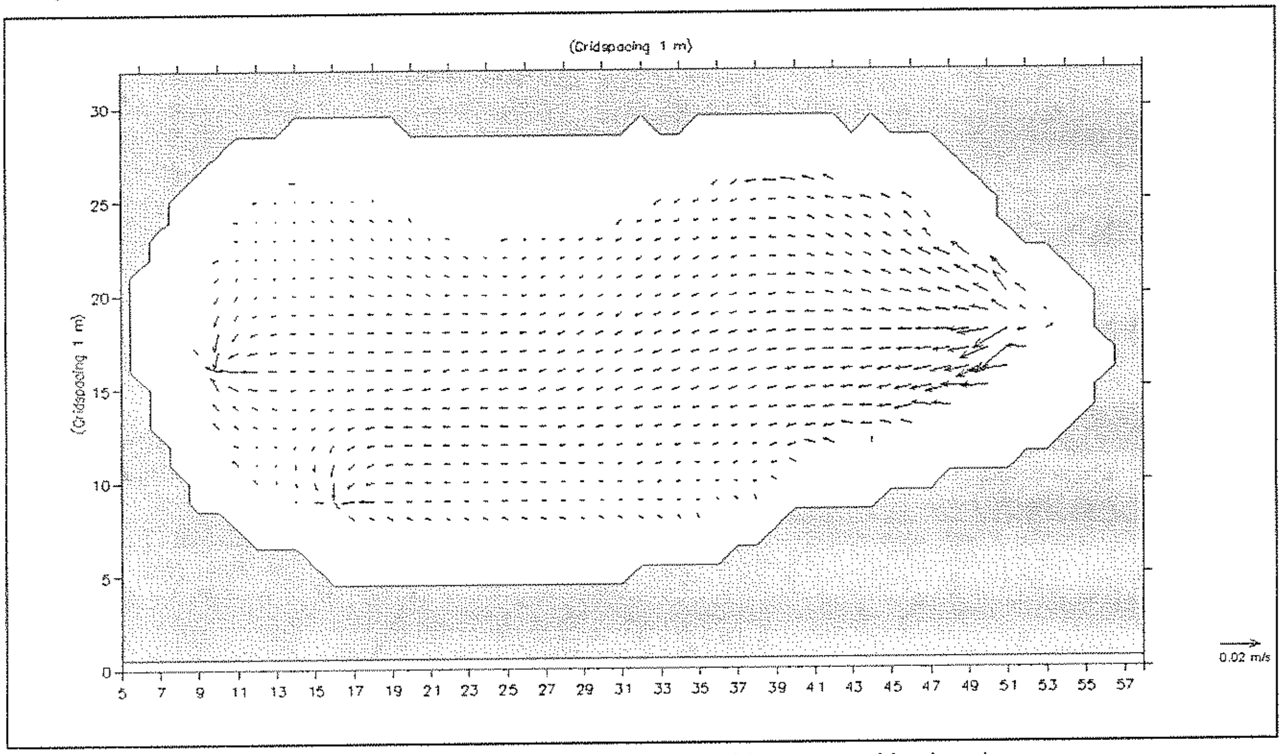

Figure 3. Plot of velocity vectors from Mike 21 simulation with constant eddy viscosity

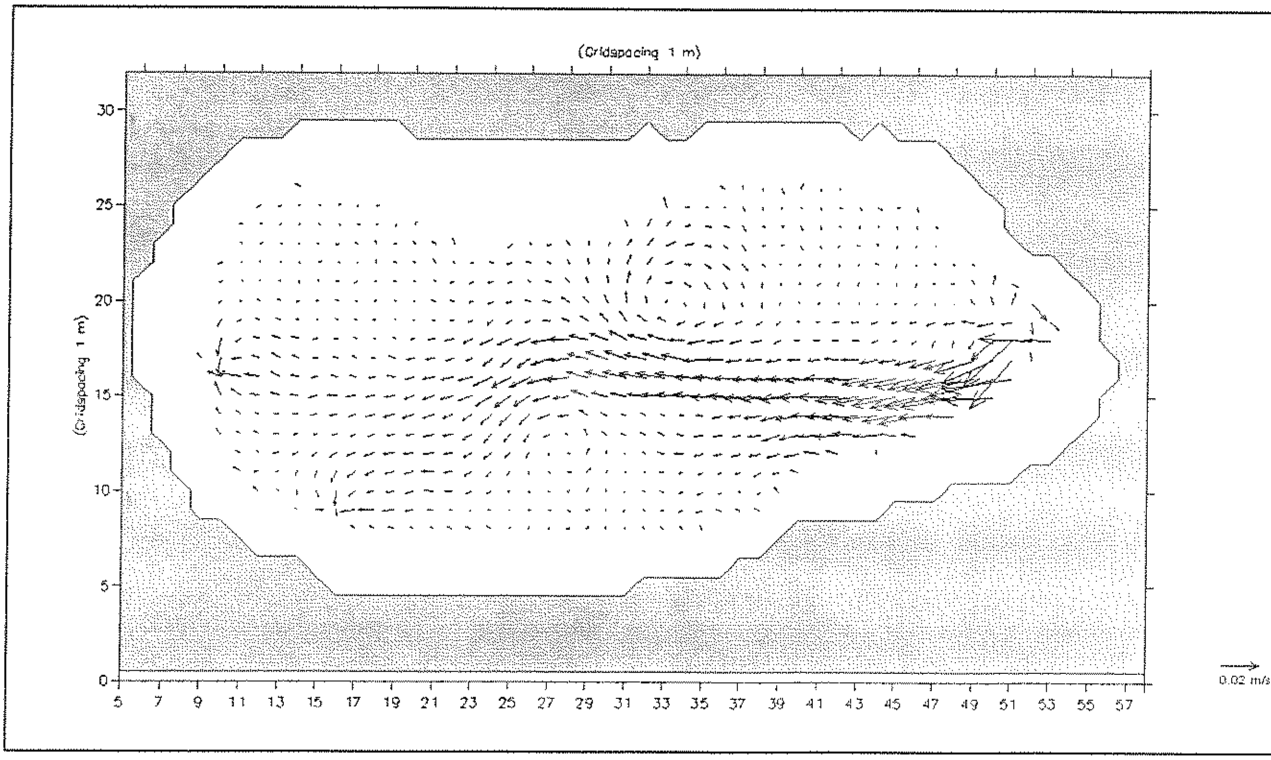

Figure 4. Plot of velocity vectors from Mike 21 simulation with time-varying eddy viscosity

worthwhile as measurements could be taken without disturbing the flows or vegetation wetland.

This paper has shown that a numerical model correctly calibrated can replicate flow patterns within a constructed wetland. Eddy viscosity was found to be the calibration factor with the most influence on flow patterns. This was due to the flow being dominated by inertia and being relatively insensitive to friction due to low velocities.

The findings of this study have the potential to provide both researchers and designers with a tool to investigate the conditions that optimize hydrodynamics within wetlands. Using a calibrated model as a basis, simulations can be undertaken to investigate the role of different design components on hydrodynamics. Factors such as inlet and outlet conditions, cross section and long section shape and vegetation distribution can be varied then simulated. By inspecting the flow patterns and RTD functions for each variation of wetland configuration the relative effect of a single component can be investigated. This method is significantly quicker than investigating sites in the field. Adopting this methodology has potential to greatly improve the understanding of wetland hydrodynamics.

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