

Modelling storm runoff and flooding in urban catchments including runoff from green areas: Nørrebro, Denmark

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1. INTRODUCTION

In the recent years natural phenomena such as flood have cost billions of euros and numerous losses of human life. Over the next decades, extreme weather events are expected to become even more frequent due to climate changes (Arnbjerg-Nielsen, Leonardsen, & Madsen, 2015). The extent and nature of expected changes varies across the globe. In the past 30 years, changes in rain patterns have been observed in Denmark in terms of extreme precipitation. These changes are mainly visible in the frequency of extreme events, but there is also a tendency for an effect on their magnitude (Arnbjerg-Nielsen, 2012). There are different approaches to adapt cities to these extreme events. One approach is the conventional adaptation where the sewer system is enlarged, but this is not always possible due to very big implementation costs. Another approach is adapting the urban landscape for stormwater management, which is often called Low Impact Development (LID) or Sustainable Urban Drainage Systems (SUDS) and involves elements of Green Infrastructure (GI) (Fletcher et al., 2014). There are several possibilities to ‘reconstruct’ the cities taking into account the space needed for stormwater. This will allow the cities to redirect the stormwater to areas that are designed and suitable for flooding, inside or outside the cities, during extreme rain events. This approach has become increasingly popular in Denmark over the past few years (The City of Copenhagen, 2015).

In this context, accurate modelling of storm runoff from urban catchments is very important, but it is difficult to achieve because of the complexity of modelling green areas (DHI, 2015). Depending on the local practice, the available software, the data availability, the possibility of data processing, computation time, and even the experience of the modeller, storm runoff from urban catchments can be analysed using different modelling approaches. Choosing the modelling approach, the rainfall loads to the model and the model parameters are very important steps that have to be made with caution, and there is thus a need to establish more precise guidelines to help modellers in choosing the most suitable modelling approach.

The research presented here focuses on the complexity of modelling stormwater movements in urban catchments during extreme events with an emphasis on the consideration of green areas and LID’s. Four different modelling approaches are applied to the 276 ha area of Nørrebro, Denmark where a large number of Lid’s measures will be implemented as part of the Copenhagen cloudburst management plan (The City of Copenhagen, 2015).

2. MODELLING APPROACHES

In Denmark the primary conceptual runoff model used in is ‘**MOUSE Model A**’. ‘MOUSE Model A’ uses the “Time-Area” method with a linear reservoir based runoff model with a fixed permeable area. This method includes minor losses in form of initial loss and a hydrological reduction factor that is usually a calibration factor. The time-area curve describes the area that is contributing to the runoff discharged from the catchment and is defined based on the area of the catchment, time of concentration (TOC) and the shape of the catchment. Recently in Denmark the conceptual runoff model ‘**MOUSE Model B**’ is slowly replacing the conceptual runoff model ‘MOUSE Model A’. This method is based on a non-linear reservoir model that is described by the kinematic wave equation that assumes uniform flow conditions on the surface and a uniform distribution of the rainfall across the catchment.

The physical system included in the model consists of the following components: runoff model (catchments), sewer system (drainage network) and the 2D surface (terrain surface):

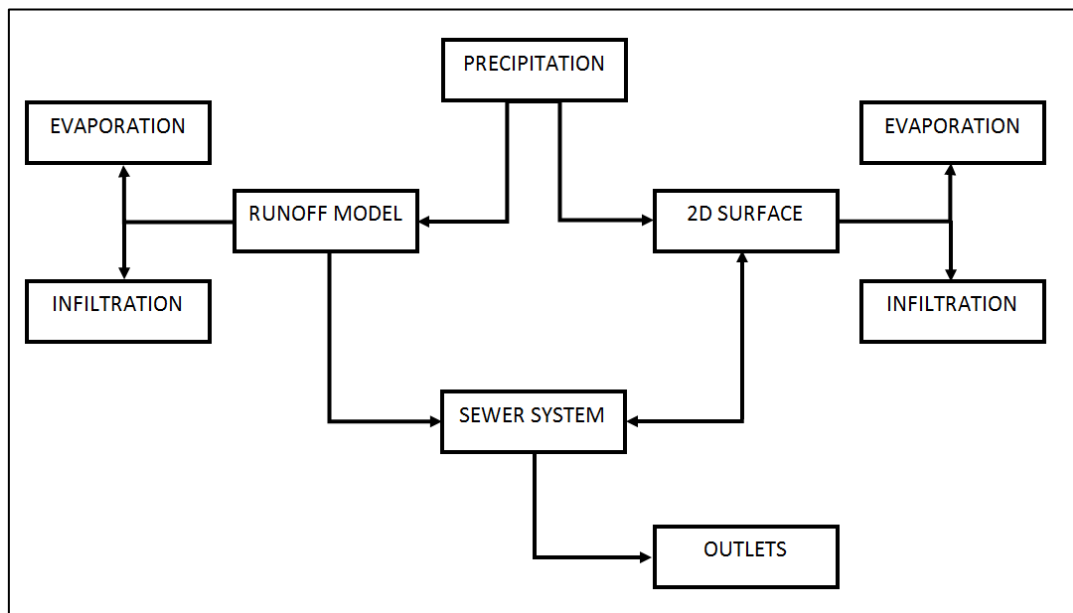


Figure (1): Links between the main components of the urban flood model

The first adopted modelling approach (**M1**) is to consider both pervious and impervious urban areas through an initial loss in the runoff model. The conceptual runoff model used here is ‘MOUSE Model A’. Runoff from all the pervious surfaces and impervious surfaces such as roofs, roads and parking areas is reduced by the initial losses that is considered to be 0,00065 m. These losses are limited, which means with growing the return period of the rain event the relative importance of this loss is reduced and the runoff approaches 100% for very extreme events (DHI, 2015). In this case the imperviousness of the contributing areas will be included

in the analyses. Runoff from the impervious surfaces such as roofs will be reduced with 5%, roads with 10% and the runoff from the parking areas will be reduced with 15%. For this analyse the hydrological reduction factor was set to 1 that means all the runoff losses will be included in the initial losses and the imperviousness.

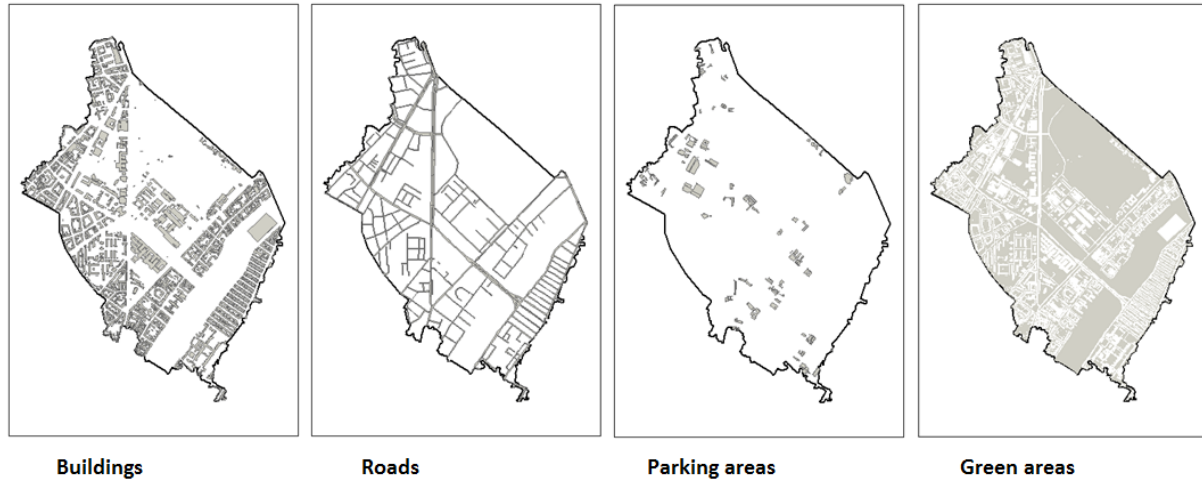


Figure (2): Representation of the contributing areas that are included M1 modelling approach

Runoff from pervious areas will depend on the soil infiltration capacity. It is expected that urban pervious surfaces such as parks, gardens, will generate a surface runoff no matter the return period of the event. This surface runoff will become more significant once the return period of the rain event will increase. Typically the runoff from green areas is not included when a new urban drainage is designed based on the assumption that on a 10 year event the pervious area will have enough infiltration capacity. For a more realistic analysis of the urban flooding in Nørrebro catchment where 60% of the catchment is pervious area the runoff from the green areas will be included.

The second modelling approach (**M2**) is to include only the storm runoff from impervious areas in the runoff model as a runoff that loads the drainage system. The conceptual runoff model used will be 'MOUSE Model A' that means the runoff from the impervious areas will be calculated the same as in the M1 modelling approach. The difference between **M2** and **M1** is that in **M2** modelling approach the runoff from pervious areas will be loaded to the 2D surface model. It is expected that a part of this runoff will flow on the surface towards local terrain depressions and it will end up evaporating or infiltrating into the soil instead of being a runoff that loads the drainage system.

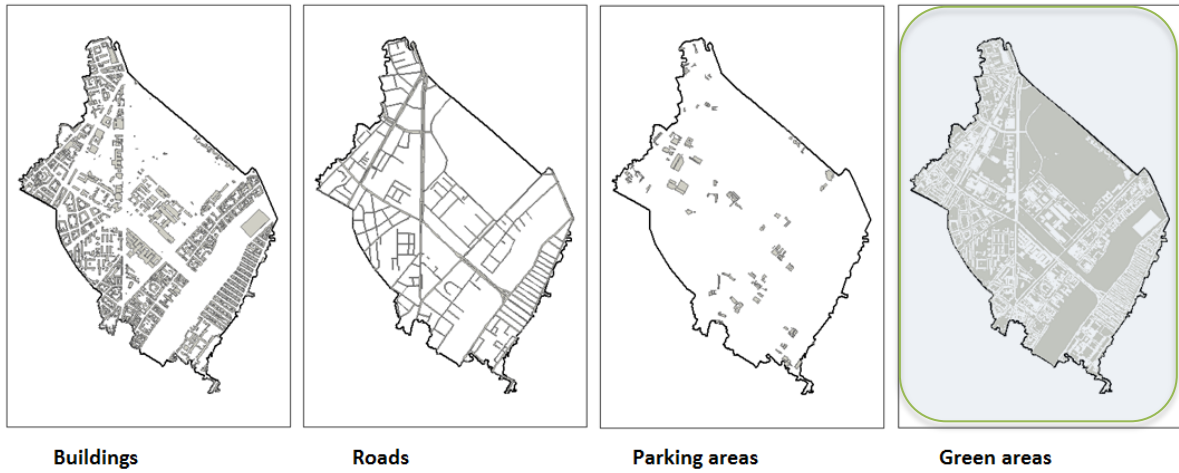


Figure (3): Representation of the contributing areas that are included **M2** modelling approach

The third modelling approach (**M3**) is to divide the catchments into pervious and impervious areas. The conceptual runoff model used here is ‘MOUSE Model B’ that applies the Horton’s infiltration equation:

$$I_H(t) = I_{Imin} + (I_{Imax} - I_{Imin}) \cdot e^{-k_a \cdot t} \quad , \text{ where:}$$

$I_H(t)$ = Horton’s infiltration (LT^{-1})

I_{Imin} = initial (maximum) infiltration capacity (LT^{-1})

I_{Imax} = final (minimum) infiltration capacity (LT^{-1})

k_a = empirical constant (time factor) (T^{-1})

t = time since the start of rainfall (T)

The impervious areas are divided into steep (roof) and flat surfaces while pervious areas are divided into low, medium and high infiltration. In this study the assumption is that all the impervious areas are flat and all the pervious areas are having medium infiltration. Nørrebo catchment is divided into 40% flat impervious areas and 60% medium pervious areas. Runoff from impervious surfaces such as roofs, roads and parking areas is reduced by the initial losses that in this case it is divided into: $5 \times 10^{-5}m$ wetting losses and $6 \times 10^{-4}m$ storage losses. Runoff from the previous surfaces is also reduced by the initial losses: $5 \times 10^{-5}m$ wetting losses and $4 \times 10^{-2}m$ storage losses. This method permits the consideration of infiltration for the previous areas where infiltration is an exponentially decaying process with large infiltration capacity in the beginning of the event. The soil properties are represented by the input parameters for this infiltration model. In Nørrebo the soil type is clayey loam and based on the infiltration

parameters from the literature the maxim infiltration capacity was set to 5×10^{-5} m/s and it will be reduced over time during the rainfall down to 1×10^{-6} m/s.

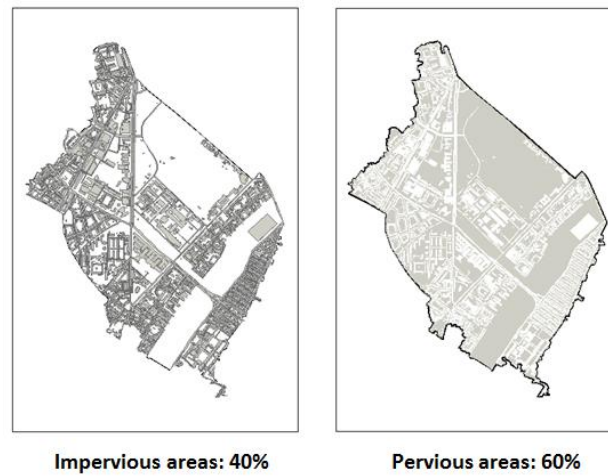


Figure (4): Representation of the contributing areas that are included **M3** modelling approach

The fourth modelling approach (**M4**) is to include only the storm runoff from impervious areas calculated with the conceptual runoff model ‘MOUSE Model B’ as a runoff that loads the drainage system. The runoff from the impervious areas will be calculated the same as in the M1 modelling approach. As well as in M2 modelling approach, in M4 modelling approach the runoff from pervious areas will be loaded on to the 2D surface model. In those 2 approaches the precipitation data it was be pre-processed in order to include only the surface runoff. It was developed a tool in Python that modifies the precipitation file. This will exclude the initial losses: 5×10^{-5} m wetting losses and 4×10^{-2} m storage losses and also the infiltration: the maxim infiltration capacity 5×10^{-5} m/s will be reduced over time during the rainfall down to 1×10^{-6} m/s.

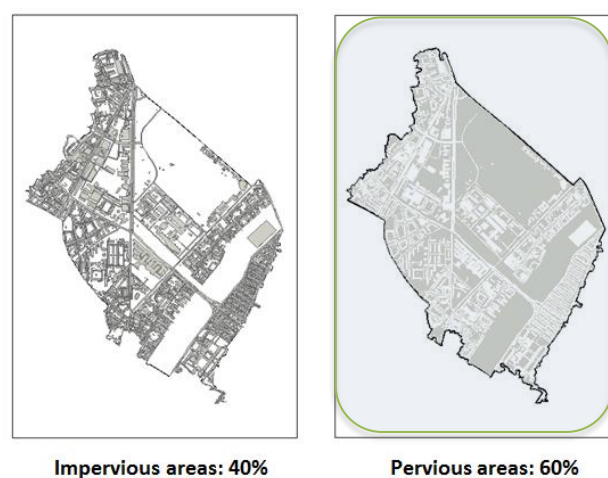


Figure (5): Representation of the contributing areas that are included **M4** modelling approach

3. RUNOFF MODELL CALIBRATION

No direct model validation will be possible within this research because observations of flooding are not available. However, we can employ model-to-model comparison to investigate the influence of different choices that need to be made in the modelling process to achieve a suitable representation of the green infrastructure in modelling floods.

Differences or changes in hydrological parameters might have a very big impact on the surface runoff calculation. Typically the runoff from green areas is not included when a new urban drainage is designed based on the assumption that on a 10 year event the pervious area will have enough infiltration capacity.

In Nørrebro catchment 60% of the catchment area represents pervious area. For a more realistic analysis of the urban flooding the runoff from the green areas will be included. In this study the runoff model to model calibration was made based on the most detailed modelling approach (**M3**) that showed that even for a 10 year event in pervious areas rainfall cannot completely infiltrate into the ground. The calibration of the hydrological model used in the modelling method M1 using the hydrological model used in the modelling method M3 showed that 7% of the precipitation event cannot infiltrate and is contributing to the volumes transported by the sewer system.

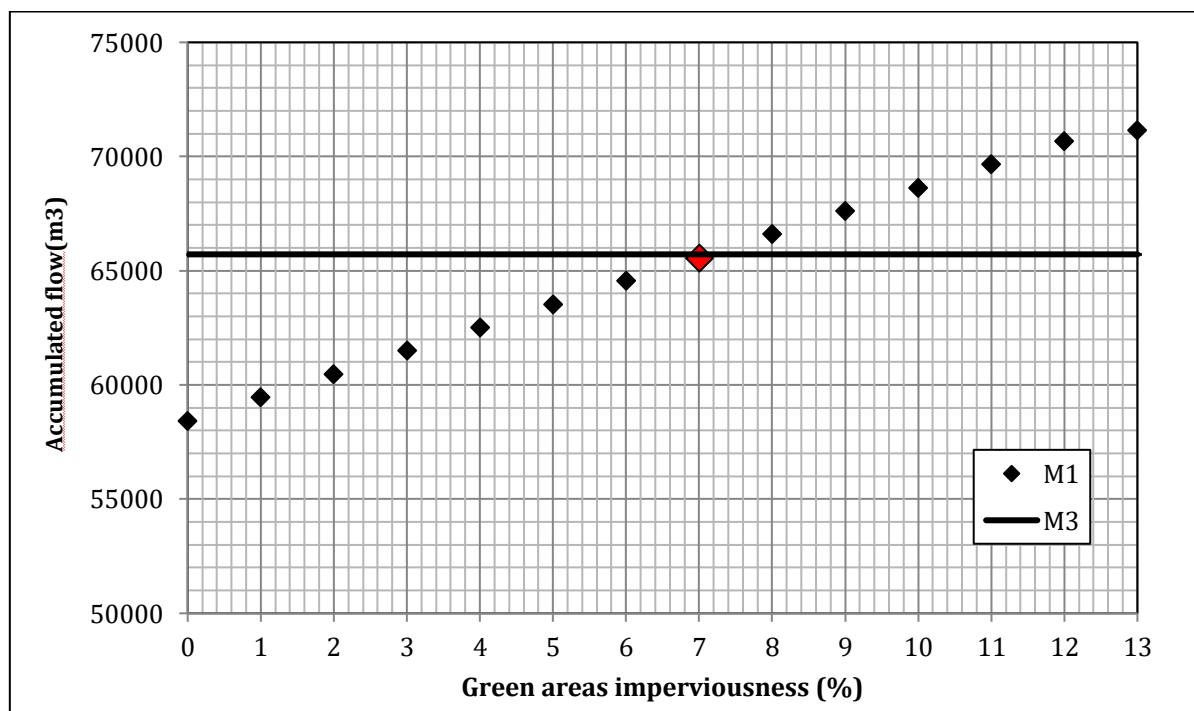


Figure (6): Runoff model calibration for the 10 year event showed that the imperviousness of the green areas in **M1** modelling approach is 7%

According to the study the pervious surfaces in Nørrebo catchment will generate a significant amount of surface runoff under extreme rain events. As shown in the figure below after excluding the initial loss, 42 % of the rainfall will generate surface runoff.

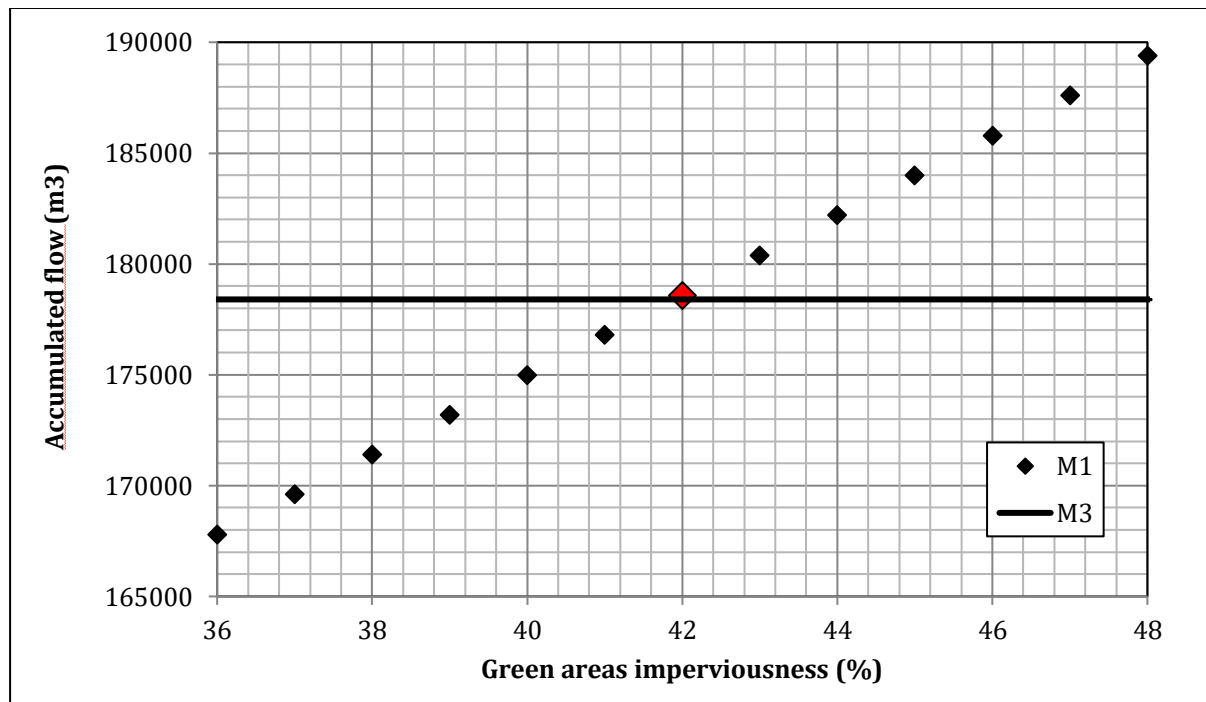


Figure (7): Runoff model calibration for the 100 year event showed that the imperviousness of the green areas in M1 modelling approach is 42%

In Denmark a very commune way of modelling urban areas is to consider both impervious and pervious areas connected to the sewer system and applying a delay for the pervious areas. This is a fact that may generate unrealistically loading of the sewer system if the runoff from this type of areas becomes a significant part of the total runoff model. The model set-up is that one sub-catchment can be connected to only one manhole and more sub-catchments can be connected to the same manhole. This means that the runoff from the whole catchment area is loaded into a single manhole and if the total area of the sub-catchments is large on extreme events the runoff that loads the sewer system will be so high that will create hydraulic instability in the 1D network model. To load the network in a more realistic way a detailed network model and a detailed sub-catchments representation was created for Nørrebo catchment. The same network model and the same catchments representation was used in all the four different modelling approaches listed above.



Figure (8): Representation of the catchments representation used in all the modelling approaches

For an even more realistic approach in **M2** and **M4** the runoff from the green areas is loaded on to the 2D surface model. In this way a part of this runoff will flow on the surface towards local terrain depressions. To be able to reproduce that with having the same catchments representation as the models where the runoff from the green areas it was necessary to make some adjustments on the runoff parameters. For the **M2** modelling approach the impervious area of the green areas was set to "0%" and for the **M4** modelling approach the maximum and the minimum infiltration capacity was set to 1m/s. In this way it will be no runoff contribution from the green areas and the overlapping runoff volumes will be avoided.

If the physical representation of the sewer sub-basins does not change, it is necessary to make adjustments to the runoff parameters. In the **M2** modelling approach, the permeability of the green areas was set to "0%" and in the **M4** modelling approach the minimum infiltration capacity was set to 1 m/s. In this way the runoff from green areas that is directly connected to the sewer system will be excluded and the runoff volumes overlap will be avoided.

After the computation of the hydrological model used in the **M3** modelling method for a rain water event with a 10 years probability of occurrence, it resulted that in permeable areas the 10 year rain cannot fully infiltrate. A calibration of the hydrological model used in modelling methods **M2** and **M4** using the hydrological model used in the **M3** modelling method indicated the accumulated rain to be applied directly to the surface of the 2D field.

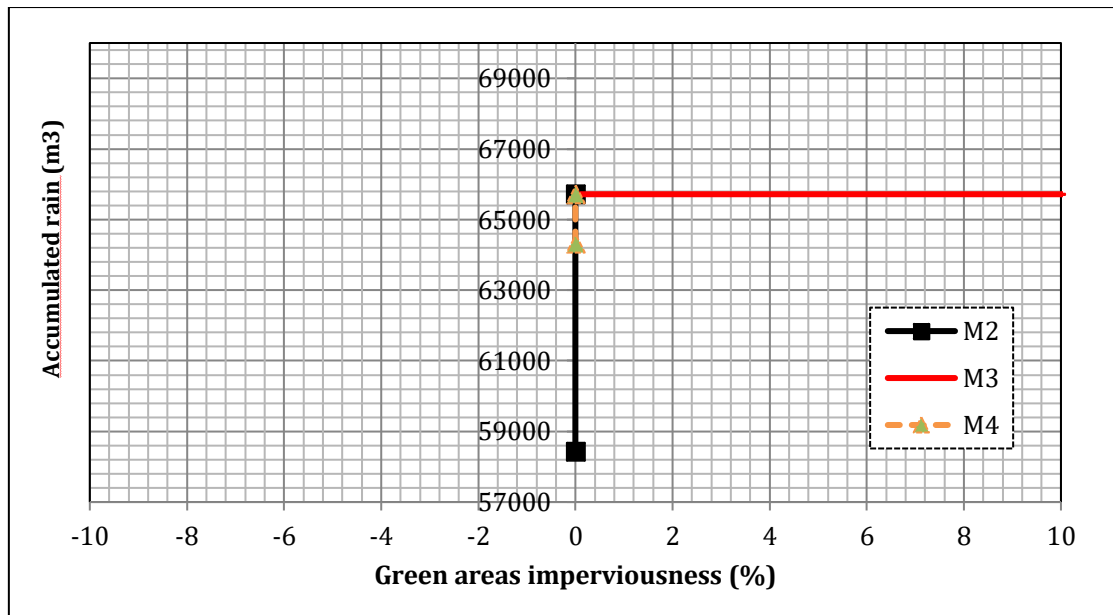


Figure (9): The calibration of the hydrological model used in the M2 and M4 modeling method using the hydrological model used in the M3 modeling method for a 10-year probability event

It is expected the permeable surfaces of the Nørrebo catchment will generate a significant runoff in case of a 100-year probability of occurrence event. The calibration of the hydrological model used in modelling methods M2 and M4 using the hydrological model used in the M3 modelling method indicated the accumulated rain volume to be applied directly to the surface of the 2D field also in case of a 100-year probability of occurrence event:

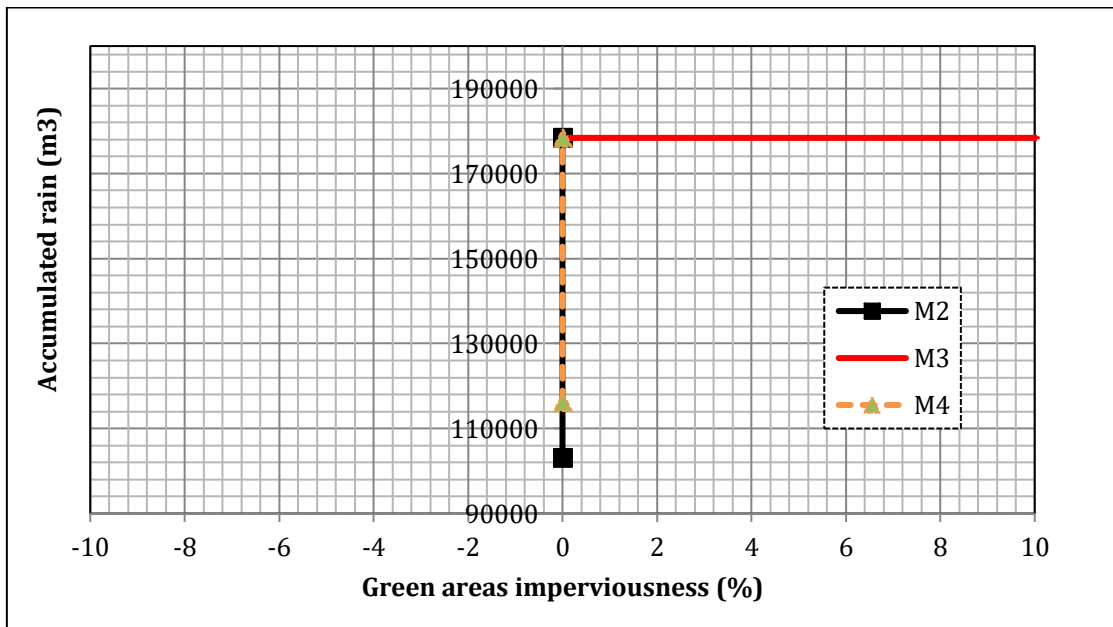


Figure (10): The calibration of the hydrological model used in the M2 and M4 modeling method using the hydrological model used in the M3 modeling method for a 100-year probability event.

4. RESULTS

In this study are used different methods for comparing the proposed modelling approaches and their performance. The comparison will be made based on commune criteria of comparison:

- The runoff from the impervious and pervious surfaces is applied to the sewer system model (M1 vs M3);
- The runoff from impervious surfaces is applied to the sewer system model and the runoff from pervious surfaces is applied directly to the 2D surface (M2 vs M4);
- The runoff from the impervious and pervious surfaces is computed using the conceptual Model A (M1 vs M2);
- The runoff from the impervious and pervious surfaces is computed using the conceptual Model B (M3 vs M4).

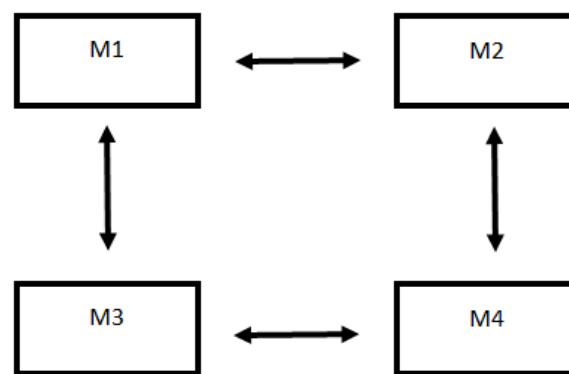


Figure (11): Model-to-model comparison

4.1.Runoff models results

In this study, the hydrological model used for the calibration is "MOUSE Model B" used in the M3 modelling method. The run of the hydrological model used in the M3 modelling method for an event with a probability of occurrence of 10 years, indicated that in the previous surfaces the runoff cannot infiltrate completely. After the calibration of the hydrological models used in the M1, M2, M3 methods using M3 hydrological model the runoff introduced in the hydraulic model is approximately equal:

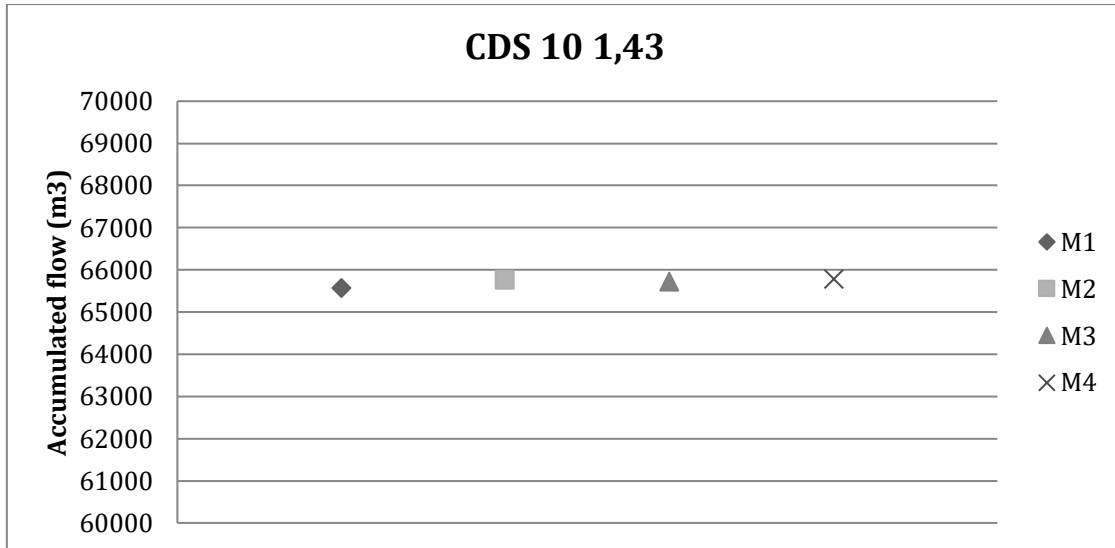


Figure (12): Accumulated rain depth for CDS 10 rain with a duration of 12 hours

Also, the hydrological model used in the M3 modelling method for an event with a probability of occurrence of once every 100 years was used for the calibration of the hydrological models used in modelling methods M1, M2, M3, indicated that the runoff introduced into the hydraulic model is approximately equal:

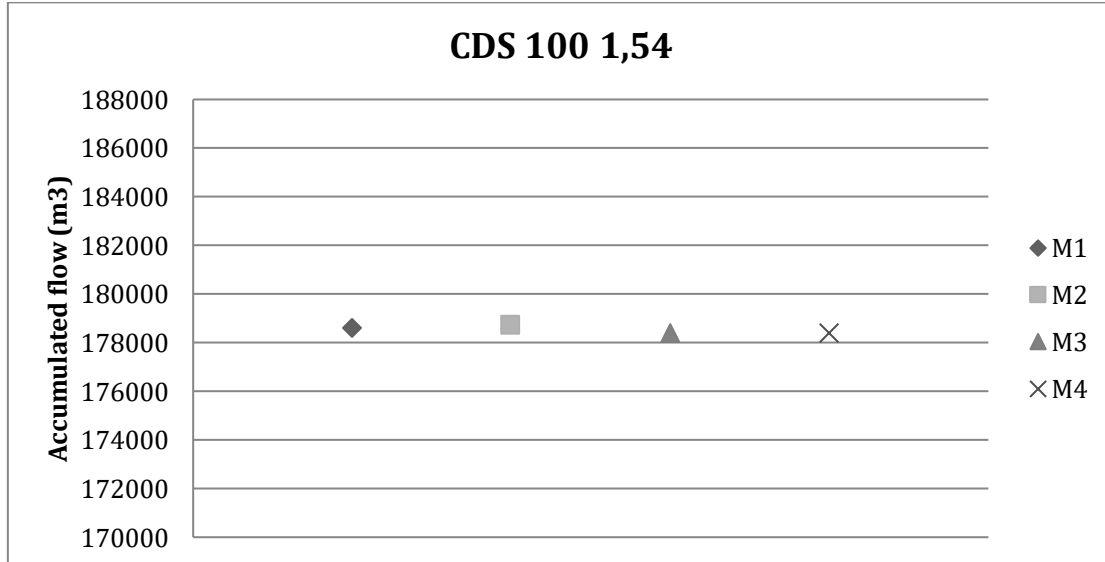


Figure (13): Accumulated rain depth for CDS 100 rain with a duration of 12 hours

4.2.MODEL TO MODEL COMPARISON

4.2.1 Maximum flood extend

In Denmark, the most commonly used method of flood modelling in urban areas is to consider both permeable and non-permeable areas connected directly to sewer system nodes. In that way the assumption is to consider that the runoff from both permeable and non-permeable areas is directly contributing to the volumes transported by the sewer system (M1 and M3).

It was noticed that in M1 and M3 modelling approaches this approach can generate an unrealistic loading of the sewer system especially if the runoff becomes significant (> CDS100). Instabilities were observed in the hydraulic model of the sewer system due to the fact that runoff has filled a small part the sewer system in a very short period of time. In reality is more probable that the runoff is filling the sewer system through all the connection points (manholes). Those instabilities are generating flooding in areas where the floods should not have been quantitatively significant.

In the M2 and M4 modelling approaches where the runoff from permeable surfaces was applied directly to the surface of 2D land it was noticed on a 100 year event that part of the runoff was transported to the field to the depression areas. In case of a precipitation event with the probability of occurrence every 10 years, no significant loads of the sewerage system were observed, the contribution of the green areas being very small:

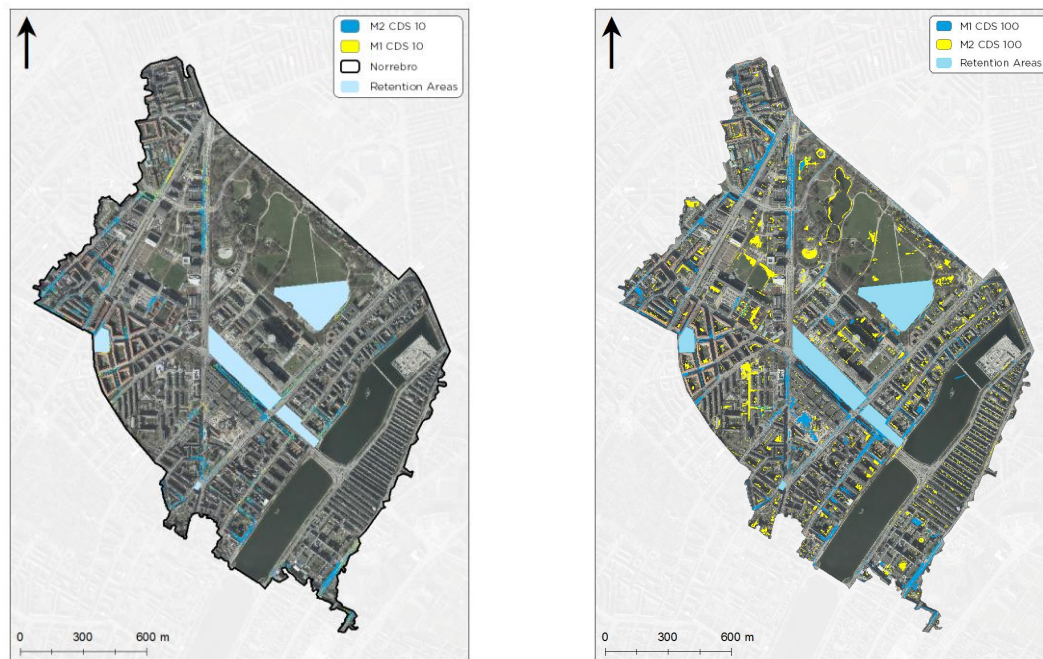


Figure (14): The maximum flood extend observed for an event with a 10-year probability of occurrence (left) and the flood limit observed for an event with a 100-year probability of occurrence (right)

4.2.2 Maximum depth

The depth of the flooding for each rain event is represented in depth ranges in different shades of blue (dark blue for deep depths and light blue for small depths).

The hydraulic model of the existing sewer system has been upgraded with the 36 sub-projects (green-blue solutions) as part of the Copenhagen Master Plan, 2015 (The City of Copenhagen, 2015), which have the role of transporting a big part of the runoff. As expected, it was observed in case of a rainfall event with a probability of occurrence once every 10 years that Nørrebro living area is protected.

In the case of a precipitation event with the probability of occurring once every 100 years, the flooded areas and the depth of the flood differs according to the modelling method chosen. If the catchments are directly connected to the sewer system, the precipitation volumes will be transported by the existing system and after the capacity of the transport is exceeded, the water will be transported by the green-blue solutions (M1 and M3). In case of M2 and M4 modelling methods, where the runoff from the green areas is not directly connected to the sewer system, a significant runoff volume will remain blocked in the depression areas:

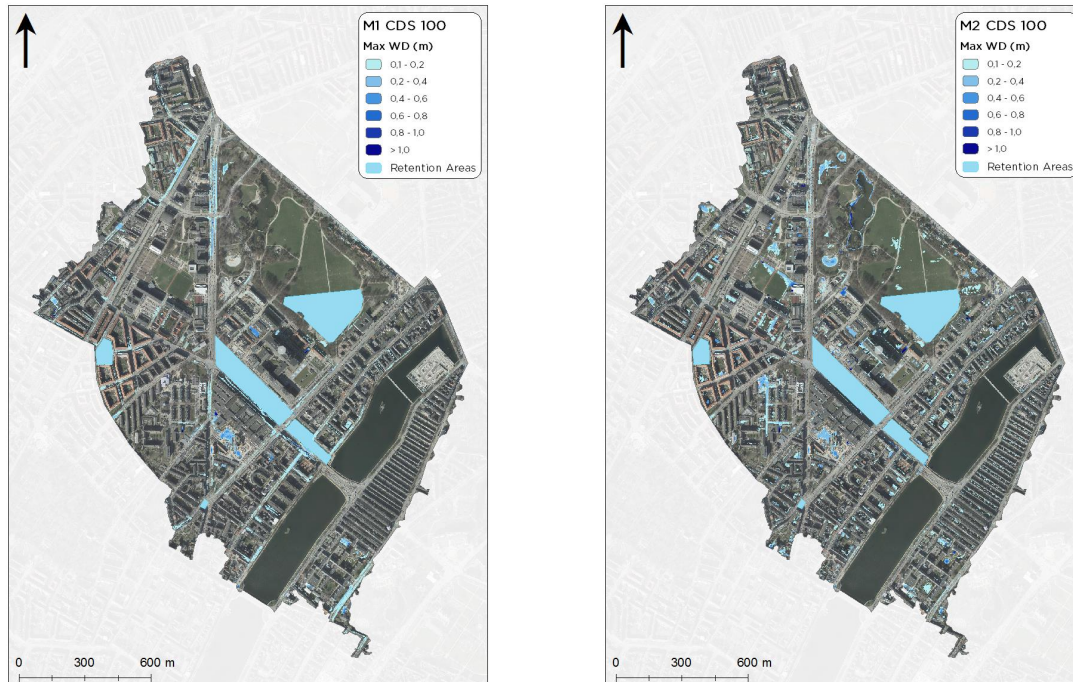


Figure (15): The depth of the flood calculated for an event with a 10-year probability of occurrence (left), respectively the flood depth calculated for an event with a probability of occurrence once every 100 years (right)

4.2.3 The computation time and the wet cells

The computation time of a model represents the amount of time that it takes to perform a calculation process and is proportional to the number of unit transformations performed. The model's resolution is the number of wet cells (cells that actively participate in flood calculations) and the number of dry cells (cells that do not participate actively in flood calculations).

The choice of model resolution leads to the determination of the computation time and it has a big influence on the quality of the results. Of course, a 1D-2D model like this one it offers a good estimation of the vulnerable areas in the sewer system, about the flooding extend and water depth, but it's not necessary a used approach because it requires a long computation time. This is why for the real-time calculations 1D models are preferred and for making predictions the 2D models.

The resolution used in the 2D models usually depends on the existent data and it can be a 10x10 m, 5x5m, 2 x2 m, etc. resolution. Of course, it is desirable to use a smaller resolution as possible to obtain a good estimation of the flooding. In the research presented here the resolution of the model is 1,6x1,6 m, which of course leads to a long computation time but also leads to a good flooding estimation.

Also, the computation time increases with including in the calculation a bigger number of wet cells. A computation time of 27 up to 43 hours was obtained on a 10 years event:

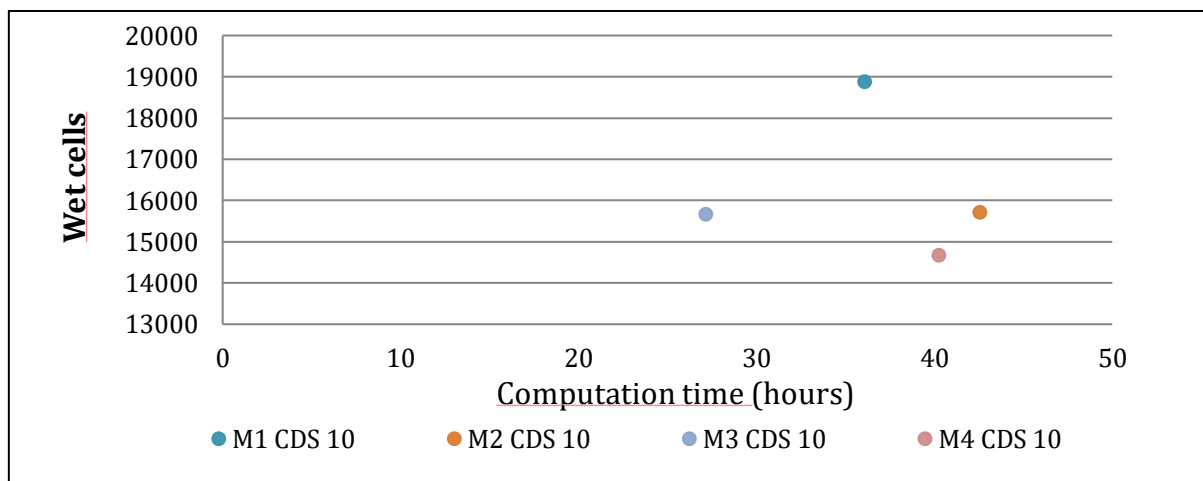


Figure (16): The computation time and the number of wet cells counted for the flood calculation on a 10 years rain event in all the four modelling approaches: M1, M2, M3 and M4

As it was expected, in the case of direct surface leakage on the 2D surface, the number of wet cells (active cells) increases, resulting longer computation times.

The computation times were: up to 43 hours if we look at a 10 years event and up to 116 hours if we look at a 100 years event.

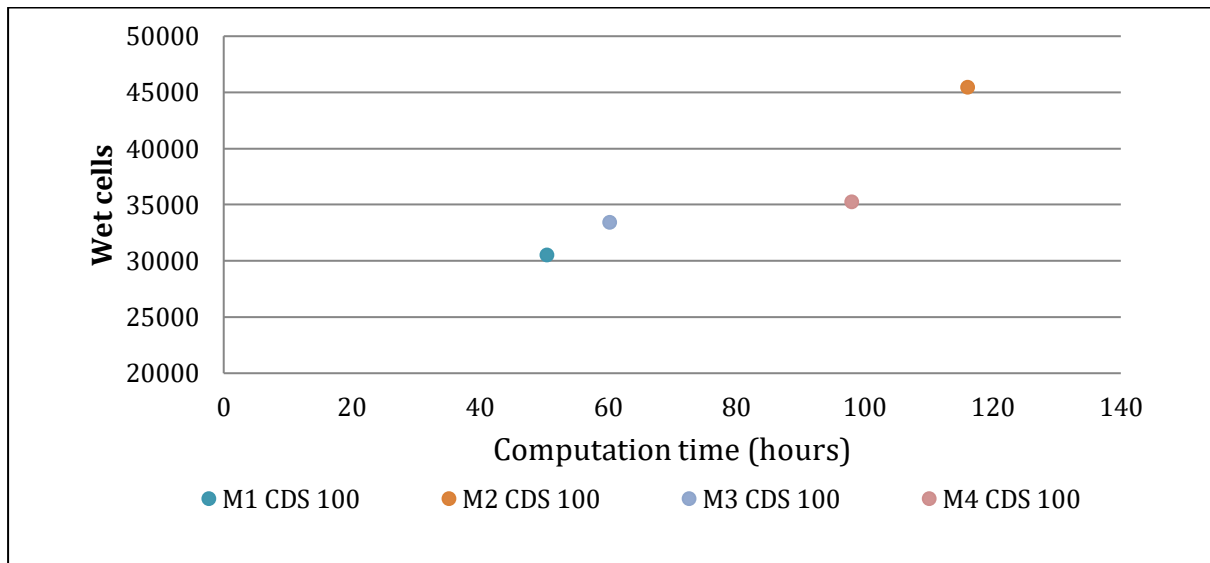


Figure (17): The computation time and the number of wet cells counted for the flood calculation on a 100 years rain event in all the four modelling approaches: M1, M2, M3 and M4

4.2.4 The flooded area and the flood volume

After analysing the flooded areas in relation to the flood volume for each of the four models, there is a direct link between the flooded area and the flood volume. In all four models the 10 year event flooding calculation leads to a large flooded area where the water depth does not exceed a few millimetres and a small flooded area where the water depth does not exceed a few centimetres.

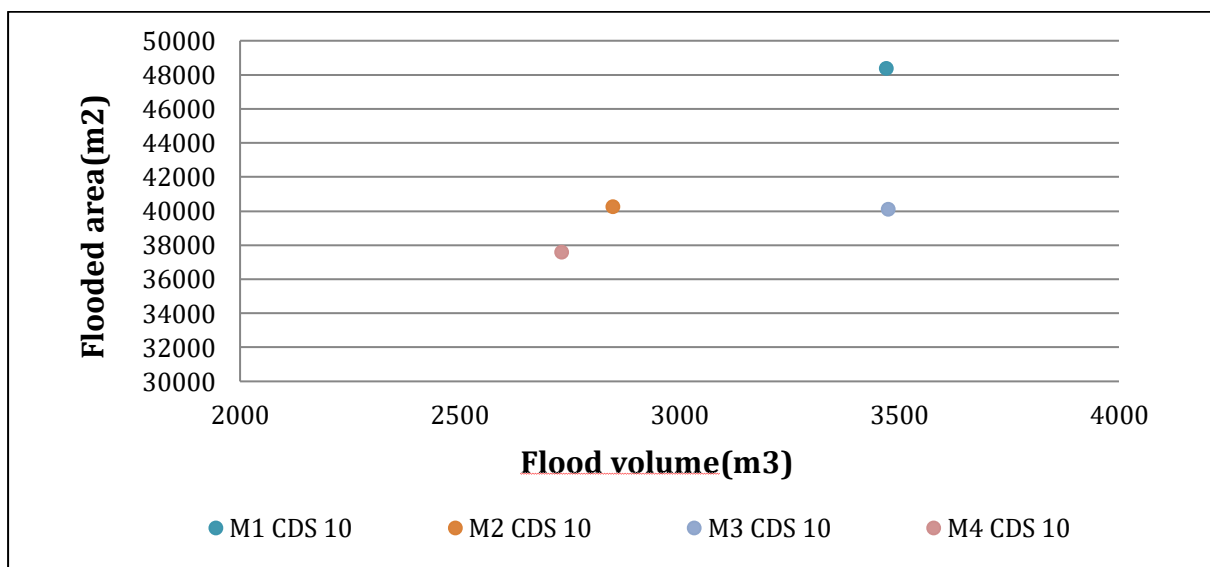


Figure (18): Flooded areas and volume on a 10 years rain event

If both permeable and non-permeable surfaces are connected directly to the sewer system, both the flooded area and the calculated flood volume are lower than if only non-permeable surfaces are directly connected to the sewerage system. This is because a big part of the runoff from the permeable surfaces has been transported to the depression areas where it remains stuck before reaching the sewer system.

In all four models the 100 year event flooding calculation leads to a small flooded area where the water depth does not exceed a few millimetres and a large flooded area where the water depth does not exceed a few centimetres.

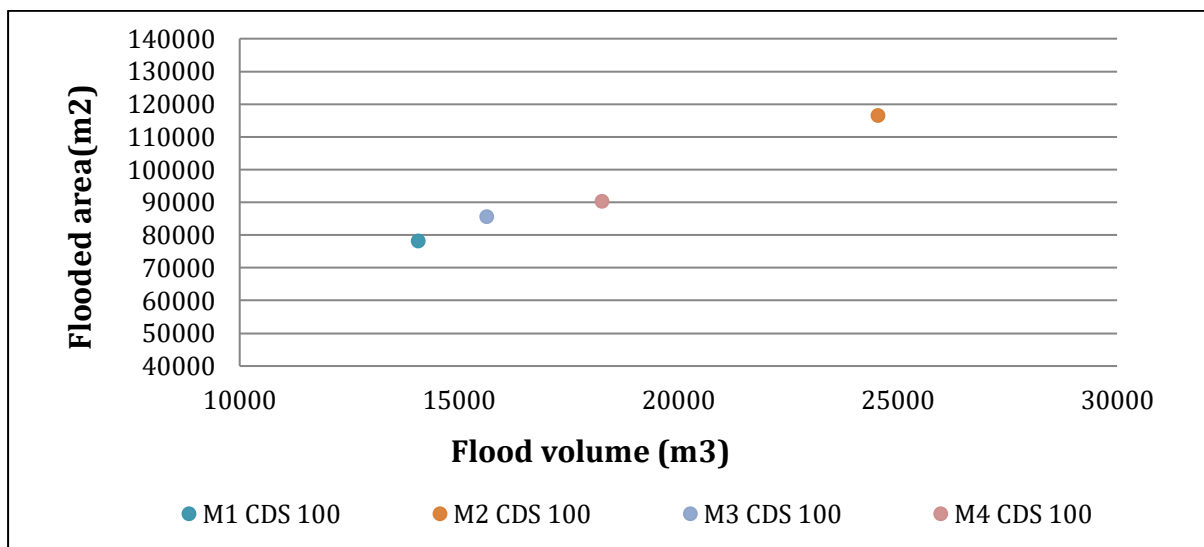


Figure (19): Flooded areas and volume on a 100 years rain event

5. CONCLUSIONS

Green areas without drainage systems should be handled carefully, especially in the case of very large green areas (parks). If a very large green area is docked at a single point to the sewer system, it will cause unrealistic flooding around the connection point.

As a result of the obtained results it was observed that considering both the permeable and the non-permeable areas connected to the sewer system nodes thus directly contributing to the volumes of water transported by the sewerage network (M1 and M3), and this approach can generate a load unrealistic of the sewer system where surface leakage becomes significant. It has also been observed that in M2 and M4 modeling methods where surface leakage from permeable surfaces was applied directly to the surface of 2D land, some of the surface leakage remained blocked in the depression areas. Modeling methods M2 and M4 manage to simulate reality better, but the main drawback of these methods is rolling time, which can be double or even triple of running time in M1 and M3 modeling methods.

The choice of the correct modeling approach, the correct calculation of the rains in the model and the calibration parameters should be made on the basis of very clear criteria to simulate the reality better.

There is now a worldwide need for standards to help modelers to have a common approach, suited to the project area studied. This research can guide the model maker in choosing the most appropriate modeling approach.

6. REFERENCES

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