HYDRODYNAMICALLY COUPLED STORMWATER MODEL OF THE AUCKLAND CENTRAL BUSINESS DISTRICT

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ABSTRACT

The Auckland Central Business District (CBD) has been experiencing flooding problems, particularly in the downtown area close to Waitemata Harbour. It was thought that these problems were being caused by a number of factors; including, insufficient inletting capacity, insufficient network capacity and backwater effects. A stormwater network model was considered necessary to understand the response of the catchment and its existing network to rainfall, to identify areas potentially at risk of flooding and to identify the critical factors contributing to the flooding.

A hydrodynamically coupled one-dimensional (1D) and two-dimensional (2D) model of the CBD was developed for this purpose. Due to the complexity of the CBD catchment, a unique model setup was required to ensure all flow regimes were represented accurately. AECOM collaborated with DHI New Zealand to conceptualise an innovative methodology that incorporated catchpit modelling and a combination of hydrological methods using MIKE 21 "rain-on-grid" approach, MIKE 21 source points and MIKE URBAN catchment loading.

This paper outlines the methodology for the detailed stormwater modelling of the Auckland CBD. This complex modelling approach posed a few interesting technical challenges that are also discussed including the relevant solutions found and the lessons learnt.

KEYWORDS

1D and 2D modelling, Catchpit modelling, Flood Hazard Mapping

PRESENTER PROFILE

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1 INTRODUCTION

A major concern within the Auckland Central Business District (CBD) has been the flooding incidents, especially in the area close to Waitemata Harbour. A number of factors such as insufficient inletting capacity, insufficient network capacity and backwater effects due to the tide, have been suspected as being the source of the flooding. AECOM was commissioned by Auckland City Council to investigate and isolate the factors contributing to the flooding problems.

The objectives of the project were to:

- Develop hydraulic and hydrological model of the Auckland CBD Drainage Management Area (DMA)
- Undertake Flood Hazard Mapping (FHM) for the CBD DMA

In addition to the above project objectives, Auckland Transport also commissioned AECOM to carry out detailed modelling of the "Shared Space" areas. Shared Space areas are an urban design concept whereby pedestrians have the right of way but vehicles are also allowed to use the same street area (Jones, et al., 2010). The Shared Space areas being Fort and Customs Street, Elliot and Darby Street and Lorne Street (refer to Figure 1). The results from detailed assessment were required to assist in Auckland Transport's stormwater management design process.

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Figure 1: CBD Shared Space Areas

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A stormwater model was necessary to understand:

- the response of the catchment and its existing network to rainfall,
- areas potentially at risk of flooding and
- the critical factors contributing to the flooding.

A hydro-dynamically coupled one-dimensional (1D) and two-dimensional (2D) detailed model of the CBD DMA was developed to provide results in sufficient detail for the design of the Shared Space areas. During model conceptualisation, Auckland City Council operations staff identified inletting issues as one of the common causes of flooding within the CBD DMA. This led to the decision to model catchpits to identify which areas have insufficient inletting capacity. AECOM collaborated with DHI New Zealand (DHI) to conceptualise an innovative methodology that incorporated catchpit modelling with a combination of hydrological methods.

This paper outlines the methodology for the detailed stormwater modelling of the CBD DMA. Given the complexity of the CBD model, with the added complication of catchpit modelling, several interesting technical challenges were encountered. The challenges encountered will be discussed in the paper, along with the relevant solutions found and the lessons learnt. This paper does not discuss the catchment issues identified during the investigation or other outcomes of the project; rather it focuses on the modelling methodology.

2 CBD CATCHMENT

The CBD DMA has an area of approximately 223 hectares. It is located along the northern fringe of the Auckland Isthmus and is bounded by Waitemata Harbour to the north, the Stanley DMA to the east, Motions DMA to the south and Freemans Bay DMA to the west (refer to Figure 2).

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The Ports of Auckland area have been removed from the model extent following discussions between AECOM and Auckland City Council. This was due to the area having mainly private drainage and due to the lack of information available on the private drainage. The model extent incorporates all areas with stormwater drainage flowing into the CBD(AECOM, 2011).

Figure 2: CBD DMA Model Extent

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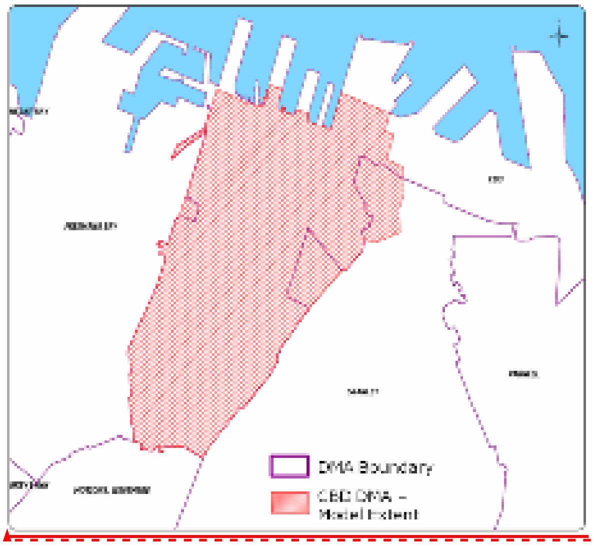

The land use within the CBD DMA is mainly commercial, with medium to high-rise development. The CBD DMA is considered impervious and fully developed in terms of stormwater. The CBD drainage system is a predominantly separated system with some overflow connections from the wastewater system.

The CBD DMA has elevations ranging from near sea level at the northern end (near Waitemata Harbour) to approx 70m above sea level in the upper parts of the catchment (refer to Figure 3). Queen Street, which runs along a natural valley, bisects the catchment in a northerly direction from the Karangahape Road ridge to Waitemata Harbour. The valley falls steeply in the upper catchment, but flattens substantially in the lower catchment areas. The majority of these flatter areas along the water's edge have been reclaimed over the years. This varying elevation of the catchment causes problems with the model stability as discussed in more detail in Section 4.

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Figure 3: CBD DMA Elevations

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3 MODEL BUILD PROCESS

3.1 SOFTWARE

The MIKE BY DHI 2009 (with Service Pack 5) software has been used to model the CBD DMA. The individual modelling software used included MIKE URBAN, MIKE 21 and MIKE FLOOD.

The MIKE URBAN software models the one-dimensional (1D) pipe network model and the MIKE 21 software models the two-dimensional (2D) surface terrain model. The MIKE FLOOD software acts as a bridge that integrates the 1D and 2D models together into a single, dynamically coupled modelling system.

3.2 DATA SOURCE

The network data used for the CBD model was sourced from the Council's GIS and survey data. The MIKE 21 digital terrain model was developed using LiDAR data. For the CBD model, a 2m square grid size was selected. A bigger grid size could cause more uncertainty in the flood extent and would not be able to represent small flow paths or roads less than a few grid cells wide. With smaller grid sizes, the simulation time increases significantly. Therefore, 2m grid size was a reasonable compromise between simulation time and model quality.

The CBD DMA has eleven (11) stormwater outfalls discharging into Waitemata Harbour. These outfalls have been represented in the model with a tidal boundary condition applied. A constant level RL 1.39m, (Mean High Water Springs Level) has been used for the tidal boundary.

3.3 HYDROLOGY

A unique approach was applied to represent the hydrology of the CBD DMA (Jones, et al., 2010). Each sub-catchment within the CBD DMA was analysed to identify the portion that was made up of roads, paved areas, buildings/roofs and parks (refer to Figure 4) and a combination of hydrological approaches was applied to each portion of the sub-catchment (refer to Figure 5). The following sub-sections will outline the hydrological approach for each component.

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Figure 4: Sub-Catchment Components

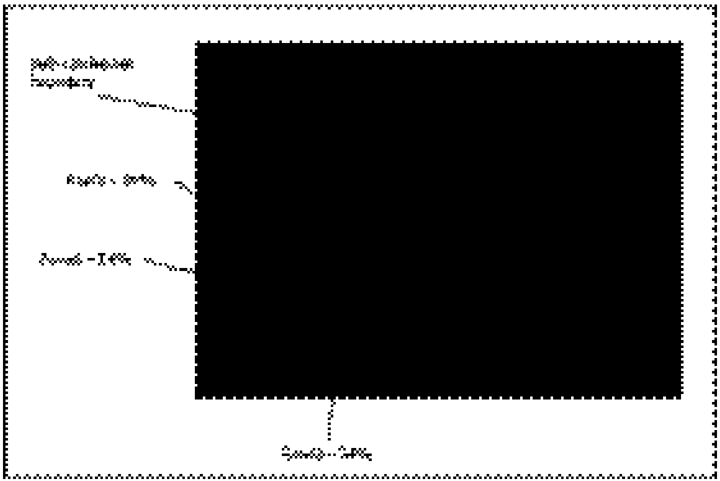

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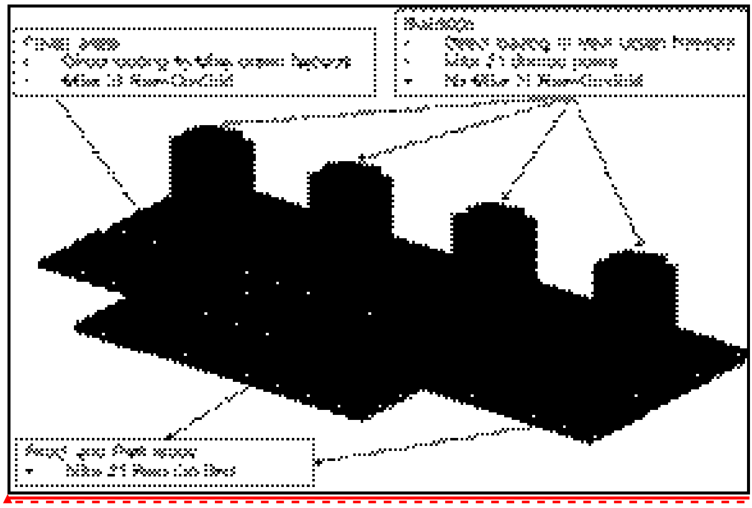
Figure 5: Hydrological Approaches for Buildings, Paved Areas, Roads and Parks



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3.3.1 BUILDINGS

The buildings in the CBD were set to land; i.e. assigned a high elevation value, so that they are not included in the MIKE 21 "rain-on-grid" calculations. Runoff from buildings was modelled using direct loading to MIKE URBAN network and MIKE 21 source points (refer to Figure 5).

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The stormwater pipe network is assumed to drain away a portion of the runoff from the building roofs. The remaining runoff would flow along the road surface as overland flow.Adjusted rainfall intensity graphs (hyetographs) were used to assign the portion of runoff that would be entering the MIKE URBAN network directly and the portion that would become MIKE 21 surface flow. The hyetographs were generated using TP108 design storm profiles that were adjusted to remove the assumed drainage capacity for the buildings. For the building roofs, the stormwater network is estimated to be able to cope with runoff upto 10-year Average Recurrence Interval (ARI) storm intensity.

Figure 6: Example Hyetograph for Developing Adjusted Hyetographs for Buildings

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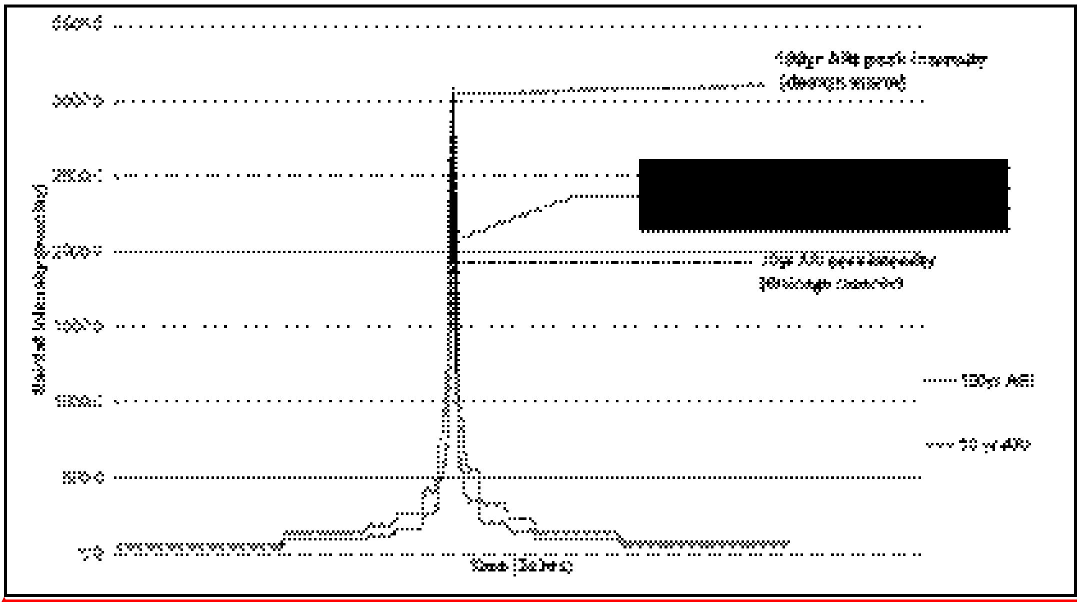

3.3.2 PAVED AREAS

Runoff from the paved areas within each CBD sub-catchment was modelled using direct loading to the MIKE URBAN network and the MIKE 21 "rain-on-grid" approach (refer to Figure 5). Using the system of adjusted hyetographs, the MIKE URBAN network was assumed to have the capacity to drain runoff from paved areas for up toa 2-year ARI storm. The remaining runoff was setup to enter the MIKE 21 surface via the "rain-on-grid" approach.

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The "rain-on-grid" approach in MIKE 21 makes use of user-specified hyetographs to compute spatially distributed rainfall over the MIKE 21 terrain. MIKE 21 assumes that any rainfall that hits the terrain becomes surface runoff and does not account for infiltration losses. This method was deemed appropriate for CBD, as most of theCBD DMA is considered fully developed except for the park areas (Jones, et al., 2010).

3.3.3 ROADS AND PARK AREAS

The runoff from the roads and park areas within the CBD sub-catchments were modelled using the "rain-on-grid" approach (refer to Figure 5). The "rain-on-grid" hyetographs for park areas was adjusted with Horton's Losses to account for rainfall loss due to infiltration.

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3.4 MODEL HYDRAULICS

3.4.1 CATCHPIT COUPLING

The purpose for incorporating catchpit coupling into the CBD model was to identify areas with inletting issues within the CBD DMA. Catchpit coupling allows surface runoff from roads to enter the pipe network andallowsoverflows from the pipe network onto roads when the system surcharges after exceeding capacity (refer to Figure 7).

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Catchpit coupling involves identifying the MIKE 21 grid cells at the catchpit locations and coupling the grid cells to MIKE URBAN manholes (refer to Figure 7). The locations of catchpits were obtained from GIS and from AECOM site visits where the data was incomplete. To simplify the model, multiple catchpits were loaded to the same MIKE URBAN manhole in some cases.

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Figure 7: Catchpit coupling in MIKE FLOOD

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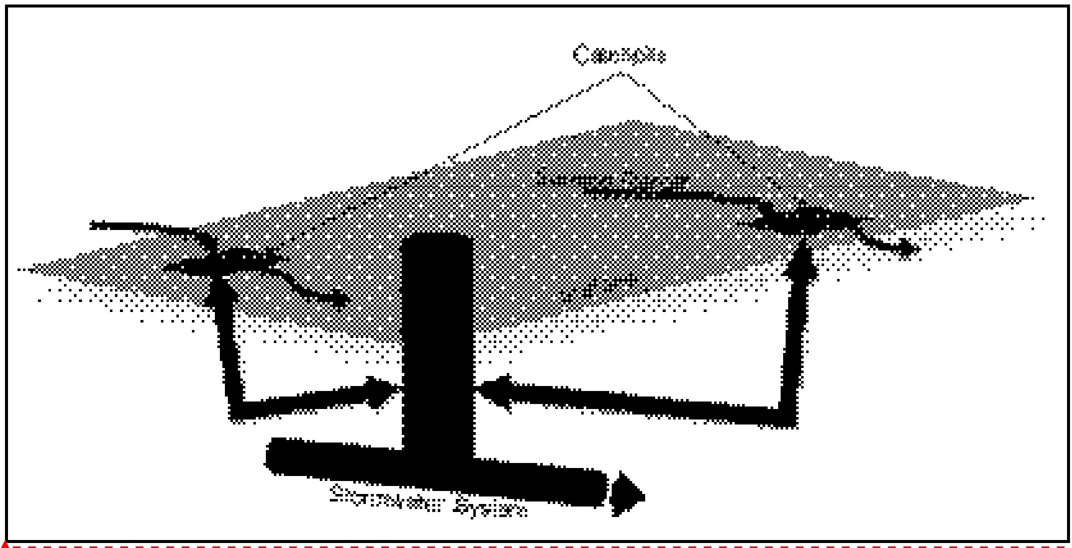

The coupling process couples the grid cell corresponding to the catchpit x and y coordinates (sourced from Auckland City Council GIS database)as well as the surrounding eight (8) cells (refer to Figure 8). Multiple cell coupling was applied in order to capture flow that bypasses the modelled catchpit and where the catchpit location was inaccurate or not at the lowest point.This ensures that the model representation of catchpit flow is close to reality.

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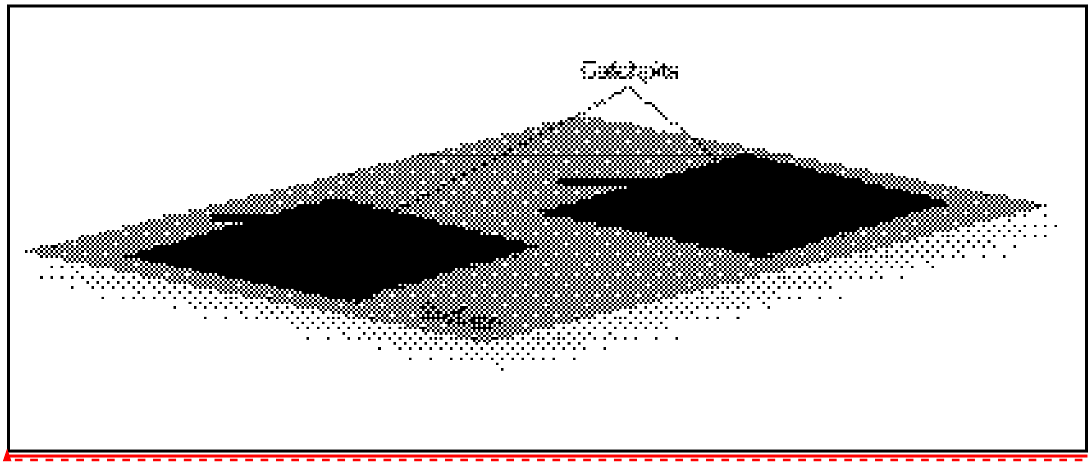
The "M21 to Inlet" urban coupling link in MIKE FLOOD allows flow from the MIKE 21 surface to enter the MIKE URBAN pipe network and vice versa. The coupling can be regulated to control the maximum flow that can pass through the coupling at any particular time.

An inletting capacity was assigned to each catchpit coupling in the model based on the type of catchpit, using information from an earlier study completed by AECOM (Maunsell

AECOM, 2008). For example, standard catchpits, max-pits and mega-pits were assumed to have an inletting capacity of 20 litres per second, 100 litres per second and 500 litres per second respectively.

Figure 8: *Multi-Cell Catchpit Coupling*



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3.4.2 WEIR COUPLING

Weir couplings have been used in the CBD MIKE FLOOD model to convey water surcharging from the 1D stormwater pipe network onto the MIKE 21 grid surface (refer to Figure 9). Weir coupling was selected because it restricts flow to one direction and has unrestricted capacity. It is modelled by adding dummy weirs to all the MIKE URBAN manholes except for the dummy nodes, basins and outlets. These dummy weirs were then coupled to the MIKE 21 grid surface using the urban link, "Weir to Inlet" in MIKE FLOOD. This method provided an indication of whether the stormwater pipe network has sufficient capacity and whether the inletting capacity is sufficient.

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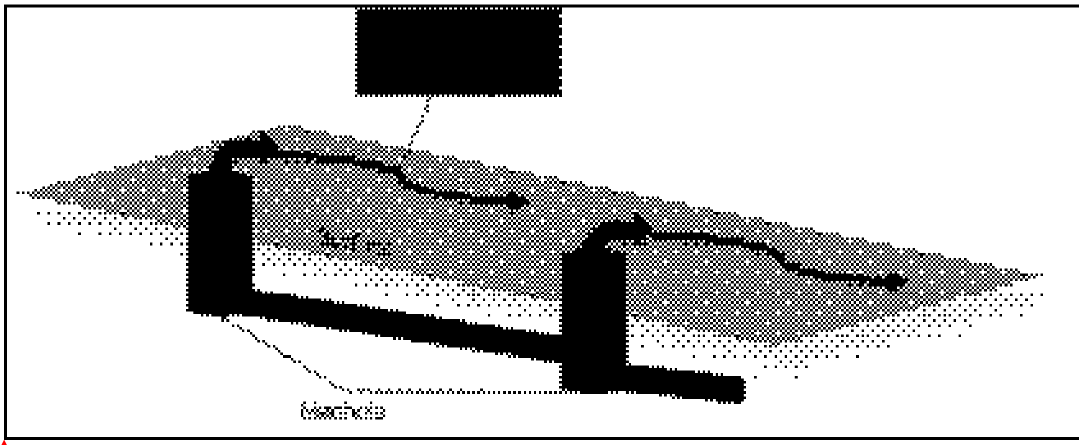
Figure 9: *Surface Runoff from Surcharged Stormwater System*



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4 PROBLEMS ENCOUNTERED AND SOLUTIONS APPLIED

Given the complexity of the CBD model, several problems were encountered during the course of the model build. A few examples of the problems and their relevant solutions are provided in this paper.

4.1 MODEL INSTABILITY

4.1.1 BACKWATER EFFECTS

One of the issues faced during the early stages of the model build process was instability due to backwater effects from the tidal boundary condition. Within the CBD catchment there are currently eleven (11) coastal stormwater outfalls discharging into Waitemata Harbour. These outfalls have all been represented in the CBD model and assigned a constant boundary condition of mean high water springs. Instabilities in the model were encountered because the lower part of the CBD is very flat and a majority of the discharge pipes are partially submerged.

Following consultation with DHI, changes were made to the model by adjusting manhole diameters and energy losses to overcome the instability due to backwater effects. These changes stabilised the model by reducing the effects of water level instabilities at the manholes.

4.1.2 MODEL COMPLEXITY

Within the CBD MIKE URBAN network model, there are approximately 216 pipes with lengths less than 10m. There are also several pipes with negative, steep or flat grades. These factors contributed to model instability.

Several changes had to be made to the model to overcome this instability:

- The default pipe length in MIKE URBAN was modified from 10m to 2m so that any pipes less than 2m in length were rounded to 2m during the MIKE URBAN model pipe-flow calculations.
- Several areas of the model with complex pipe junctions and negative grades were simplified.

The CBD model became more stable after the changes. Figure 10 shows snapshots of the modelled pipe flows before and after simplification. The huge fluctuations in pipe flow in the snapshot to the left represent model instability. These fluctuations have disappeared almost completely in the second snapshot indicating a significant improvement in the stability of pipe flow in the model after the model simplification.

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Figure 10: Model Results Pre- and Post- Model Simplification

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4.1.3 STEEP ROADS

Another challenge encountered during the model build process was the 2D model becoming unstable along the steeper sections of the CBD. Since MIKE 21 has been more commonly used to model flood plains within New Zealand, this attempt at using MIKE 21 to model the CBD DMA with its significant variation in elevation, caused some unexpected problems. The model became unstable when experiencing fast and shallow flows that were occurring along parts of CBD with steep roads.

To overcome this instability, the roughness of the steep road section was increased and the overall model eddy viscosity was increased. This increase in roughness and viscosity slowed down the flow along the road. Since the water was flowing to a land-locked area downstream, there were no significant changes to the model results as the parameters were only modified enough to make the model stable.

4.1.4 DUMMY WEIRS

As discussed in the earlier section, dummy weirs were added to the CBD model in MIKE URBAN to enable unrestricted one-way flow for water surcharging from the MIKE URBAN pipe system onto the MIKE 21 ground surface. However, the large number of weir to MIKE 21 couplings in the model contributed to the model instability and large computation times.

Generally, the inletting capacity in the coupled 1D/2D model will determine how much flow can enter or also leave the system. However, the maximum flow that can enter the MIKE URBAN pipe system is not always the same as the maximum flow that leaves the system once the pipe system is full and surcharging. In order to obtain a good understanding of the performance of the pipe system and inletting issues, we would ideally be able to assign different inletting and outgoing capacities for coupling. The current version of MIKE FLOOD software assigns the same maximum flow restriction for both incoming and outgoing flow through a coupling. Therefore, weir couplings were chosen as the most appropriate coupling to assess the flow surcharging from the system, despite the cost to computational time and model stability.

4.2 CATCHPIT COUPLING

Modelling catchpits in the coupled 1D/2D model added a layer of complexity that posed a few challenges during the model build process.

4.2.1 ARTIFICIAL WATER GENERATION

The issue with artificial water generation arose due to a discrepancy between the MIKE URBAN lid level and the MIKE 21 grid cell elevation at the coupled cell.

The default MIKE URBAN setting is that if the MIKE 21 grid cell elevation is different to MIKE URBAN, then the MIKE 21 level overwrites the MIKE URBAN lid level. However, this setting is only applicable to situations where we couple the cell directly on top of the MIKE URBAN manhole. This setting was turned off for the CBD modelsince multiple catchpits at various locations and elevations were being loaded to the same MIKE URBAN manhole. Switching off the default setting led to artificial water generationoccurring at instances where:

- The coupled MIKE 21 cells were located at a higher elevation than the MIKE URBAN lid level, and

- The water level in the MIKE URBAN manhole was less than the ground level.

The lowest coupled MIKE 21 grid cell was effectively being used as the water level boundary (even when the MIKE 21 was completely dry) and resulting in the artificial generation of water within the MIKE URBAN network (refer to Figure 11).

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Figure 11 : Illustration of Conditions Arising to Artificial Water Generation

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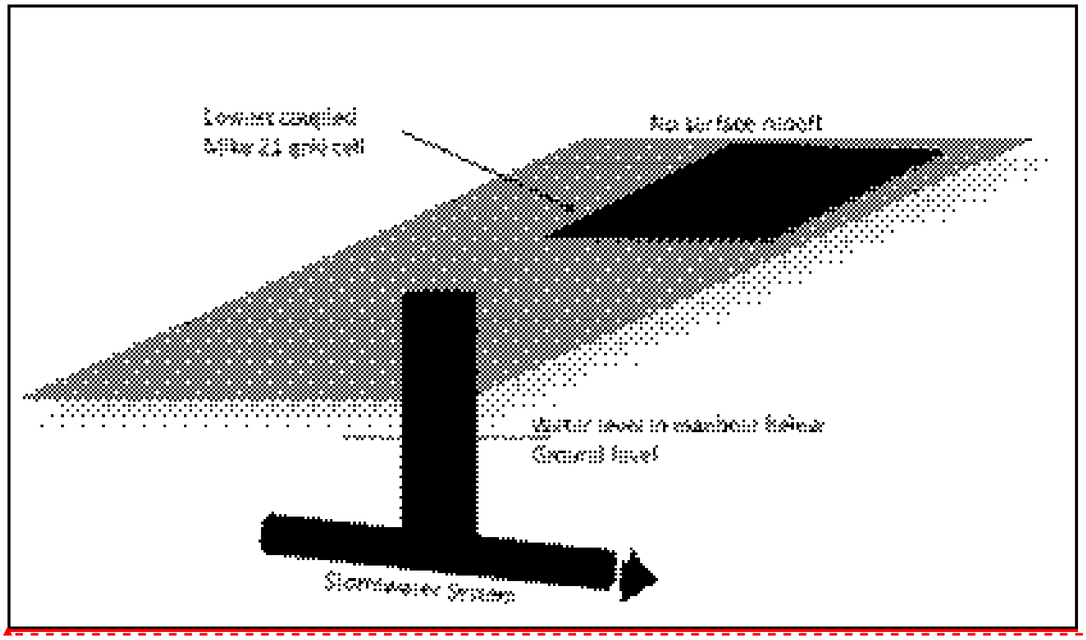

AECOM brought this issue to DHI, who then identified the root of the problem and provided a MIKE URBAN hotfix to prevent artificial water generation. The hotfix ensured that in the cases of MIKE URBAN lid level and MIKE 21 grid elevation discrepancy, the MIKE 21 grid elevation would not be taken as the water level for the manhole.

Figure 12 shows snapshots of the model results illustrating changes in MIKE URBAN pipe flow at areas of catchpit loadings, before and after fixing the artificial water generation issue. The snapshot to the left shows flow through the model pipes increasing rapidly at the start of the simulation when there is no rain, signifying artificial generation of water within the model pipe network. The second snapshot shows more realistic modelled pipe flow results obtained after applying the MIKE URBAN hotfix.

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Figure 12: Model Results Before and After Artificial Water Generation Error Fixing

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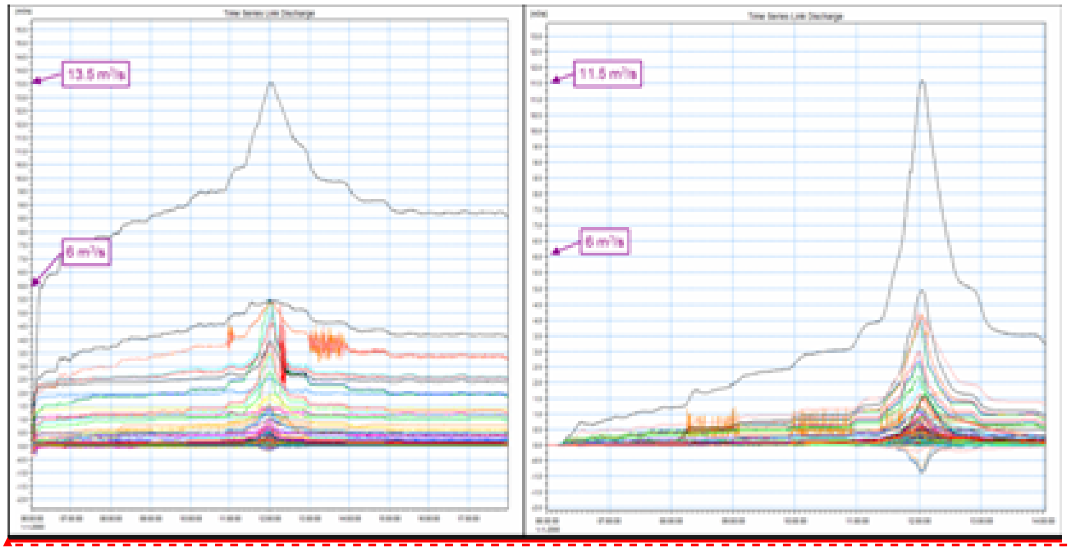

4.2.2 INLETTING ISSUE

Another problem encountered was to do with the catchpits in the model not taking in water. A logic check of the model results showed that there was no decrease in the flow down a road, despite the presence of numerous large capacity catchpits. Figure 13 shows the model results along Queen Street in downtown CBD, where upstream flows totalling up to 1.48 m^3/s (0.314 m^3/s + 0.732 m^3/s + 0.375 m^3/s), show only a very small reduction down to 1.3 m^3/s at the downstream end. The large flow that was making its way to the downstream end of Queen Street despite numerous large capacity catchpits, which had been newly constructed, proved that the catchpit coupling in the model were not capturing enough surface flow.

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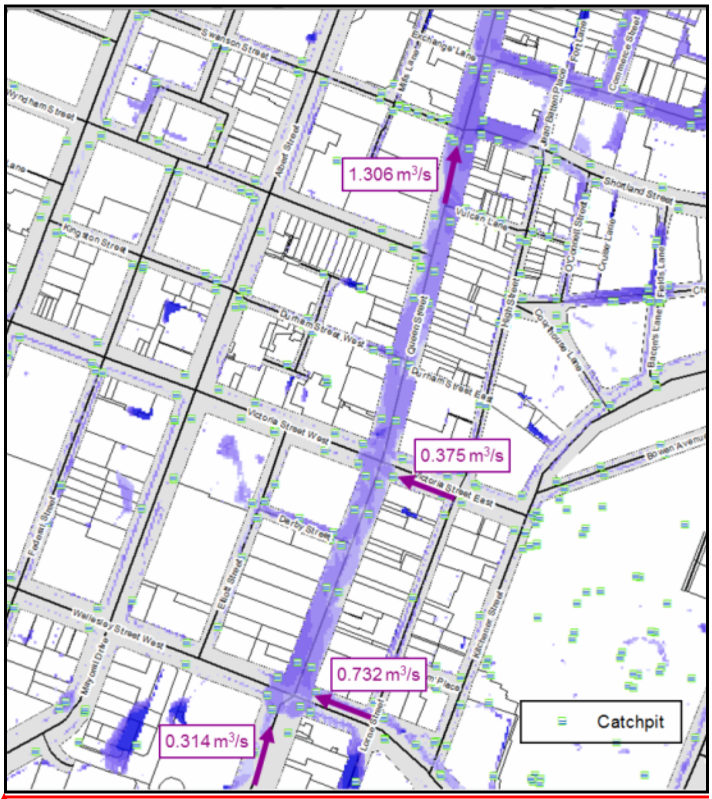
Figure 13 : Illustration of Logic Check Used to Identify Inletting Issue



Further investigation and discussions with DHI identified the problem as a coupling issue.For each coupling in MIKE 21, the coupling crest level is calculated as the maximum out of the manhole lid level and the highest of the coupled cells (refer to Figure 14). This meant that in cases where MIKE 21 grid elevations were higher than the manhole lid level, water flowing over the remaining eight (8) lower cells would not be entering the pipe system. Hence, only surface runoff flowing over 4m^2 out of a total of 36m^2, would enter the pipe system.

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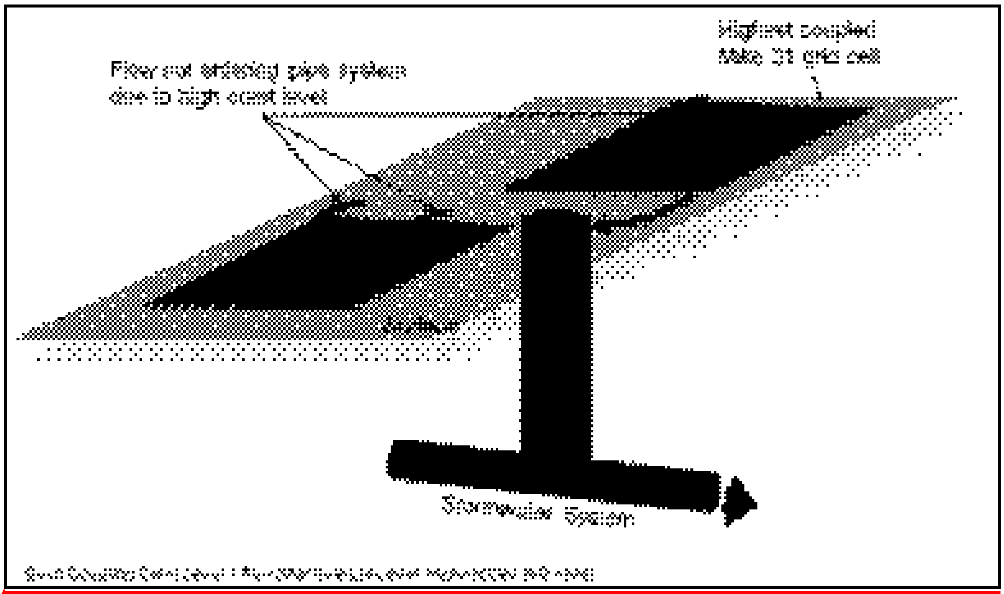
Figure 14: Methodology for Calculating of Crest Level for each Catchpit Coupling



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Following discussions with DHI, AECOM decided to adopt the following approach to this problem:

- Reducing the 9-cell coupling per catchpit down to a single cell. The single MIKE 21 grid cell chosen for the new catchpit coupling would be the lowest out of the nine (9) MIKE 21 grid cells, in order to ensure that there is flow over the grid cells.
- Lowering the MIKE URBAN manhole lid level to match the elevation of the lowest coupled MIKE 21 grid cell

Applying this simplified methodology increased the number of functioning catchpits in the model by approximately 30%. This approach provided the best catchpit performance in the model and reduced model instabilities due to the multiple cell coupling. The multiple cell coupling approach would ideally provide a better model representation of catchpits; however, attempting this approach pushed the software beyond its computing limits.

4.3 OTHER PROBLEMS

4.3.1 TROUBLESHOOTING RESULTS

One of the challenges experienced during the catchpit coupling issue was with troubleshooting the model results. In the MIKE 21 result-viewing interface, there are currently no tools available to distinguish between the results for individual couplings, when multiple catchpits are coupled to the same MIKE URBAN manhole. This makes it difficult to differentiate and identify the flow through each individual catchpit (refer to Figure 15).

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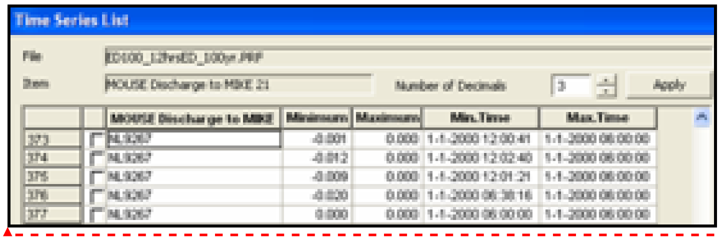
Figure 15: Model Results (in MIKE VIEW) for a Manhole with Multiple Catchpit Loadings



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Item: MOUSE Discharge to MIKE 21

Number of Decimals: 3

		MOUSE Discharge to MIKE	Minimum	Maximum	Min.Time	Max.Time
373	☐	NL9267	-0.001	0.000	1-1-2000 12:00:41	1-1-2000 06:00:00
374	☐	NL9267	-0.012	0.000	1-1-2000 12:02:40	1-1-2000 06:00:00
375	☐	NL9267	-0.009	0.000	1-1-2000 12:01:21	1-1-2000 06:00:00
376	☐	NL9267	-0.020	0.000	1-1-2000 06:38:16	1-1-2000 06:00:00
377	☐	NL9267	0.000	0.000	1-1-2000 06:00:00	1-1-2000 06:00:00

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4.3.2 LARGE COMPUTATION TIME

A typical FHM model runs a 24-hour storm event, however, due to the large computation time, model runs were shortened to 12-hours. Even then, the CBD model took up to six and a half days to run a 12-hour simulation,and this was with 2m grid cells in MIKE 21. This meant long waiting times between model runs. During the model build process, smaller simulations were setup. However, this large computation time posed a challenge for obtaining detailed results for the Shared Space areas.

Some of the factors contributing to the long computation times were:

- Applying the "rain-on-grid" approach in MIKE 21 for calculating precipitation on roads, parks and paved areas
- Large number of dummy weirs for the weir coupling
- Large number of multi-cell catchpit coupling

To overcome this issue, smaller cut-down models were setup for the Shared Space models using a square grid size of 1m in MIKE 21. The full CBD model was used to setup the boundary conditions for the smaller models. This reduced simulation times from six and a half days to 12 hours for the 12-hour simulations.

5 LESSONS LEARNT AND RECOMMENDATIONS

The following lessons were learnt from this project:

- Initial modelling should be carried out on a simple model of a catchment to identify areas of concern.
- In cases where detailed models are required, such as in the CBD where inletting issues had to be identified, detailed modelling should be carried out in cut-down models for critical areas.
- With currently available technology, it is not recommended to attempt such detailed catchpit modelling.
- Close communication between the modellers and the software vendors is beneficial in resolving problems, especially when modellers are pushing the boundaries of the software.

Some of the features that should be considered for future releases of MIKE by DHI software, to expand the capability of the modelling tools:

- Improved functionality for troubleshooting coupling issues
- Ability to specify separate incoming and outgoing flow regulations for couplings
- Better tools for catchpit modelling

ACKNOWLEDGEMENTS

We would like to thank the following people for providing assistance and guidance during this project and in preparation of this paper:

- Nadia Nitsche, Ralph Little, Warwick Absolon, Mark Gibbs – AECOM
- Richard Smedley – Auckland Council
- DHI New Zealand for their assistance with model issues resolution

The work presented in this paper was funded by the Auckland City Council. Views expressed in this paper are those of the authors and do not necessarily represent policy or position of the Auckland City Council.

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