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Flooding in Urban Areas - 2D Modelling Approaches for Buildings and Fences

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Abstract: Flooding in urban areas presents a range of challenges to the modeller due to the complexity of the flow patterns and paths that occur. It is very difficult, if not at times impossible, to represent the myriad of flow behaviour that occurs as water flows down roads, through/under/over fences, and around/through houses. Additional complexity occurs due to fence collapses, debris blockages, and the displacement of cars and other obstructions.

With continued advances in computer hardware and software, 2D solutions are increasingly being used for modelling overland flooding of urban areas. Whilst 1D hydrodynamic schemes readily model the underground pipe networks and manholes, they are generally inadequate for representing above surface flooding. When 2D schemes are linked with a 1D solution for the pipe network, they become a powerful modelling tool.

One of the challenges for the modeller is how best to represent the roads, fences, houses and other features within the limitations and constraints he/she has to work with. 2D solutions are very computationally intensive and it is not always practical to utilise a mesh of very fine elements. This forces the modeller to make approximations when representing the urban domain to represent the fences, buildings, and other obstructions.

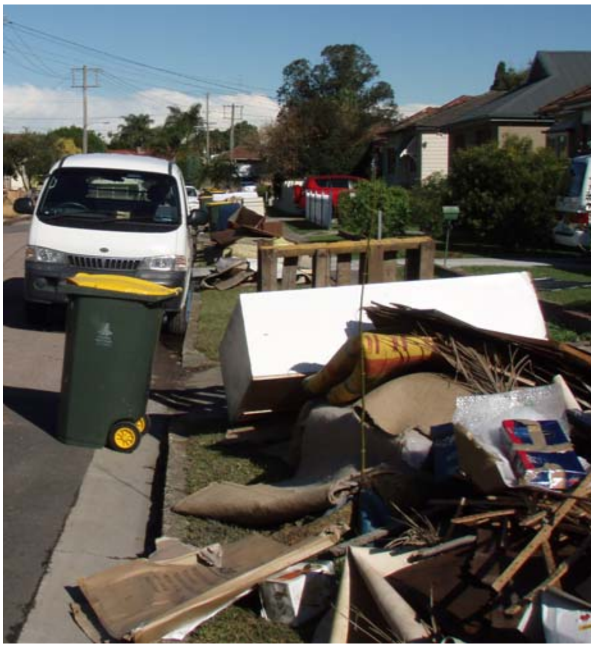
Various approaches to modelling buildings and fences within a fixed 2D grid are presented, and their pros and cons discussed. The approaches would be of interest to 2D modellers and recipients of 2D urban flood modelling outputs. Real world and test model results using the TUFLOW software are presented.

Keywords: Flooding, Urban, 2D Modelling, TUFLOW

1. INTRODUCTION

Floodwaters flowing through urban areas follow a tortuous path as the water negotiates buildings, fences and other obstructions. These obstructions dissipate energy by forcing the water to change its direction and speed, and by forming eddies behind them. Historically, 1D and 2D models have represented this energy dissipation by either increasing the bed friction parameter (eg. Manning’s n), where buildings and fences lie within the 1D cross-section or 2D domain. Another common approach is to block out sections of the 1D cross-section, or remove/deactivate 2D elements, although this latter approach will not include the storage effects of water entering a building.

As 2D models become finer and finer in their discretisation of urban areas, it is worthwhile evaluating and investigating alternative methods for representing buildings and fences. Those examined for this paper include: blocking out 2D elements; using higher bed roughness or form losses to increase energy dissipation; modelling the building’s exterior walls with a gap to let water in; and partially blocking 2D element sides to emulate the constricted flow through a building.



Cleanup after the June 2007 Newcastle Flood

2. REPRESENTATION OF BUILDINGS

2.1 Increased Roughness

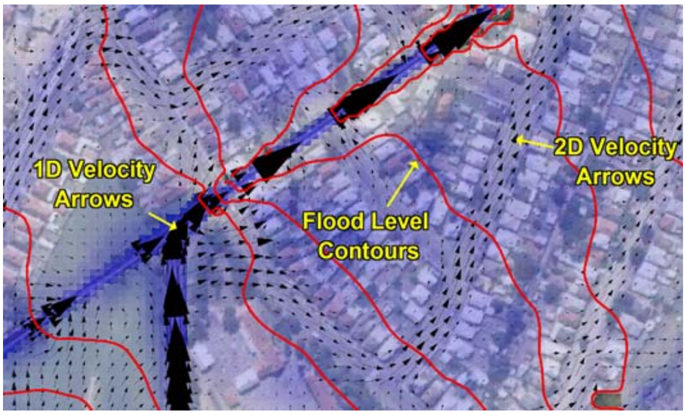


Figure 2.1 – Example of Using Higher Roughness for Houses and Gardens (Throsby Creek Flood Study courtesy Newcastle CC)

Increasing the bed resistance parameter is a commonly used method for representing the increased energy dissipation of water flowing through and around buildings. It is often favoured over blocking out the building as it includes the storage effects of the building being inundated. The parameter may also be varied. For example, a lower Manning's n value can be used for houses and gardens compared with a higher value for commercial properties on the basis that residential areas are less "dense" than commercial areas. Figure 2.1 shows TUFLOW output for a model where higher roughness was used for urban areas as illustrated by the higher velocities on the roads and lower velocities through the houses and gardens.

Varying the Manning's n value also works well when the resolution of the 2D elements is coarse. For example, a fixed grid model using 10m square cells will struggle to adequately represent the flow between buildings if the buildings have been blocked out (as illustrated by the images in Figure 2.2), whereas varying the Manning's n value is somewhat less sensitive to this effect. The difficult question for the modeller is what is an appropriate Manning's n value. For urban areas, the author has observed Manning's n values used in the range from 0.08 to 20.0 – a wide range to choose from!

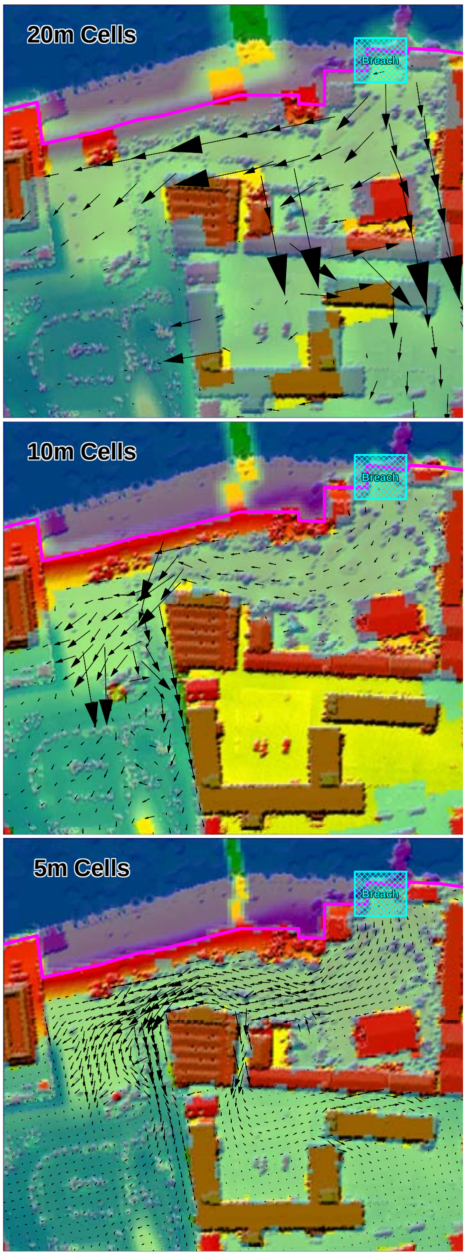


Figure 2.2 – Effect of Different 2D Grids on Flow around Buildings
(Benchmarking of TUFLOW in 2004 for Thames Embayments Inundation Study, London by Halcrow and HR Wallingford)

2.2 Blocking Out of Elements

The blocking out of 2D elements to represent buildings is also commonly used. Where the building is designed or protected so that water cannot enter it, this is clearly an appropriate representation provided the element sizes are sufficiently fine. However, this is rarely the case as most buildings "absorb" water, thereby contributing to the floodplain storage and attenuation of the flood wave. In this case, deactivating or blocking out the 2D elements may not be an appropriate representation of the buildings. Commercial buildings often have underground parking, thereby contributing further to the flood storage.

Often buildings are constructed on an earth pad. In these cases if the building floor remains flood free, it can be appropriate to block out the 2D elements. However, with the increasing emphasis on modelling extreme events, which will often cause above floor flooding, a more appropriate approach is to elevate the ground level of the 2D elements to that of the floor level, and model the building using one of the other methods discussed.

Another issue related to blocking out elements is that there will be "holes" in the 2D model results, and the flood level will need to be interpolated from surrounding flood levels. This can be a nuisance when interrogating a 3D water level surface to assign flood levels to buildings for a flood damages assessment, or for setting minimum floor levels for building planning controls.

2.3 Using Energy Loss Coefficient

An alternative to using an increased Manning's n value, is to specify form (energy) loss coefficients to represent the fine-scale energy dissipation within and around the building. This is arguably more correct in that the energy loss is mostly due to the water contracting and expanding as it flows through and around the building. Whilst a 2D scheme models some of these form losses (eg. the expansion of water downstream of the building), the fine scale losses that are not well represented, need to be included, hence the need for additional energy dissipation.

As for the increased Manning's n option, what constitutes appropriate form loss value(s) for modelling buildings is a difficult question and the author has not found guidance from the literature. Unfortunately, data obtained following flood events is not normally of sufficient detail to determine appropriated form loss values.

2.4 Modelling Buildings' Exterior Walls

The approach of modelling just the building's exterior walls has merit in that the walls will deflect the water, and provided that there is a break in the wall, the water enters the building to represent the storage effects (as shown in Figure 2.3).

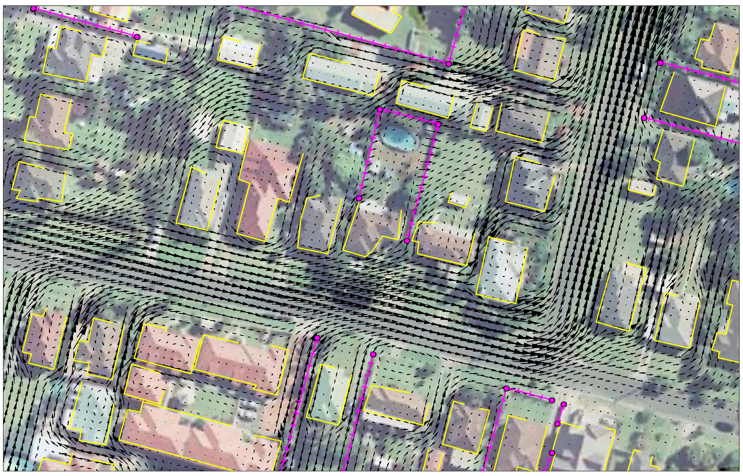


Figure 2.3 – Example of Modelling Exterior Walls

One of the drawbacks to this approach is that some knowledge on the direction of water flow is needed prior to digitising the buildings so as to have a consistent approach to how water enters the building. When modelling thousands of buildings, this approach is not particularly amenable as any building outlines provided via photogrammetry or other aerial survey will not be in this form, and will have to be manually modified (a daunting task when dealing with thousands of buildings!).

2.5 Modelling Buildings as "Porous"

Another approach is to model buildings as being "porous". The 2D element sides within the building outline are partially blocked to represent the blockage of interior and exterior walls, and other obstructions. The TUFLOW software has the capability of adjusting the flow widths of the cell sides to model partial blockages, so this offers an interesting alternative to the other approaches. The element's storage is not affected by this approach.

3. HYPOTHETICAL TEST MODEL OF A BUILDING

3.1 Description

A simple hypothetical model was set up to test the influence of the different approaches for modelling buildings. The model, which is illustrated in Figure 3.1, depicts a single house 10m wide and 15m long. The 2D cell size is 1m, the bed was kept horizontal and the downstream boundary was located well away so as to minimise its influence on the flow patterns downstream of the building. In the case of no building being present, the inflow of 20m^3/s produces a depth averaged velocity of around 0.9m/s to 1m/s at a depth of approximately 1.1m to 1.0m. The Manning's n was set to 0.03 and the downstream boundary water depth was held constant at 1m. The 2008 release of the TUFLOW software (www.tuflow.com) was used to simulate the various scenarios as listed in Table 3.1. This release includes enhancements over previous releases that were utilised and tested for this paper. All simulations used a timestep of 0.5s, had zero mass error, were stable and reached steady state conditions.

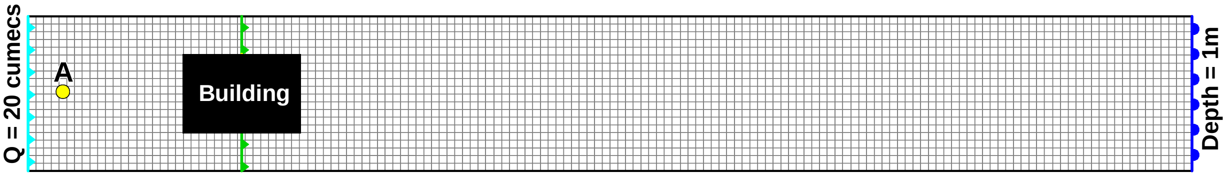


Figure 3.1 – Hypothetical Building Model Layout

Table 3.1 – Building Test Scenarios

Scenario	Description
No Building	No building exists. Flow should be close to uniform. Manning's n = 0.03.
Blocked Out	The building is represented by deactivating the 2D cells. n = 0.03.
High Roughness	A Manning's n value of 0.3 is applied to each cell side within the building. n = 0.03 elsewhere.
Add Form Loss	A form loss of 0.5 (of velocity head) is applied to each 2D cell side within the building. n = 0.03.
Ext Walls, Open D/S	The 2D cell sides along the exterior walls are raised except for the downstream side. n = 0.03.
Ext Walls, Open U/S	The 2D cell sides along the exterior walls are raised except for the upstream side. n = 0.03.
Porous	The 2D cell sides within the building have a blockage of 90%. n = 0.03.
Porous + Form Loss	The 2D cell sides within the building have a blockage of 90% and a form loss of 0.1. n = 0.03.

3.2 Comparison of Approaches

Table 3.2 provides a comparison of the water level at Point A in Figure 3.1, and the corresponding increase in this water level due to the building. The table also compares the distribution of flow and average velocity between the building and garden. Figure 3.2 illustrates the water surface profile along the centreline of the model for each scenario. Of interest is that all scenarios show surcharging against the building to varying degrees. The surcharges are within the kinematic energy of the approaching water (~0.04m). Further discussion on the results of each scenario is provided in Table 3.3.

Table 3.2 – Comparison of Building Test Scenarios

	Water Level (m)		Flow Distribution (%)		Average Velocity (m/s)	
Scenario	**Point A**	**Increase**	**Building**	**Garden**	**Building**	**Garden**
No Building	1.118	0.000	50%	50%	0.91	0.91
Blocked Out	1.255	0.137	0%	100%	n/a	1.90
High Roughness	1.240	0.122	21%	79%	0.38	1.41
Add Form Loss	1.195	0.077	31%	69%	0.55	1.23
Ext Walls, Open D/S	1.250	0.132	0%	100%	0.00	1.92
Ext Walls, Open U/S	1.263	0.145	0%	100%	0.00	1.93
Porous	1.170	0.052	9%	91%	1.87	1.80
Porous + Form Loss	1.225	0.107	7%	93%	1.28	1.78

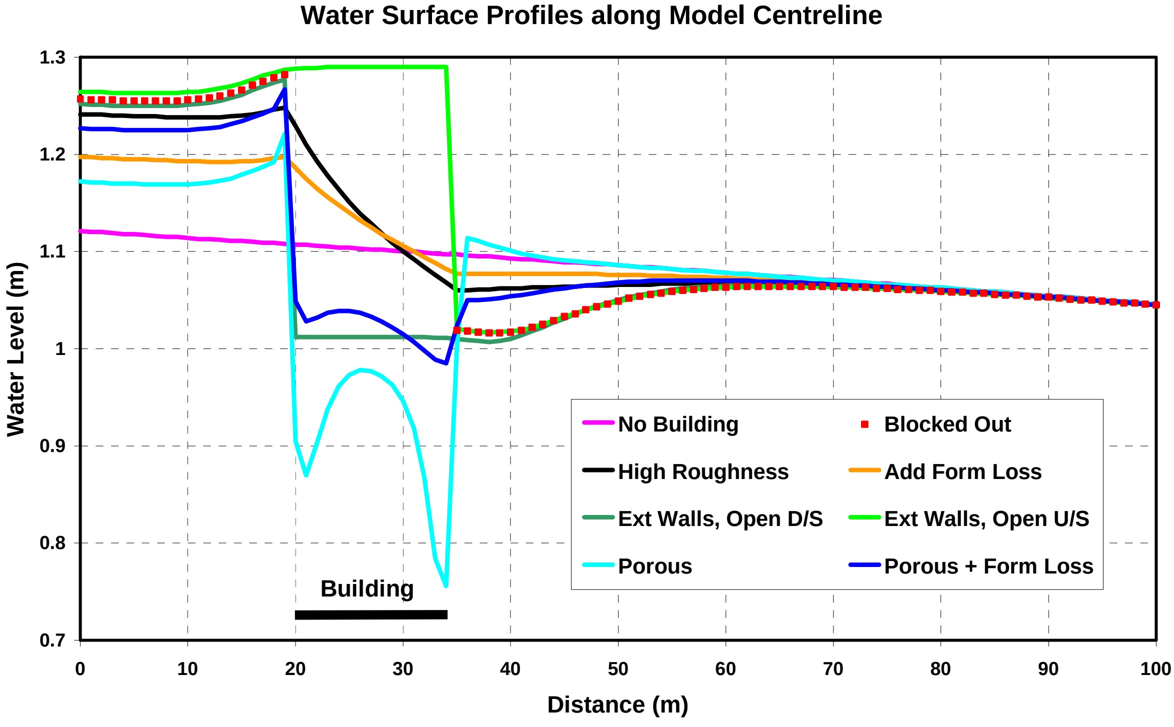


Figure 3.2 – Comparison of Water Level Profiles along Model Centreline

Table 3.3 – Discussion on Building Test Scenario Results

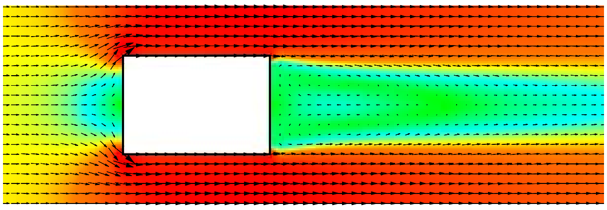
Scenario	**Description of Results**
No Building	The flow is uniform and results agree with Manning's equation giving a water surface slope of around 0.079%.
Blocked Out	As would be expected, the constriction doubles the velocities and an eddy forms on the downstream side. Due to the higher velocities (increased friction) and form losses (eg. flow expansion downstream), the upstream water level rises by 0.137m. **It is noted that the Blocked Out case should not be used as the benchmark.** This is because it is unlikely to simulate all energy losses, as the 2D elements are too coarse to represent the fine-scale losses such as the flow separation that would occur at the corners of the building. By illustration, the rise in upstream water level represents less than 0.75 of the velocity head – bluff constrictions such as this would typically dissipate 1.0 or more of the constriction velocity head. It also does not take into account flow through the building.
High Roughness	The much higher Manning's n value for the building (0.3 cf 0.03) increases levels upstream to a similar amount to that for the Blocked Out Scenario (0.122m cf 0.137m). The flow patterns are, however, different, particularly at the upstream corners of the building and downstream (no eddy forms) – also see Figure 3.3.
Add Form Loss	Somewhat similar outcome to that for Higher Roughness. A higher form loss coefficient would be needed to match the results of the Higher Roughness scenario.
Ext Walls, Open D/S	Very similar outcome to the Blocked Out Case, except that inside the building is flooded.
Ext Walls, Open U/S	Very similar outcome to the Blocked Out Case, except that inside the building is flooded (to a higher level than for Open D/S).
Porous	The flow distribution between building and garden (9% cf 91%) is in accordance with the 90% blockage applied. The water level profile through the building (see Figure 3.2) is a consequence of the velocity increasing as it enters the building, slowing down through the building then increasing again as it exits the building before rapidly slowing down on the downstream face of the building.
Porous + Form Loss	The addition of the form loss has a pronounced effect on the increase in the upstream water level – this is due to the much higher velocities inside the building as the additional energy loss is the form loss coefficient times $V^2/(2g)$.

Whilst parameters can be varied so that the different approaches produce a similar upstream flood level, one of the main differences between the different approaches is the velocity field computed within the building. This varies widely from no velocity for the Blocked Out case to close to zero for the Exterior Walls scenarios to low velocities for the High Roughness and Add Form Loss cases to high velocities for the Porous scenarios (see Figure 3.3). In reality, if floodwaters flow through a building the velocity will vary widely from fast flowing through doorways to relatively still away from openings. If there is a need to quantify or highlight the flood hazard within buildings, then adopting the Porous approach would be preferable as this produces VxD (hazard) values commensurate with those likely to occur through doorways.

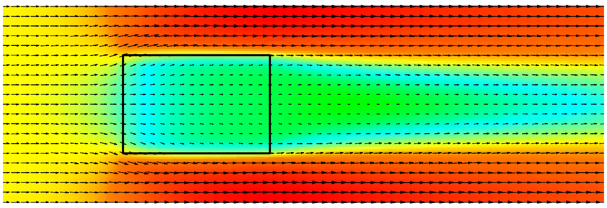
3.3 Effect of Varying Manning's n

As previously discussed, the use of a higher Manning's n value is a common method for representing the energy dissipation caused by buildings. The difficulty faced by the modeller is how much higher should the Manning's n value be?

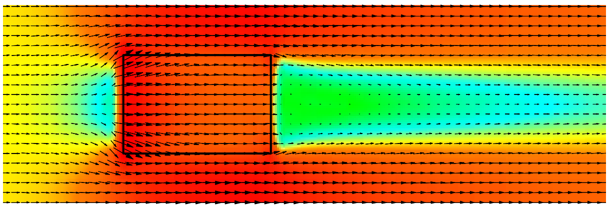
The Higher Roughness scenario was simulated using a range of Manning's n values to ascertain their influence. Table 3.4 presents the results from these simulations. As indicated by the results, the effect of the building on upstream flood levels and flow distribution between building and garden varies significantly depending on the Manning's n value. A Manning's n value of about 0.4 would provide a similar increase in water level to that provided by the Blocked Out scenario, which represents a 50% blockage. More expansive testing could provide indicative Manning's n values for a range of blockage scenarios.



Blocked Out Scenario



High Roughness Scenario



Porous + Form Loss Scenario

Figure 3.3 – Comparison of Velocity Patterns
(Red shades indicate the higher velocities)

Table 3.4 – Effect of Varying Manning's n

	Water Level (m)		**Flow Distribution (%)**		**Average Velocity (m/s)**	
Manning's n	**Point A**	**Increase**	**Building**	**Garden**	**Building**	**Garden**
0.05	1.127	0.009	48%	52%	0.86	0.94
0.1	1.156	0.038	41%	59%	0.73	1.06
0.2	1.206	0.088	29%	71%	0.51	1.27
0.3	1.240	0.122	21%	79%	0.38	1.41
0.5	1.278	0.160	14%	86%	0.25	1.56
1	1.315	0.197	7%	93%	0.13	1.69
5	1.353	0.235	2%	98%	0.03	1.81
20	1.361	0.243	0%	100%	0.01	1.84
100	1.363	0.245	0%	100%	0.00	1.84

3.4 Effect of Viscosity (Sub-Grid Scale Turbulence) Term

The viscosity term becomes particularly relevant with increasingly finer element resolution (the term is proportional to the inverse of the element length squared, therefore, the smaller the element, the greater the influence). The term also only has any influence where there is a change in the velocity direction and/or magnitude, such as flow around buildings, into and out of structures, and at bends.

For the No Building case, there is virtually no spatial variation in velocity as the flow is very close to uniform, therefore, varying the viscosity coefficient and/or formulation had no measurable influence on the results for this scenario. However, for the other scenarios, the velocity field does vary spatially as the water flows around/through the building. The influence of this parameter was tested using the Blocked Out scenario. As TUFLOW allows the viscosity coefficient to be split into a Smagorinsky Formulation component and a constant component (Ref BMT 2008), combinations of these two were tested.

Table 3.5 – Effect of Varying Viscosity Coefficient

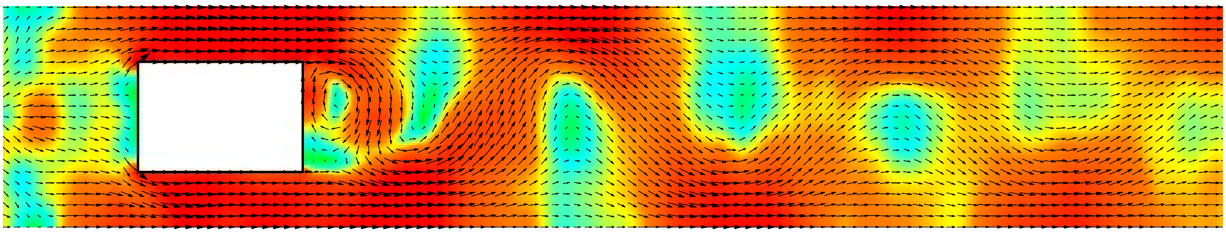
Viscosity Coefficient		**Water Level (m)**	
Smagorinsky Component	**Constant Component**	**Upstream (Point A)**	**Increase due to Bldg**
0.0	0.0	Not Steady	
0.2	0.0	1.250	0.132
0.2*	0.1*	1.255	0.137
0.4	0.1	1.257	0.139
0.5	0.5	1.288	0.170
1.0	0.0	1.260	0.142
0.0	1.0	1.319	0.201
1.0	1.0	1.337	0.219
5.0	0.0	1.316	0.198
0.0	5.0	1.628	0.510
5.0	5.0	1.687	0.569

* Values used for all other simulations

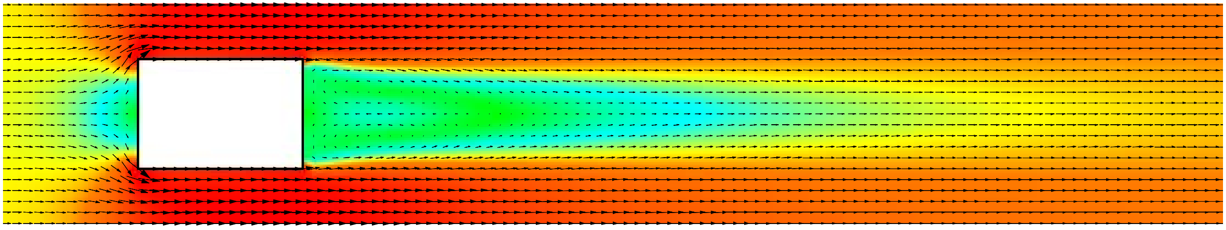
Table 3.5 shows the effect on the upstream water level for a range of combinations of viscosity coefficients. As the constant viscosity component is increased the water becomes "thicker" and the upstream water level increases (this is analogous to simulating "oil" rather than water). Varying the Smagorinsky component has some influence, but not as markedly.

Specifying zero viscosity causes the model to experience the formation of oscillating eddies as illustrated in the top image in Figure 3.4. Whilst oscillating eddies can occur in reality, they should dissipate with distance and the streamlines should reform, which is not the case here. Also, the flow patterns upstream of the building were not steady. At the other extreme, specification of excessively high constant viscosity coefficients inappropriately distorts the results (note the rapid and unrealistic recovery of the velocity field downstream of the building in the bottom image of Figure 3.4). With standard coefficients (middle image) the distance to full recovery of the flow is similar to that found in the literature, ie. 4 to 5 times the width of the obstruction perpendicular to the flow. Eddies form behind the building but remain steady without any significant oscillations, so this case could be viewed as approximating the time-averaged velocity distribution.

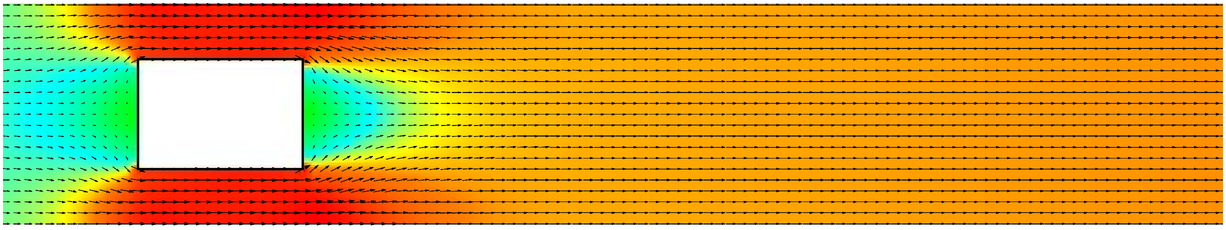
In conclusion, if a constant viscosity coefficient is specified it should not exceed 0.5 for the flow conditions analysed, and the Smagorinsky coefficient, though not as influential, should probably not exceed 1.0. This example also highlights the need to include the viscosity term for fine-scale resolution models, particularly as a number of mainstream 2D schemes omit this term.



No Viscosity



Smagorinsky Coefficient = 0.2; Constant Coefficient = 0.1



Smagorinsky Coefficient = 5.0; Constant Coefficient = 5.0

Figure 3.4 – The Effect of the Viscosity Term

3.5 Effect of Fixed Grid Orientation

Fixed cell size 2D domains, such as those used by TUFLOW, may block or artificially choke narrow flowpaths when the flow is at an angle to the grid orientation. This effect is more likely when the flowpath is less than two cells in width. The scenarios presented were remodelled with the grid rotated 45°, and the results are presented in Table 3.6 with the original (ie. not orientated) results in brackets. In most cases the results are very similar, except for the Blocked Out and Ext Walls scenarios where rises of around 40mm in the upstream water level occurred. On this basis, it can be concluded that a preference for fixed grid models is to not block cells out or raise cell sides, but to use the other approaches, particularly if the grid is coarse.

Table 3.6 – Effect of Rotating Grid 45°

	Water Level (m)		**Flow Distribution (%)**		**Average Velocity (m/s)**	
Scenario	**Point A**	**Increase**	**Building**	**Garden**	**Building**	**Garden**
No Building	1.119 (1.118)	0.000	50% (50%)	50% (50%)	0.91 (0.91)	0.92 (0.91)
Blocked Out	1.295 (1.255)	0.176 (0.137)	n/a	100% (100%)	n/a	2.39 (1.90)
High Roughness	1.245 (1.240)	0.126 (0.122)	21% (21%)	79% (79%)	0.38 (0.38)	1.41 (1.41)
Add Form Loss	1.198 (1.195)	0.079 (0.077)	31% (31%)	69% (69%)	0.55 (0.55)	1.24 (1.23)
Ext Walls, Open D/S	1.294 (1.250)	0.175 (0.132)	0% (0%)	100% (100%)	0.00 (0.00)	2.40 (1.92)
Ext Walls, Open U/S	1.299 (1.263)	0.180 (0.145)	0% (0%)	100% (100%)	0.00 (0.00)	2.40 (1.93)
Porous	1.177 (1.170)	0.058 (0.052)	9% (9%)	91% (91%)	1.78 (1.87)	1.82 (1.80)
Porous + Form Loss	1.224 (1.225)	0.105 (0.107)	6% (7%)	94% (93%)	1.19 (1.28)	1.80 (1.78)

3.6 Effect of Cell Size

Tests were carried out to ascertain the effects of varying the 2D cell size. Reducing the cell size by half to 0.5m caused no or little change in the results except for the Blocked Out and Ext Wall cases, which experienced an increase in the upstream water level between 6 and 15mm. However, increasing the 2D cell size to 2m caused significant changes as the house covered 60% of the flow width rather than 50%. This caused increases in the increased water level at Point A in some scenarios of double that previously. The scenarios that did not block out elements, raised element sides or constricted element flow widths (ie. Blocked Out, Ext Walls and Porous) experienced the most pronounced change, whilst High Roughness and Add Form Loss were less influenced. This highlights the need to be using a sufficiently fine cell size to satisfy the modelling objectives.

4. FENCES AND OTHER "THIN" OBSTRUCTIONS

Fences can cause significant blockages to floodwaters and they have the added complication of tending to collapse during a flood. They may also be partially open (eg. a picket fence), and will also become blocked with debris. If the floodwaters are sufficiently high they will be overtopped and may act like a weir. Blocking out whole elements is not a good option for fences unless the element size is very small. To represent fences, the features needed are a subset of those described above for buildings as follows.

- The ability to raise the cell side elevations to the height of the fence. This effectively models the fence as a thin, or zero width obstruction (ie. does not affect storage).
- Automatic switching with upstream controlled weir flow across the element side if overtopping occurs.
- Partial blockage of the element flow width below the top of the fence to model partially open fences.
- Apply additional energy (form) losses that are likely to occur.

A new feature in TUFLOW 2008 is the ability to collapse element sides once the water depth, or the water level difference across the side, exceeds a specified amount. This is particularly useful for sensitivity testing the effect on flood levels and flood hazard, due to collapsing fences.

5. CONCLUSIONS & RECOMMENDATIONS

A range of options exist for representing buildings in 2D schemes. These range from: blocking out (deactivating) 2D elements and/or 2D element sides; increasing the bed roughness or applying additional energy (form) losses; and partially blocking element sides within the building. The conclusions drawn are:

- Blocking out elements may provide a more visually "correct" impression of the water flowing around the building, but does not simulate the effects of storage and produces no flood level within the building.
- Raising the element sides around three sides of the building overcomes these disadvantages, and is a good option provided the elements' sizes are sufficiently fine.
- Increasing the Manning's n value or applying form losses are good options, especially if the 2D element size is coarse. Form losses are arguably a better representation of the energy losses caused by the house, in that the energy losses are better described by contraction and expansion losses as the water flows through the building. Another advantage of these approaches is that the Manning's n and/or form loss values can be varied according to the building type. However, the difficult decision to be made by the modeller is what are appropriate values to use!
- The option of reducing the flow widths of 2D element sides within the building footprint in combination with a form loss coefficient (or increased Manning's n) is appealing as this tries to replicate the effect of water being restricted as it flows through the building, whilst preserving the full storage covered by the building. One advantage of this approach is that the velocities within the building are much higher resulting in a more realistic representation of the flood hazard within the building.

The modelling of fences may also be required. A key requirement for the 2D scheme is to allow wetting and drying of 2D element sides, so that the element sides act as a thin (no storage) barrier until they are overtopped, at which point the scheme must be capable of switching in and out of upstream controlled weir flow across the element side. The option of reducing the flow widths of element sides also allows the modelling of "porous" fences (eg. a picket fence).

As 2D models become increasingly finer in their resolution, further testing, research and calibration of approaches to modelling buildings and fences is needed to provide guidance to modellers. Research opportunities include testing different blockage widths to derive recommendations for Manning's n values, element side blockages and form loss coefficients under different flow conditions.

6. REFERENCES

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