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This project has received European Regional Development Funding through INTERREG IV B.

INTERREG IVB

URBAN PLUVIAL FLOOD MODELLING:

CURRENT THEORY AND PRACTICE

Review document related to Work Package 3 – Action 13

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October 2013 (final revision in August 2015)

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INTRODUCTION

The purpose of this document is to provide a review of the inputs and components of urban pluvial flood models, including the current theory and practice of this subject. This is expected to serve as 'road map' for the implementation of urban pluvial flood models for the different pilot locations of the RainGain project.

1. DEFINITION OF URBAN PLUVIAL FLOODING

As its name suggests, pluvial flooding refers to rain-related flooding. It is caused by either intense or prolonged rainfall which generates a runoff volume that exceeds the capacity of the existing drainage system. This type of flooding is usually characterised by rapid-onset (or flash flooding) and by being localised. In fact, the small spatial and temporal scales at which this type of flooding generally occurs make it difficult to predict and pinpoint, much more so than river or coastal flooding (EA, 2011). Although it can occur in both urban and rural areas, pluvial flooding is a predominantly urban phenomenon and it is in urban areas where its effects are more pronounced and damaging (EA, 2009; Priest et al., 2011). The focus of this review and of the RainGain project is exclusively on pluvial flooding in **urban areas** (i.e. urban pluvial flooding).

Even though the general definition of urban pluvial flooding appears to be clear, there is some debate about its specific characteristics and how it relates to other named types of flooding, such as surface water, minor watercourses and sewer flooding. Having a clear definition of this type of flooding is essential for understanding the issues associated to its modelling, forecasting and management.

The main debate is about whether pluvial flooding only relates to direct runoff flow[1] and/or ponding **before** it enters a natural or man-made drainage system or water course (Defra, 2010; Parker et al., 2011; Scottish Environment Protection Agency, 2012), or whether in addition to direct runoff, it also includes floodwater coming from surcharged sewers and/or urban minor watercourses the flow capacity of which has been exceeded as a result of heavy rainfall (Schmitt et al., 2004; Pitt, 2008). When the second and broader approach is adopted, the term urban pluvial flooding is often used interchangeably with **surface water flooding** (Pitt, 2008; Local Government Association, 2012). Nonetheless, in the UK a new definition has been recently introduced by Defra (2010) according to which surface water flooding also includes flooding from groundwater[2], in addition to flooding from direct runoff, sewers and minor urban watercourses.

In the context of the RainGain project, **urban pluvial flooding will be understood as a condition where, as a result of heavy or prolonged rainfall, water escapes from or cannot enter the sewer**

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[1] Direct runoff corresponds to the proportion of rainwater that is not infiltrated into the ground, intercepted by vegetation or retained on the surface, but instead flows over the surface.

[2] Groundwater flooding occurs when levels of water in the ground (i.e. water table) rise above the surface. This type of flooding is not necessarily linked directly to a specific rainfall event; instead, it occurs as a result of prolonged wet weather. Groundwater flooding is generally of longer duration than other causes of flooding, possibly lasting for weeks or even months (British Geological Survey, 2012).

system or minor urban watercourses, thus remaining on the surface and eventually entering buildings. According to this definition, urban pluvial flooding comprises flooding from direct runoff, sewers and minor urban watercourses, resulting from heavy rainfall. This definition is adopted given that these three phenomena (namely runoff, sewer surcharge and minor watercourse flooding) are **intrinsically linked** and must be analysed and modelled together if rain-related urban flooding is to be properly understood and represented. With regard to the new definition proposed by Defra, it is not considered appropriate to include groundwater flooding as part of surface water (pluvial) flooding within the context of this project. Although there are interactions between urban pluvial and groundwater flooding and both sources of flooding make part of what in the UK is known as 'local flooding' (UK Parliament, 2010), the time scales, models, forecasting systems and management strategies of these two types of flooding are basically different. Within this project, the influence of groundwater levels in urban pluvial flooding will be taken into account via model parameters and boundary conditions, which, as will be explained in the following sections, is the common practice. In the same way, the influence of other sources of flooding (e.g. fluvial and coastal flooding), which may coincide with and exacerbate urban pluvial flooding, will also be taken into account via model boundary conditions.

2. THE INPUTS AND COMPONENTS OF URBAN PLUVIAL FLOOD MODELS

As has been explained before, the driving force of urban pluvial flooding is intense or prolonged rainfall over the area of interest. Rainfall falling over an urban catchment may either fall on a pervious area (e.g. urban parks, gardens), or on an impervious one (e.g. roofs, streets, parking areas). On a pervious area, some rainfall may be intercepted by vegetation cover, some may infiltrate the sub-surface, some may be stored in surface depressions and later evaporate and the remainder becomes surface runoff. In impervious areas, in contrast, nearly all the rainfall becomes runoff (some losses may occur due to interception of rainfall by building's facades, storage in surface depressions and infiltration through cracks; nonetheless, these losses are generally small). Moreover, both in pervious and impervious areas a thin layer of runoff is first formed before it actually starts to flow. The thickness of this layer varies between a fraction of a millimetre (in impervious areas) and a few millimetres (in vegetated/grassed areas) (Maksimović & Radovic, 1986). Surface runoff initially flows along urban surface pathways (e.g. streets and allies) until reaching either a water body (e.g. an urban watercourse) or, more likely, a gully through which it may enter the underground pipe system (which ultimately discharges or is pumped into a water body or a treatment plant). The processes described up to here are illustrated in Figure 2-1.

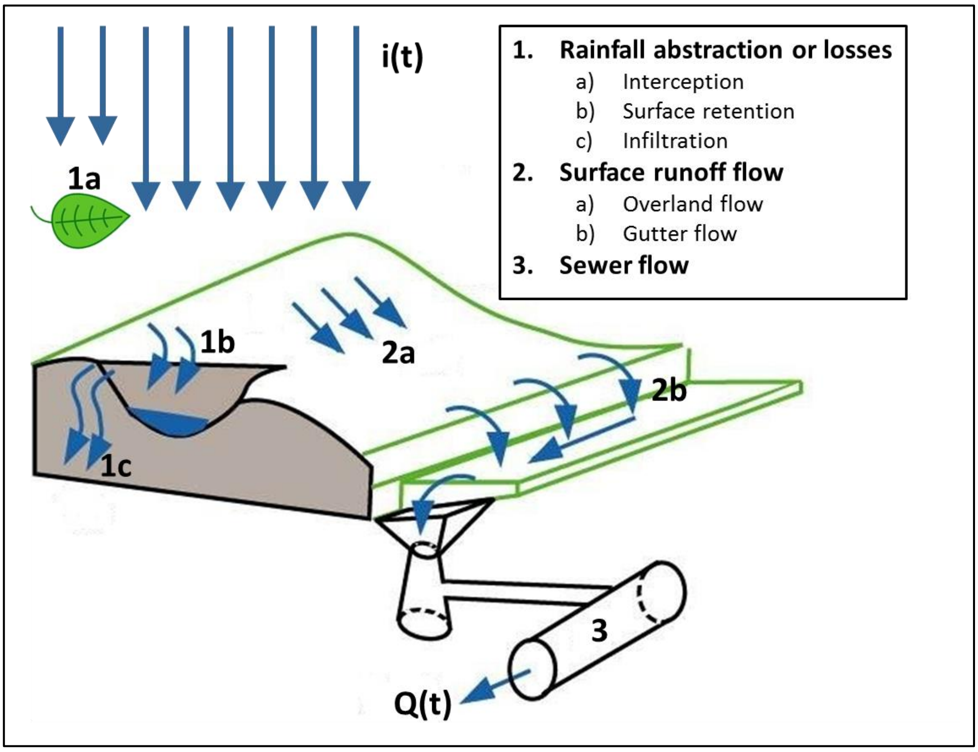
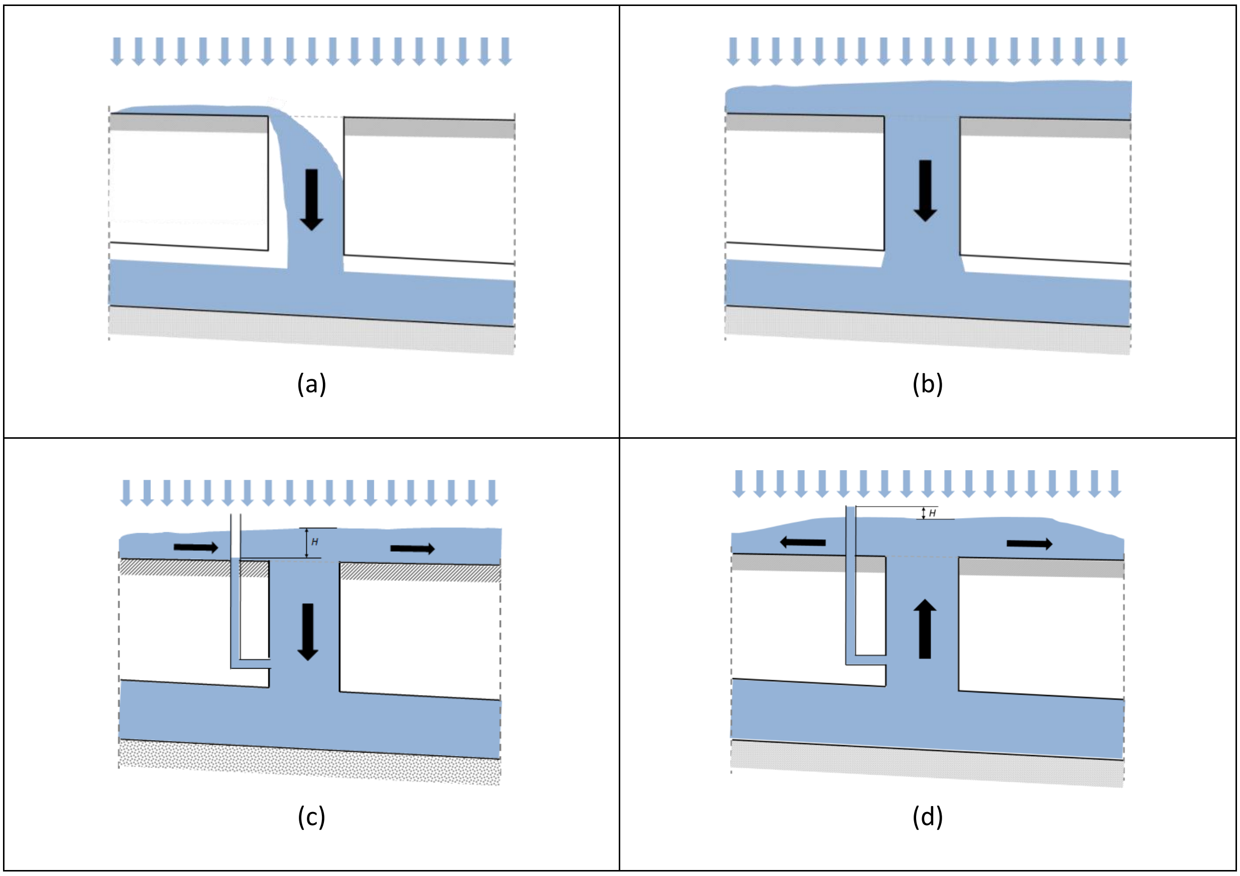


Figure 2-1: Runoff generation process in urban catchments (adapted from Maksimović (2007))

The amount of water entering the sewer system will depend on the intake capacity of the gully or manhole and of the sewer system itself. When intense rainfall occurs, it may happen that not all the runoff can enter the sewer system, even if the pipes have sufficient capacity (Mark et al., 2004); this is due to the limited hydraulic capacity of the gullies and manholes, which may behave as weirs or orifices, depending on the water depth around them (Djordjević et al., 2005; Saul, 2012) (the behaviour of gullies and manholes under different flow conditions is illustrated in Figure 2-2). As the storm progresses, part of the runoff continues to pond on the urban surface and the other part continues to enter the sewer system until its maximum capacity is eventually reached and the system surcharges (i.e. sewers become full and act as conduits under pressure – see Figure 2-2 (c)). If there is sufficient pressure in the sewer system so that the piezometric head rises above the surface water level, then overflow occurs through manholes and gullies and the excess volume of flow becomes again surface runoff (Zoppou, 2001) (this situation is illustrated in Figure 2-2 (d)). After the storm finishes, sewers continue to drain water and they may again have enough capacity to receive runoff from the surface. The duration of flooding on the urban surface depends on the runoff volume, the intake capacity of the gullies, the drainage capacity of the pipe system, the topography, infiltration and evaporation in the catchment area (Mark et al., 2004).

It is worth noting that in lowlands and delta areas sewer flow and flood dynamics, especially surcharge and pressurised flow events, may differ significantly from those in relatively sloped areas. The peculiarities of these areas, which are common in The Netherlands, are summarised in Box 2-1 below.



(a) (b) (c) (d)

Figure 2-2: Cases of flow exchange between the surface flow and the sewer system through gullies and manholes. (a) Free inflow and free flow in pipes: inlet behaves as a weir and both inlet and sewers have enough capacity to accommodate more water; (b) Submerged inflow and free flow in pipes: the free surface inlet capacity has been exceeded and it starts to work as an orifice, only a fraction of the water can flow into the pipe, although the capacity of pipes has not yet been exceeded; (c) Submerged inflow and pressurised pipe flow: pipes have become full, but pressure is still not enough to cause overflow (the piezometric head is still below surface water level); (d) Overflow: the piezometric head in the sewer system is higher than that of surface water, thus causing overflow. Adapted from Mark et al. (2004), Schmitt et al. (2004) and Djordjević et al. (2005).

Based on this description of the processes associated to storm water drainage and urban pluvial flooding, the main inputs and components of urban pluvial flood models can be identified. As is evident, the main input for urban pluvial flood models is rainfall. Moreover, the processes that take place once rainfall falls over an urban area can be classified into three main components or sub-models; these are: (1) runoff generation (which includes rainfall interception, retention, evaporation and infiltration), (2) overland flow, and (3) sewer flow. The interactions between these components are schematised in Figure 2-3. Each of these components has been the object of a number of studies in the past and several different approaches for modelling them have been developed, including physically-based, conceptual, empirical and, more recently, data-driven approaches (for a definition of these modelling approaches see Maskey (2004)). In addition, the way in which these components -especially components 2 and 3- are integrated is of utmost importance in urban pluvial flood modelling and has also been the object of a number of recent studies (Djordjević et al., 1991; Djordjević et al., 1999; Djordjević et al., 2005; Leandro, 2008; Giangola-Murzyn et al., 2012a).

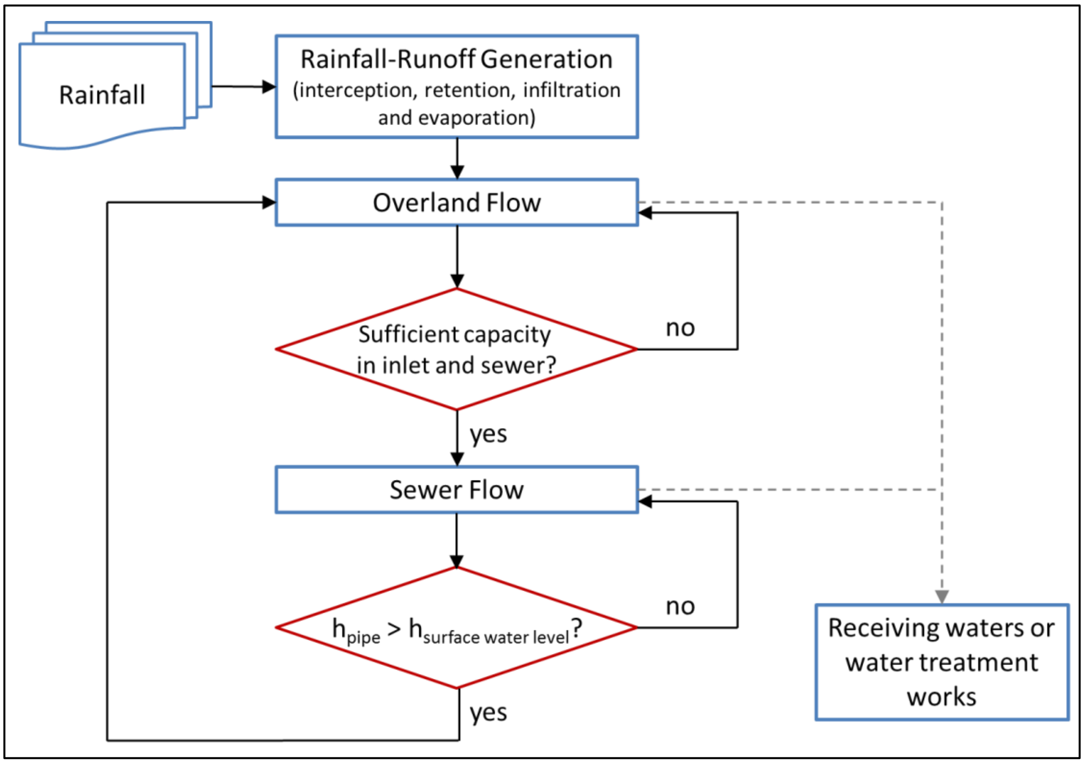


Figure 2-3: Overview of processes associated to urban pluvial flood models (*h* stands for piezometric head)

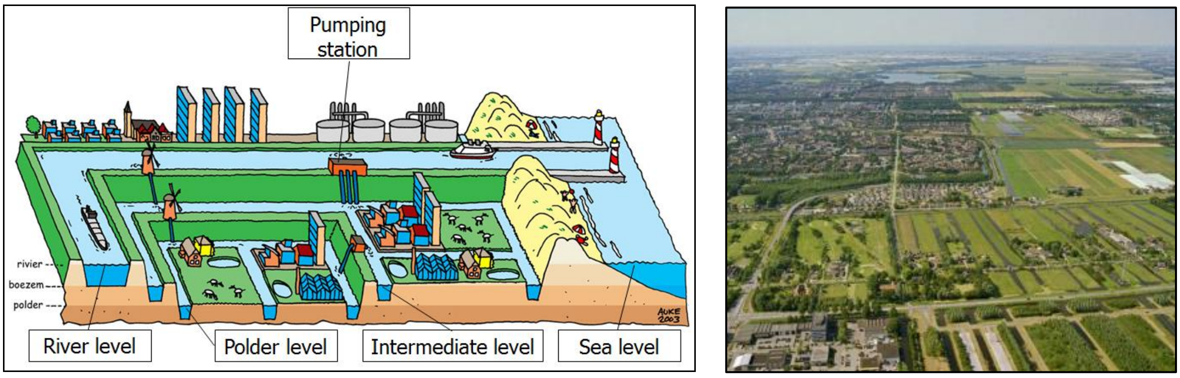
In what follows an overview is provided of the above mentioned inputs and components of urban pluvial flood models and the way in which they are integrated. This includes an overview of the theories behind them and a compendium of the main modelling developments. Special emphasis is placed on the most commonly used modelling approaches, which will be implemented in the different pilot locations of the RainGain project. It is worth mentioning that this report focuses mainly on water quantity modelling given that the final aim is to simulate and forecast flooding; although water quality is a very important aspect of urban drainage systems, the detailed modelling of it falls outside the scope of the RainGain project.

Box 2-1: Peculiarities of sewer flow and flood dynamics in lowlands and delta areas

Peculiarities of sewer flow and flood dynamics in lowlands and delta areas: An example from the RainGain pilot locations

Lowlands and delta areas, common in countries such as The Netherlands, are characterised by flat terrain, often located at or below sea level, in so-called polders where lands are artificially kept dry by constant pumping (see Figure 2-4). In these areas natural slopes are absent which creates some challenges when it comes to urban drainage. In areas with sloped terrain flow is driven by gravity and sewer pipe configuration is determined by the topography of the terrain. In contrast, in polder areas the flow is mostly pressure driven as no natural bottom gradient is available to convey the water. As a result, drainage systems and sewer flow dynamics in these areas differ quite significantly in mainly three ways:

- Drainage systems are often interlinked and looped.
- The direction of flows changes over the course of a storm event as the system first fills and subsequently starts conveying the storm water. This implies that flow directions and subcatchment boundaries in urban drainage systems are changeable and cannot be defined based on topography or network configuration.
- Differences between ground levels, surface water levels and groundwater levels in polder areas are typically small, of the order of 0.5 to 1.5 meters. As a result, sewers are generally located below groundwater and below surface water levels. Bottom gradients are kept small, to avoid digging too deep below ground level. Consequently, sewer systems easily get surcharged and pressurised flow is the dominating flow condition in lowland areas.



(a) (b)

Figure 2-4: Polder systems (a) schematic representation of drainage systems in polders; (b) Alexanderpolder, The Netherlands (source: TU Delft educational material)

2.1. RAINFALL AS INPUT TO URBAN PLUVIAL FLOOD MODELS

Depending on the purpose of the modelling exercise, rainfall inputs for urban drainage models may come from synthetically generated storms (e.g. design storms), measurements/estimates or forecasts.

The focus of RainGain project’s Work Package 3 (WP3) is on the implementation of urban pluvial flood models for each pilot location and further testing of these using the **improved rainfall**

estimates and forecasts resulting from Work Package 2 (WP2). Considering the focus of the project and of WP3, this section will only discuss the general requirements of rainfall estimates for urban hydrological applications. More details of rainfall estimation and forecasting for urban areas can be found in WP2 Review Document (Decloedt et al., 2013).

General requirements of rainfall estimates for urban hydrological applications

Rainfall is the main input for urban pluvial flood models and the uncertainty associated to it dominates the overall uncertainty in the modelling and forecasting of this type of flooding (Golding, 2009). The rainfall events which generate pluvial flooding are often associated with thunderstorms of small spatial scale (~ 10 km), whose magnitude and spatial distribution are difficult to monitor and predict (Collier, 2009; Golding, 2009; Vieux & Imgarten, 2012). In addition, urban catchments are in general highly impervious and of small size; consequently, the associated drainage areas are small and the concentration times are short, making these catchments very sensitive to the spatial and temporal variability of precipitation (Aronica & Cannarozzo, 2000; Segond et al., 2007). As a result, rainfall estimates (or forecasts) of the highest standard, in terms of accuracy as well as spatial and temporal resolutions, are required in order to obtain accurate flow estimates in urban catchments (Einfalt, 2005). In a study conducted for a sewer system in Belgium, Willems (2008) concluded that 30-70 % of the total uncertainty in the downstream flow discharges is due to the rainfall input uncertainty. Improving rainfall inputs, e.g. by better accounting for the spatial variability of rainfall fields may improve the performance of urban drainage models significantly.

A study undertaken by Schilling (1991) suggested that, for urban drainage modelling, rainfall data of at least 1-5 min and 1 km resolutions should be used. Similar recommendations were made by Niemczynowicz, who established a 1-1-0.1 rule of thumb: 1 raingauge per km^2 with 1 min temporal resolution and 0.1 mm rainfall depth resolution (see Maksimović (1996)). Another study undertaken by Fabry et al. (1994) suggested finer resolution data (i.e. 1-5 min in time and 100 – 500 m in space) for urban hydrological applications in order to obtain the necessary hydraulic details. This however may vary according to the application (Einfalt et al., 2004; Einfalt, 2005); for detailed sewer system simulation, for example, it is believed that the spatial-temporal resolutions suggested in Fabry et al. (1994) are essential. Using semi-distributed urban drainage models of two different catchments, Auguste Gires et al. (2012) and A. Gires et al. (2013) showed that the unmeasured small-scale rainfall variability (i.e. occurring below the scale of 1 km in space and 5 min in time usually available with the C-band radar networks of western European meteorological services) has a significant impact on the simulated flows. This variability should therefore be taken into account at least in a probabilistic way while higher resolution data remain unavailable.

Moreover, the desired temporal and spatial resolutions of rainfall estimates also vary according to the catchment characteristics (e.g. drainage area). For example, Berne et al. (2004) analysed the relation between the catchment size and the spatial and temporal resolutions of rainfall estimates, and confirmed the high dependency between them (i.e. small catchments require finer-scale rainfall inputs). Another study undertaken by L.-P. Wang et al. (2012) analysed the impact of the spatial variability of rainfall estimates on urban sewer flow depth estimates and concluded that the impact is highly related to the drainage area: rainfall estimates of coarse resolution in relation to the drainage area (e.g. rainfall estimates with 1 km spatial resolution and sub-catchments with drainage area smaller than 1 km^2) lead to over-smooth runoff hydrographs, which do not reflect the dynamic behaviour of the area under consideration.

The two sensors that are commonly used for rainfall estimation at urban scales are raingauge and radar (Cole & Moore, 2008). The main characteristics, advantages and disadvantages of these two sensors are described in WP2's Review Document (Decloedt et al., 2013). Regarding rainfall forecasting, there are three main techniques: nowcasting, Numerical Weather Prediction (NWP) and statistical methods (Sene, 2010). Due to the small spatial and temporal scales which characterise runoff processes in urban catchments, the most accurate QPFs for these areas must be achieved in the forecast horizon between 30 min and 2 hours (Einfalt et al., 2004). At these short lead times, nowcasting forecasts are, in general, more suitable (Golding, 1998; Liguori et al., 2012; Liguori & Rico-Ramirez, 2012). More details about rainfall forecasting methods and their suitability for urban hydrological applications can be found in in RainGain's WP2 Review Document (Decloedt et al., 2013).

2.2. RUNOFF GENERATION MODELLING

Runoff generation modelling, also known as rainfall-runoff modelling, entails estimating which part of the total rainfall (h_{total}) becomes effective rainfall or runoff ($h_{effective}$) which will flow over the urban surface and may eventually find its way into the sewer system. There are many reasons for rainwater not to become runoff. For example, rainwater may soak into the ground (even on an impervious surface, via cracks), it may be retained in depressions and later evaporate, or may be caught in the leaves (canopy) of a tree (Butler & Davies, 2011). Part of the rainwater is lost immediately after the storm begins (i.e. initial losses - $h_{initial}$); whereas other part is lost as it runs overland (i.e. continuing losses - $h_{continuous}$). A number of approaches have been developed to estimate each of these losses as a function of the catchment land use, soil type, topography and wetness; some of these methods are described in what follows. Depending on whether the model is semi-distributed or fully-distributed[3], losses are estimated, respectively, at each subcatchment (e.g. InfoWorks CS, Canoe and Sobek software packages described in Section 3) or grid element (e.g. Multi-Hydro and InfoWorks ICM software packages described in Section 3). Once losses are estimated, effective rainfall or runoff can be obtained by subtracting the losses from the total rainfall hyetograph (initial losses are subtracted from the initial values of the rainfall hyetograph, whereas

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[3] Depending on how urban drainage models treat spatial variability, they can be classified as semi-distributed or fully-distributed. In semi-distributed models, the whole catchment is split into a number of sub-catchments, each of which is treated as a lumped model (i.e. within each subcatchment rainfall input and hydrologic responses are assumed to be uniform; their spatial variability is not accounted for). Each subcatchment contains a mix of pervious and impervious surfaces whose runoff drains to a common outlet point, which could be either a node of the drainage network or another subcatchment (Rossman, 2010). Each subcatchment is characterised by a number of parameters, including total area, length, slope, proportion of each land use and soil type characteristics, amongst others. Rainfall is inputted uniformly within each subcatchment and based on the subcatchment's characteristics, the total runoff is estimated and routed to the outlet point (as will be explained in Section 2.3). In fully-distributed models, the whole catchment is discretised as a grid or mesh of regular or irregular elements. In this case, a different rainfall input can be assigned to each grid element and runoff is also estimated at each element. In fully-distributed models, overland flow is necessarily modelled or routed in 2-dimensions (as will be explained in Section 2.3.4).

continuing losses are subtracted continuously at each time step of the hyetograph). This is illustrated in Figure 2-5.

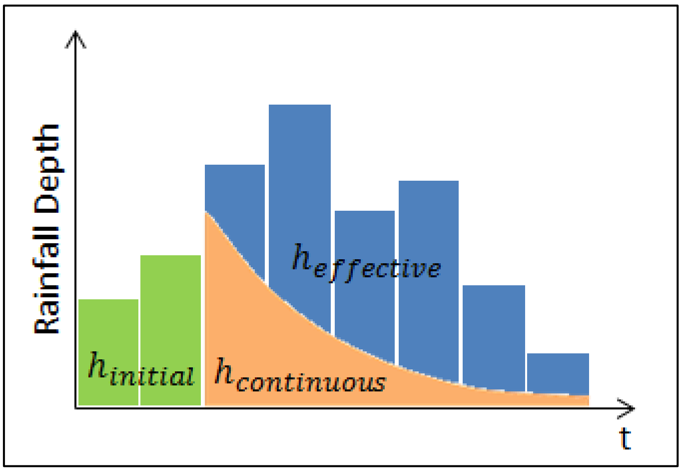


Figure 2-5: Estimation of runoff or effective rainfall from total rainfall

2.2.1. Initial losses or abstraction ($\boldsymbol{h_{initial}}$)

Initial losses correspond to the first few millimetres of rainfall which are lost prior to any runoff (Innovyze, 2012a). The initial part of a rainstorm is assumed to cause no runoff because it is lost in two main processes:

- **Interception ($\boldsymbol{h_i}$):** interception is the collection and retention of rainwater by vegetation cover, buildings' facades, etc. After an initial retention period, the interception rate rapidly approaches zero and excess rain falls through the surfaces. This type of loss can represent up to 20% of total rainfall (a couple of millimetres) in highly vegetated areas (Mansell, 2003). However, it is usually small for impervious areas (< 1 mm) and is often neglected or combined with depression storage in urban drainage models (Butler & Davies, 2011).

- **Depression storage and surface wetting ($\boldsymbol{h_d}$):** depression storage is the initial storage within depressions on the ground surface (puddle forming) and also within the surface layers of nominally impervious materials (surface wetting) (Mansell, 2003). The water stored in puddles is eventually removed by infiltration, evaporation or leakage. The magnitude of depression storage depends on factors such as surface type, slope and antecedent rainfall conditions. In models, the maximum possible depression storage is calculated using a regression equation or is specified as an absolute value. A regression equation commonly used in the UK and Belgium to estimate the maximum depression storage (h_d in mm) is that incorporated in the Wallingford Procedure (HR Wallingford, 1983):

$$h_d = \frac{k}{\sqrt{s}} \tag{2-1}$$

where k (mm) is a coefficient depending on surface type and s (dimensionless) is the ground slope. Recommended values for k are 0.071 mm for impervious surfaces and 0.28 mm for pervious surfaces. Pitched roof surfaces have the same coefficient as impervious surfaces but use a slope of 0.05 (Butler & Davies, 2011; Innovyze, 2011). In The Netherlands, the absolute value approach is normally used; recommended h_d values for different types of surfaces and slopes are given in the 'Dutch guidelines for sewer systems computations and hydraulic functioning' (Rioleringsberekeningen, hydraulisch functioneren, Leidraad Riolering) (Stichting RIONED, 2004) (see Table 2-1). In the CANOE software tool, which is used by French partners, the initial losses include depression storage and evaporation, and are accounted for using an absolute value which depends on the type of surface and slope (see . In general, typical values for h_d are 0.5-2.5 mm for impervious surfaces and up to 10 mm for gardens or densely vegetated areas (Mansell, 2003; Rossman, 2010; Butler & Davies, 2011).

Table 2-1: Depression storage and surface wetting (h_d) absolute values (in mm) recommended in the 'Dutch guidelines for sewer systems computations and hydraulic functioning' (from Stichting RIONED (2004))

	Areas with a slope > 4 %	**Flat areas (slope < 4 %)**	**Stretched flat areas***
Closed paved	0	0.5	1
Open paved	0	0.5	1
Roof	0	2	4
Unpaved	2	4	6

*Flat areas with the distance to the nearest inflow point in the sewer system larger than 100 metres

Table 2-2: Initial losses absolute values recommended in the CANOE model (adapted from CANOE user manual, (Allison et al., 2005))

Surface type	**Slope (S) (%)**	**Initial losses (mm)**
Impervious	S < 1.5	2
	1.5 < S <3	0.5 + (3-S)
	S > 3	0.5
Pervious	S < 0.5	12
	0.5 < S < 3	2 + 4 (3-S)
	S > 3	2

In most rainfall-runoff models (whether fully-distributed or semi-distributed, suitable for urban or rural applications), interception and depression storage are treated together and its maximum possible depth ($h_{initial}^{max} = h_i + h_d$) is specified as a fixed value or is estimated using a regression equation. The specified depth or the parameters of the regression equation (depending on the modelling approach that is chosen) constitute model parameters subject to calibration.

In order to account for the effect of antecedent catchment wetness on the initial losses, an additional parameter is normally used in urban runoff models: the *antecedent rainfall depth* (h_a). h_a is usually taken as the rainfall depth that has fallen in the hour immediately prior to the storm. If individual storms are being simulated, an h_a can be specified by the modeller for each storm event. If the model is run for continuous simulation then h_a is dried out during dry periods (based on evaporation or recovery rates) and is filled up again with new storms (Osborne, 2001; Rossman, 2010). The effective initial losses are therefore estimated as:

$$\begin{aligned} h_{initial} &= h_{initial}^{max} - h_a, && \text{if} \quad h_{initial}^{max} \geq h_a \\ h_{initial} &= 0, && \text{if} \quad h_{initial}^{max} < h_a \end{aligned} \qquad (2\text{-}2)$$

The estimated initial losses are subtracted progressively from the initial values of the rainfall hyetograph, resulting in *net rainfall* which is available for evaporation, infiltration and runoff.

It must be noted that initial losses are usually small in urban areas and are not important in the simulation of intense storms. However, for less severe storms and less urbanised catchments, these losses may be significant, especially when water quality is modelled, and should not be neglected (Butler & Davies, 2011).

2.2.2. Continuing losses (h_c)

Continuing losses include evaporation and infiltration. In order to estimate effective rainfall or runoff, the equivalent depth of the continuing losses is subtracted at each time step from the rainfall hyetograph, after initial losses have been deducted.

- **Evaporation:** depending on the urban drainage model that is used, evaporation rate (normally expressed in mm/day) can be set as a constant value or can vary with time, in which case evaporation time series must be inputted. It must be noted that the effect of evaporation in short duration and intense rainfall events (such as the ones likely to cause urban pluvial flooding) is negligible; this is especially true in the case of countries where potential evaporation is not very high, such as North West (NW) European countries (average evaporation rates in NW Europe are approximately 3 mm/day during the summer and 1 mm/day during the winter (Osborne, 2001); average monthly and daily evaporation rates for The Netherlands are shown in Table 2-3). Given the scale and final aim of urban pluvial flood models, the effect of evaporation is commonly neglected in them, or a fixed evaporation rate is used (Butler & Davies, 2011).

Table 2-3: Average monthly evaporation rate in The Netherlands, estimated with Penman's equation as a function of temperature, wind speed, relative humidity and solar radiation (from Stichting RIONED (2004)).

Month	Monthly evaporation (mm/month)	Number of days per month	Daily evaporation rate (mm/day)
January	5	31	0.16
February	15	28	0.54
March	40	31	1.29
April	70	30	2.33
May	100	31	3.23
June	120	30	4.00
July	110	31	3.55
August	90	31	2.90
September	60	30	2.00
October	25	31	0.81
November	10	30	0.33
December	5	31	0.16

- **Infiltration:** infiltration is the passage of rainwater into the soil. The infiltration capacity of a given surface (i.e. the rate at which water infiltrates into it) depends on factors including the properties of the soil (e.g. soil type, porosity and hydraulic conductivity), ground slope, surface cover and depth of water on the soil. The amount of infiltration also depends on the wetness of the ground at the beginning of the rainfall event and infiltration rates normally decrease throughout the storm. Rainwater initially infiltrates the upper layer of the soil (i.e. the unsaturated zone) and part of it may eventually flow deeper until reaching the groundwater or saturated zone. Moreover, part of the water in the unsaturated zone moves laterally through it and may become surface water later on (this is known as interflow). In general, urban storm water models only consider infiltration in the upper soil layer (i.e. unsaturated zone); sub-surface and ground water flows are seldom modelled. The reason for this is that in highly impervious areas sub-surface flows are generally little (Zoppou, 2001). Nonetheless, there are some urban areas in which groundwater infiltration is significant and the exchange of groundwater with the drainage system or with adjacent water courses needs to be accounted for explicitly (see for example MacDonald et al. (2007)). In this section only methods for modelling infiltration of rainfall into the unsaturated upper soil zone are described. For details on the modelling of groundwater and its interactions with urban drainage systems, the reader may refer to Todd & Mays (2005), Rossman (2010) and Innovyze (2011).

  During the last century, a number of methods for estimating infiltration from the ground to the top soil zone (i.e. in the unsaturated zone) have been developed, including physically based as well as empirical ones. The most widely used physically based approaches are the Green and Ampt's (1911) and Richards' (1931) equations (the latter is a modification of

Darcy's law for unsaturated soils) (for details of these approaches see Chow et al. (1988)). With regard to empirical approaches, amongst the most commonly used are Horton's model (1940), fixed percentage runoff models, and the US Soil Conservation Service (SCS) (1986) Curve Number model. Horton's model assumes an exponential decay in the infiltration rate, until a constant rate is reached when the upper soil zone becomes saturated (more information about this model can be found in Chow et al. (1988)). Horton's model is the widely used in many North-West European countries; recommended parameter values for typical Dutch land uses can be found in the 'Dutch guidelines for sewer systems computations and hydraulic functioning' (Stichting RIONED, 2004), whereas recommended values for typical French land uses can be found in Allison et al. (2005). In fixed percentage runoff models, a dimensionless runoff coefficient C (taking values from 0 to 1), which represents the proportion of net rainfall which becomes runoff, is established for the different land uses present in the catchment. The amount of runoff at each time step and for each land use is estimated by multiplying the *net rainfall* (i.e. after initial losses have been deducted) by the runoff coefficient C (for recommended values of C see Butler & Davies (2011)). Refinements consisting in considering variations in C according to the rainfall intensity have been developed (Allison et al., 2005). The SCS Curve Number (SCS-CN) model was developed from empirical analysis of daily runoff from small catchments in the US and estimates runoff based on the catchment's hydrologic soil group, land use, treatment and hydrologic conditions (more information about this model can be found in Mishra & Singh (2003)). Since the SCS-CN model was developed for daily time scales, its application to the sub-daily time scales typically used in urban drainage modelling is not valid. A recent study conducted by Meert & Willems (2013) confirms the unsuitability of the model for sub-daily time scales. In addition to these general methods, empirical models are sometimes developed for specific countries. This is the case of the New UK percentage runoff (PR) model, developed in 1990 as part of the Wallingford Procedure. This model consists of an equation to estimate a PR coefficient at each time step, which can be applied to estimate the proportion of rainfall that will become runoff (in the same way as described for fixed percentage runoff models, with the difference that the New UK PR coefficient varies with time, in order to account for changes in catchment wetness, which affect the infiltration capacity of the soil). This New UK PR equation is a regression equation derived from data obtained from 11 UK catchments and 112 events.

2.3. OVERLAND FLOW MODELLING

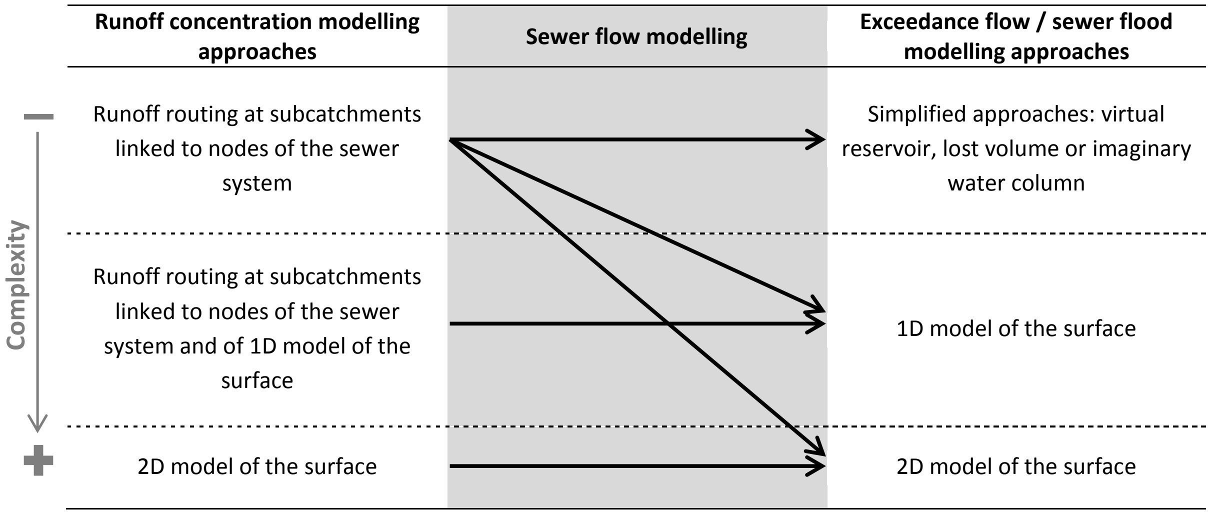
Overland flow refers to the movement of runoff water across the urban surface after rainfall, either before it enters the sewer system or is infiltrated into the ground, or after it leaves the sewer as floodwater. The first stage of the flow (i.e. from the point at which runoff is generated until it enters the sewer system) is commonly referred to as runoff concentration or conveyance. The second stage (i.e. flow of flood water from surcharged sewers) is known as exceedance flow or sewer flooding. In reality the two stages of overland flow are closely related and most often occur simultaneously; nonetheless, for modelling purposes they are commonly treated separately.

Since the appearance of storm water models in the 1970's (Zoppou, 2001), a number of methods have been developed to simulate overland flow. Initially, only methods for simulating runoff concentration in semi-distributed models were used (see Section 2.3.1) and sewer flooding was accounted for in an very simplistic and rather unrealistic way (see Section 2.3.2). However, recent urban pluvial flood events around the world have raised awareness about this type of flooding and have triggered efforts to better understand and model it. As a result, increasingly sophisticated approaches for modelling exceedance flow have emerged over the last decades and its practical application is quickly spreading (e.g. 1-dimensional (1D) and 2-dimensional (2D) models of the urban surface tightly coupled to models of the sewer system in what is known as the dual-drainage concept (Djordjević et al., 2005) – see Sections 2.3.3 and 2.3.4).

Some of the existing approaches to overland flow modelling are suitable for simulating both stages of it (i.e. runoff concentration and exceedance flow), but some are limited to the modelling of only one of the stages. In fact, it is possible that in a single storm water model one approach is used to simulate runoff concentration and a different one is used to represent sewer flooding or exceedance flow.

Table 2-4 summarises the existing modelling approaches for the two stages of overland flow. The black arrows indicate the possible combinations of runoff concentration and sewer flooding modelling approaches that can be used within a single storm water model. A description of each of these approaches is provided afterwards, including a review of their development and current practice.

Table 2-4: Modelling approaches for the two stages of overland flow



2.3.1. Runoff concentration (routing) modelling at subcatchments (in semi-distributed models)

As was previously explained, in semi-distributed models rainfall is inputted through subcatchments. Within each subcatchment rainfall is assumed to be spatially uniform and effective rainfall or runoff ($h_{effective}$) is estimated for the subcatchment as a whole. In these models, runoff concentration modelling consists in transforming the estimated effective rainfall for each subcatchment into a runoff hydrograph at the outlet point of the subcatchment, which is normally an entry point to the sewer system, but may also be another subcatchment or a node of a 1-dimensional (1D) model of the surface (1D surface models are described in Section 2.3.3). This transformation is based on an estimation of the time it takes for the runoff to reach the outlet of the subcatchment, considering the storage provided by the subcatchment and the delay it induces. Two general approaches are currently used for modelling runoff concentration in subcatchments in semi-distributed models: unit hydrograph and kinematic wave. The unit hydrograph is a conceptual approach based on the idea that a unique and time-invariant hydrograph results from effective rain falling over a particular catchment. A characteristic unit hydrograph can be estimated for each subcatchment which represents its response to a unit depth of effective rain of a given duration. Once derived, the unit hydrograph can be used to construct the hydrograph response to any rainfall event based on the principles of constancy, proportionality and superposition (Butler & Davies, 2011). Routing models based on the concept of the unit hydrograph include synthetic unit hydrographs, time-area diagrams, reservoir models and the Muskingum method. The kinematic wave approach is a simplification of the physically-based shallow water or de Saint-Venant Equations, which are described in Section 2.4. For details about these routing models the reader may refer to (Chow et al., 1988; Zoppou, 2001; Butler & Davies, 2011). Figure 2-6 illustrates the concept of runoff concentration modelling at subcatchments in semi-distributed models. It is important to note that this modelling approach can **only be used to represent the first stage of overland flow** (i.e. runoff concentration routing).

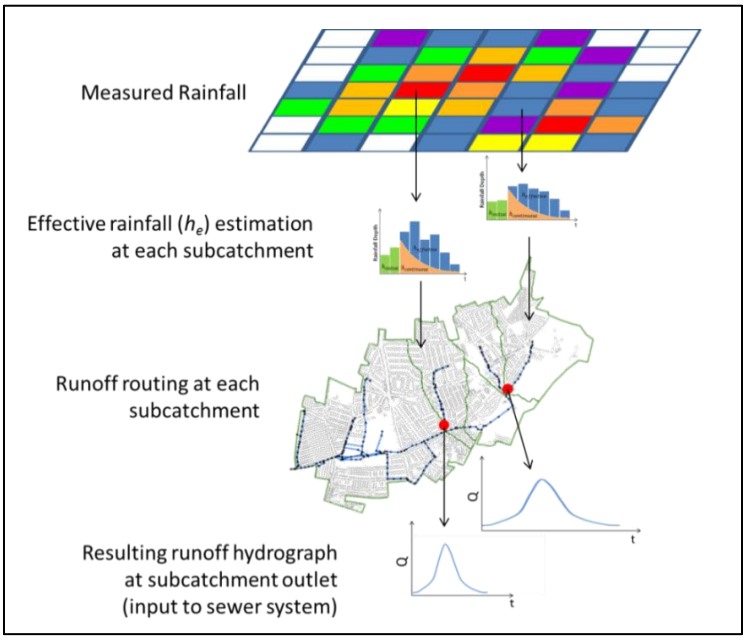


Figure 2-6: Runoff concentration (routing) modelling in semi-distributed models

2.3.2. Simplified modelling of exceedance flow

Until recently, and even now, exceedance flow has been represented in a simplistic and unrealistic manner. The simplistic approaches traditionally used for representing the flood water coming from surcharged pipes are the following (Innovyze, 2011):

a) **Virtual reservoir:** a virtual reservoir with user-defined geometry is assumed on top of each manhole. When sewers surcharge and pressure is enough to cause overflow, flood water is temporarily stored in the virtual reservoir. The stored volume is normally allowed to flow back to the underground pipe system once the system resumes free-surface flow.

b) **Virtual water column:** this approach is similar to the virtual reservoir, with the difference that the cross sectional area of the storage column on top of each manhole is assumed to be the same as that of the plan area of the manhole.
c) **Lost volume:** any flood water coming from the underground pipe system is removed from the model.

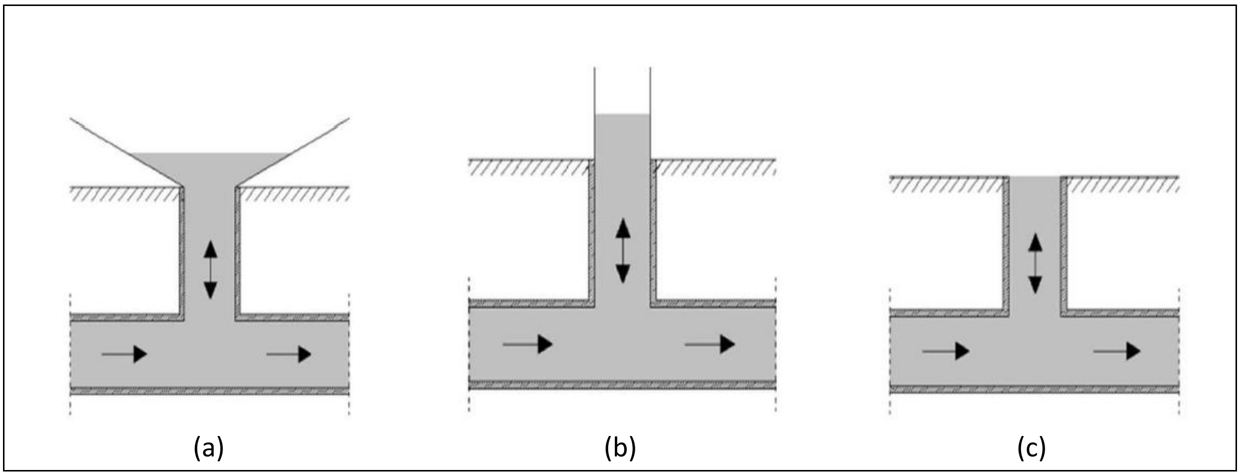


Figure 2-7: Traditional simplified approaches for modelling exceedance flow: (a) virtual reservoir; (b) virtual water column; (c) lost volume (Innovyze, 2011)

These approaches may be functional and give an indication of the order of magnitude of sewer flood volume (Butler & Davies, 2011). However, they are unrealistic, tend to significantly overestimate flood depths, and are of limited use for identifying flood extent and understanding urban flooding mechanisms (Mark et al., 2004). With the purpose of improving the modelling of urban pluvial flooding, a number of studies were conducted during the 1990's and early 2000's (Djordjević et al., 1991; Maksimović & Prodanovic, 2001; Schmitt et al., 2004), which highlighted the limitations of the simplistic approaches mentioned above and concluded by emphasising the **need for a better representation of exceedance flows over the urban surface** and of the interactions between the surface and the sewer system.

This, together with advances in simulation techniques, geographic information systems and data acquisition during the 1990's led to the incorporation of the dual-drainage concept into the modelling of urban drainage systems. This concept was introduced in North America in the eighties and refers to the integrated use of the two sub-systems which make up urban drainage systems: the minor system (i.e. underground pipes) and the major system (overland flow paths, including streets, interconnected swales, watercourses and other surface features). The incorporation of this concept into urban drainage models entails explicit and more consistent treatment of the minor and major systems and of their interactions, which leads to better design of both sub-systems and also to more reliable simulation of urban pluvial flooding and analysis of the consequences (Djordjević et al., 2005).

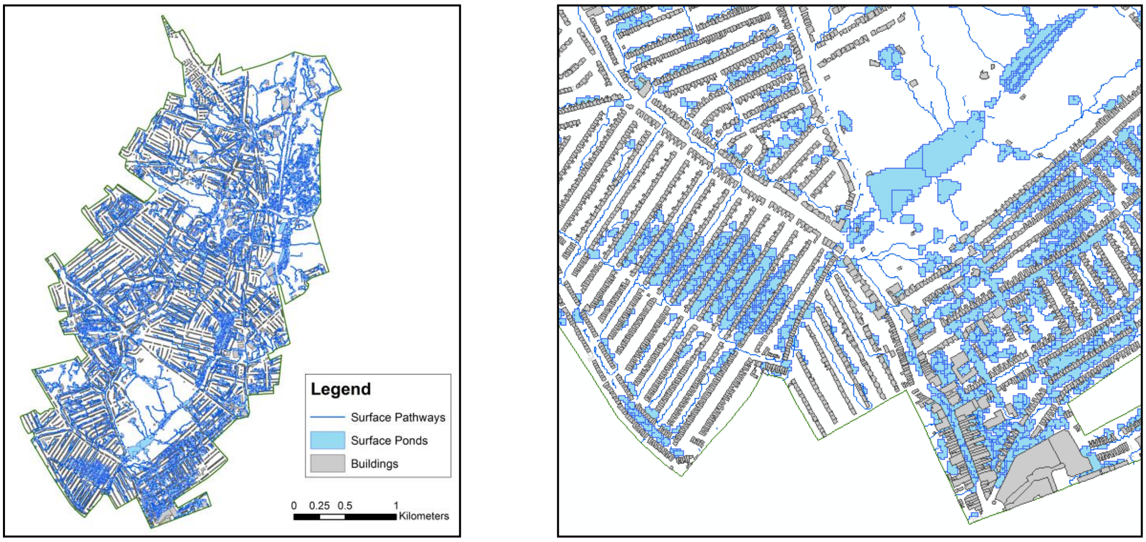
When the dual-drainage concept started to be incorporated in urban drainage models, the modelling of the minor system (i.e. underground sewer system) was pretty much a solved problem (see Section 2.4). The main challenges were therefore the modelling of exceedance flows over the urban surface (i.e. modelling of the major system) and of the interactions between the major and minor systems. The first step in this process was the development of 1-dimensional (1D) models of the urban surface, which were coupled to a model of the sewer system. This was followed by more sophisticated, but also more computationally demanding, 2-dimensional (2D) models of the surface, again coupled to sewer models. More recently, hybrid models of the surface, which combine 1D and 2D approaches, have been developed with the aim of achieving a balance between accuracy and computational demands (Simões et al., 2011). In what follows a description is provided of the 1D, 2D and hybrid modelling approaches of the urban surface.

2.3.3. 1-dimensional (1D) models of the surface

In 1D models the urban surface is discretised as a set of nodes connected by links. Nodes represent ponds or channel junctions, whereas links represent overland pathways through which runoff is likely to flow (e.g. streets, alleys). Nodes and links are characterised, respectively, by a storage capacity and geometry, which can be manually defined by the modeller or can be computed from the DTM of the catchment. The flow in 1D models of the urban surface is simulated in the same way as the flow in sewer systems; it is, through the solution of the complete or simplified de Saint-Venant equations, which are described in Section 2.4.

The first 1D models of the urban surface were not coupled with models of the sewer system, therefore the interactions between the major and minor systems were not considered (e.g. Heywood et al. (1997), J. Guo (2000)). Subsequent advances led to the coupling of 1D models of the surface with models of the sewer system in such a way that water exchange between the two systems can take place at manholes and gullies, depending on the flow regime at each sub-system. The resulting dual-drainage models are normally referred to as 1D-1D models, given that the flow in both the surface and the sewer system is modelled in 1D. Examples of 1D-1D urban dual-drainage models can be found in Lhomme et al. (2004), Djordjević et al. (2005), Nasello & Tucciarelli (2005), Spry & Zhang (2006).

Nowadays, several commercial software packages allow coupling of 1D models of the surface with 1D models of the sewer system (e.g. SWMM (Rossman, 2010), Mike Urban (DHI, 2011), InfoWorks CS (Innovyze, 2011)). However, their methodology to estimate overland flow assumes manual (hence subjective) definition of the surface flow paths and ponds, which is laborious and might lead to unreliable representations of surface flow processes. To overcome this problem, research has been conducted aiming at automatically creating 1D models of the urban surface based on the catchment DTM. Examples of this can be found in Lhomme et al. (2004) and Balmforth & Dibben (2006). A more sophisticated tool was introduced by Maksimović et al. (2009), known as the Automatic Overland Flow Delineation (AOFD) tool. Based on an accurate DTM of the catchment and using a combination of bouncing and sliding ball algorithms, the AOFD tool generates a 1D model of the surface which can realistically represent the overland flow, taking into account processes such as pond forming, flow through preferential pathways and surface drainage capacity. Furthermore, the models generated with the *AOFD* tool also take into account the interactions with the sewer system, which take place at the manholes, inlets and gullies. The output of the *AOFD* tool is a set of shapefiles which contain the information about the elements (i.e. ponds and pathways) that constitute the 1D model of the overland network. These files can be imported into several hydraulic simulation software (e.g. InfoWorks CS and SIPSON, SWMM) and can be easily coupled with 1D models of the sewer system, thus allowing for the creation of 1D-1D dual drainage models. Details of the algorithm and instructions for running the AOFD tool can be found in Boonya-Aroonnet et al. (2007), Maksimović et al. (2009) and Leitao & Ochoa-Rodriguez (2012). An example of a 1D model of the urban surface generated with the AOFD and implemented in InfoWorks CS is shown in Figure 2-8.



(a) (b)

Figure 2-8: 1D model of the overland network of the Cranbrook catchment generated with the AOFD tool: (a) entire catchment; (b) detail (Ochoa-Rodriguez et al., 2011)

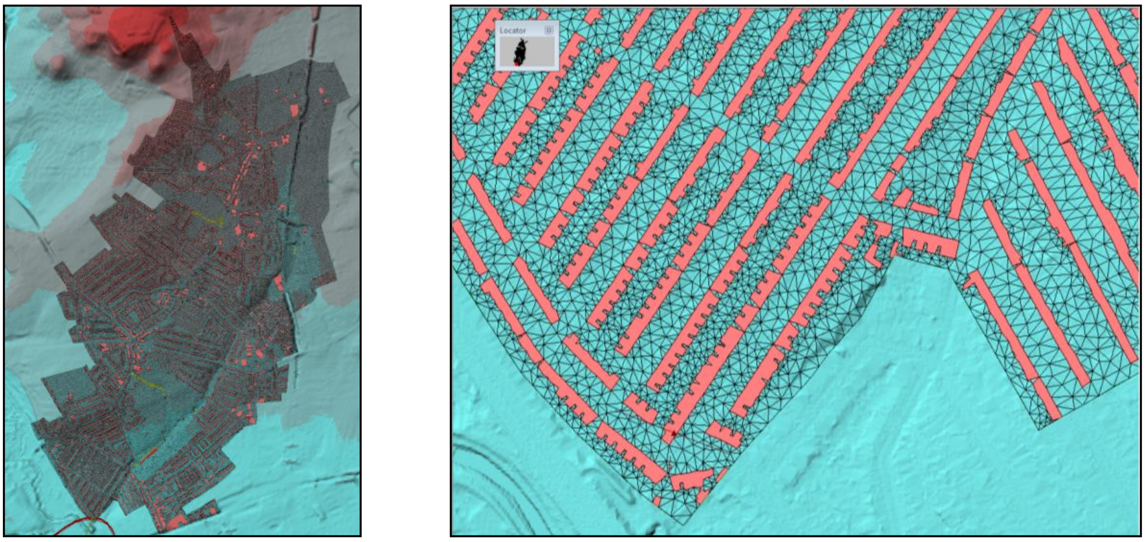
Recent advances in simulation techniques, increased computer power and availability of high-resolution terrain data have made possible the implementation and widespread use of 2D models of the urban surface (described in Section 2.3.4). This has raised questions about how 1D models of the surface compare to 2D models. A number of studies have been conducted on this matter and the following conclusions have been achieved (Mark et al., 2004; Lhomme et al., 2006; Spry & Zhang, 2006; Allitt et al., 2009; Leandro et al., 2009):

- 1D models' runtimes are significantly shorter than those of 2D models. This constitutes one of the main advantages of 1D models over 2D models and makes 1D models more suitable for real time applications.
- 1D models provide a good approximation of the surface flow in areas where the flow is well channelled; for example, in streets as long as the water remains within the street or channel profile. However, their accuracy is insufficient in areas with multidirectional flow paths, as is the case of flat areas and when the flow overtops the curbs in the streets.
- The visualisation of 1D models' results is poor, making it hard to communicate to non-technical audiences.
- The setup of 1D models of the surface is more complex and time consuming than for 2D models.

Moreover, some authors have suggested that the two approaches (i.e. 1D and 2D models of the urban surface) should be combined within a single model in order to take advantage of their abilities and overcome their shortcomings (Blanksby et al., 2007; Allitt et al., 2009). Initial work in this direction was made by Simões et al. (2011), who presented a hybrid model which uses 1D surface models in areas where flooding is less critical and 2D surface models in areas at highest risk of flooding, where flood depths may be higher. In the proposed hybrid models the delineation of 1D and 2D areas is done manually; these models could be improved by developing routines for the automatic delineation of the areas to be modelled in 1D and 2D, taking into account factors such as terrain slope, existence of defined overland pathways, expected flood depths (e.g. for different return periods), density of receptors and therefore need for detailed modelling, amongst others. Another functionality which could further improve hybrid models is the possibility of automatically switching from 1D to 2D models throughout the simulation once the flood depth overtops streets curbs and the flow becomes multidirectional.

2.3.4. 2-dimensional modelling of overland flow

In 2-dimensional (2D) models of the urban surface, the whole catchment is discretised as a continuous grid or mesh of regular or irregular elements. Such discretisation is based on the Digital Elevation Model (DEM) of the catchment, in addition to land use and soil type maps from which the parameters of each grid element can be obtained (e.g. coordinates, roughness, land cover, soil properties). Mathematically, each grid element is represented as a point with spatial coordinates (X, Y, Z) and model parameters as well as rainfall inputs are assumed to be spatially homogeneous within each element. Element size affects the resolution (i.e. degree of accuracy) of the representation of the physical properties of the study area as well as the size of the computer model and its resulting run times. It is up to the modeller to select an appropriate grid element size, such that an acceptable compromise between accuracy and run time is achieved. An example of a 2D model of the urban surface implemented in InfoWorks CS is shown in Figure 2-9.



(a) (b)

Figure 2-9: 2D model of the surface implemented in InfoWorks CS 10.5 based on 1 m resolution LiDAR data and using the Shewchuk Triangle meshing functionality of this software package: (a) entire catchment; (b) detail.

When this type of model is used, overland flow must necessarily be modelled in 2-dimensions; it is, taking into account the two orthogonal components of the flow (X, Y), whereas in 1D models only one component is considered. The 2D flow routing can be done using physically-based or conceptual models. In physically-based models the complete or simplified 2D continuity and momentum shallow water equations are resolved (these equations are briefly explained in Section 2.4). Physically based 2D models of the surface were first coupled with 1D models of the sewer system in research applications (e.g. Hsu et al. (2000); Chen et al. (2005); Chen et al. (2007)), thus originating the first 1D-2D dual drainage models. The operational use of such models has increased significantly over the last few years and nowadays several commercial and research software packages allow physically-based 1D-2D dual drainage modelling (e.g. InfoWorks CS and ICM (Innovyze, 2012b, 2013), Sobek (Bolle et al., 2006; Deltares, 2013), TUFLOW (Phillips et al., 2005), MIKE Urban (Carr & Smith, 2006; DHI, 2011), XPSWMM (XP Solutions, 2012), Multi-Hydro (Giangola-Murzyn et al., 2012b), SIPSON/UIM (Chen et al., 2007)). Physically-based 2D overland flow models involve a lower degree of averaging of fundamental hydraulic equations than 1D models and therefore can be considered as a more realistic description of flow conditions. Nonetheless, it is worth mentioning that when solving the shallow water equations in 2D surface models, the flow is assumed to be spread over each grid element and this may result in the underestimation of the flow along the preferential flow pathways; the occurrence and magnitude of the underestimation will of course depend on the grid size and on the topography of the area under consideration (this is especially problematic when a regularly spaced grid is used, but not so much when irregular triangular grids or locally refined rectangular grids are used). The advantages of 2D physically-based models of the surface are particularly evident when surface flows are not limited to well-defined routes along roads or surface channels, when flooding is mainly a “ponding” process with relatively slow water movement and when extreme events occurs, in which case most of the urban surface is covered with flood water. An obvious advantage of 2D models over 1D models is the fact that flow routes are not pre-defined and water spreading over the surface is driven by topography, urban features and physical laws. Moreover, the setup of 2D models is simpler than that of 1D models and the visualisation of 2D modelling results is also better (Allitt et al., 2009). In spite of the advantages of 2D models of the surface, the solution of the 2D shallow water equations turns out to be highly computationally demanding and time consuming. Despite recent advances in modelling and increasing computer power, physically-based 2D models of the urban surface remain too computationally intensive and the associated runtimes are still too long; this is especially critical when the area of application is large (e.g. 1000 km^2), when probabilistic approaches involving multiple simulations are required, and for real-time applications such as urban pluvial flood forecasting and warning (Neal et al., 2010; Neelz & Pender, 2010). A number of approaches have been developed with the aim of decreasing the computational requirements and associated runtimes of 2D overland flow models. Some of these approaches remain physically-based, for example (Chen et al., 2012; Neal et al., 2012):

- Grid coarsening together with porosity-based methods for representing sub-grid features in coarse resolution models (Yu & Lane, 2006a, 2006b; McMillan & Brasington, 2007)
- Adaptive grid-based methods (J. P. Wang & Liang, 2011)
- Multi-layered coarse grid methods (Chen et al., 2012)
- Simplification of the shallow water equations and development of different numerical schemes for solving them (Bradbrook et al., 2004; Lamb et al., 2009; Bates et al., 2010; Fewtrell et al., 2011; Neal et al., 2012; Seyoum et al., 2012)
- Parallelisation (Neal et al., 2010; Yu, 2010)

- Use of graphics processing units - GPUs (Lamb et al., 2009; Kalyanapu et al., 2011; Syme et al., 2012; Walker, 2012; Smith et al., 2013)[4]

Other approaches, however, fall within the realm of **conceptual models**. In conceptual models the floodplain is treated as a series of discrete basins or storage cells and **conceptual relationships** (which only satisfy the continuity equation) are used to model the flow between them (Hunter et al., 2006). In general, conceptual models keep many of the advantages of physically-based 2D models of the surface, while significantly reducing computational requirements. However, conceptual models do not allow prediction of water velocity (Liu & Pender, 2010) and may give wrong results in the case of complex topographies (Neelz & Pender, 2010). Examples of conceptual models include Cellular Automata (CA) approaches (Y. Guo et al., 2007; Dottori & Todini, 2010; Ghimire et al., 2011; Liu & Pender, 2013), Flood Risk Mapper (Mouchel, 2010), Flowroute (Ambiental, 2012), Rapid Flood Spreading Model (RFSM) (Gouldby et al., 2008; Lhomme et al., 2009), and the Rapid Flood Inundation Model (RFIM) (Krupka et al., 2007) which was later on improved to account for the rate of flow inflow and the frictional resistance of the flood plain (Liu & Pender, 2010).

The comparison of the different approaches to 2D overland flow modelling has been the subject of a number of recent studies. Comparisons of the conceptual RFSM and RFIM models against fully hydrodynamic models indicate that, in general, these conceptual models are capable of producing comparable predictions (in terms of flood depth and extent) with significantly less computer effort and shorter runtimes (Lhomme et al., 2009; Liu & Pender, 2010; Neelz & Pender, 2010); however, as was mentioned above, bad quality results may be obtained in the case of complex topographies, thus limiting the application of these models to relatively large scale applications where dynamic effects are less significant in determining the direction of water movement (Neelz & Pender, 2010). Moreover, these studies suggest that the incorporation of multiple spilling, frictional effects and rate of inflow in rapid flood simulation models significantly improves their performance (Lhomme et al., 2009; Liu & Pender, 2010). Neelz & Pender (2010) also compared the conceptual Flood Risk Mapper (Mouchel, 2010) against fully hydrodynamic models and reported significant difference in the results, thus suggesting that further work on these packages is required. Other studies have focused on the comparison of full and simplified physically-based models (Hunter et al., 2008; Neelz & Pender, 2010; Fewtrell et al., 2011; Neal et al., 2012); it is, models based on the solution of the full or simplified shallow water equations (the common simplifications of these equations are referred to as diffusion and kinematic or inertial models, these are described in Section 2.4). In general, flood depths predicted by models based on simplified equations are comparable to those predicted by full shallow water equation models (Hunter et al., 2008; Neelz & Pender, 2010; Fewtrell et al., 2011; Neal et al., 2012); however, their performance is less comparable in the prediction of velocities and in areas where supercritical flow is observed and where momentum conservation is important (e.g. prediction of water levels and velocities in complex flow fields) (Neelz & Pender, 2010; Neal et al., 2012). Moreover, these studies indicate that there is no consistent saving in computational effort when applying simplified equation models instead of complete ones; in fact, the diffusive model may eventually require longer simulation times than the full shallow water equations one (Neelz &

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[4] Some of these works cited above correspond to developments in commonly used commercial software packages: JFLOW (Bradbrook et al., 2004), JFLOW-GPU (Lamb et al., 2009), LISFLOOD-ACC (Bates et al., 2010), TUFLOW-GPU (Syme et al., 2012), InfoWorks ICM-GPU (Walker, 2012)

Pender, 2010; Neal et al., 2012). Recent studies have also analysed the relative impact of the numerical approximation that is used as compared to the impact of grid resolution, errors in topography data and model parameters. According to Fewtrell et al. (2011), errors in coarse scale topographic datasets are significantly larger than differences between numerical approximations. Moreover, Hunter et al. (2008) concluded that terrain data available from modern LiDAR systems (with 1-5 m horizontal resolution) are sufficiently accurate and resolved for simulating urban flows; when these high-resolution data are available, uncertainty in friction and model parameters become more dominant factors than topographic errors. The best way to reduce uncertainty in model predictions is to better estimate model parameters through robust calibration; however, to date few records of urban flooding are available and no mechanisms for routine monitoring of these events or post-event reconstruction are in place.

In addition to the above mentioned approaches to reduce computational requirements and runtimes of 2D models of the surface, Simões et al. (2011) proposed a ‘hybrid modelling’ approach (already described in Section 2.3.3) which consists in combining 1D and 2D models of the surface within a single flood model, so that the advantages of each of these approaches can be exploited and their shortcomings can be overcome.

As indicated in Table 2-4, when 1D-2D dual-drainage models are used, it is possible to apply the rainfall through subcatchments or directly to the 2D model of the surface. Using subcatchments has the advantage of being significantly faster; however, in this case flood water will only reach the surface when the sewer system surcharges (initial ponding before runoff reaches the sewer system is not accounted for).

As can be seen, there are numerous approaches for modelling overland flow, each of which has advantages and disadvantages. The selection of an “appropriate” approach will depend on the specific characteristics of the area, on the data and software packages that are available, and on the purpose of the modelling exercise.

2.4. SEWER FLOW MODELLING

Surface runoff enters the sewer system through gully inlets and manholes at a rate determined by the conveyance capacity of these connection elements and of the sewer system. In combined systems, sewers permanently carry wastewater and their flow is further increased by runoff during storm events. Wastewater flows alone (i.e. without storm water) are referred to as ‘dry weather flows’ (DWF) and generally exhibit repetitive-like diurnal patterns. DWF patterns can be determined through the analysis of flow records during dry weather periods and constitute an additional input to sewer models of combined systems. For details about the estimation of DWFs the reader may refer to Butler & Davies (2011), Rodríguez-Sánchez et al. (2012) and Schilperoort et al. (2012).

In general, sewer systems are modelled as a set of links and nodes. Links normally represent conduits, but may also be used to represent ancillary structures such as weirs, orifices, valves and pumps. Nodes generally represent manholes or gullies, where additional energy losses take place and bi-directional exchange of flow volume between the sewer system and the surface may occur. It is virtually impossible for an urban drainage model to include every single gully or manhole; instead, fewer nodes are included in the model, each of which represents the behaviour of a set (cluster) of neighbouring gullies and/or manholes.

The flow in sewers systems is both non-uniform (i.e. depth varies along the sewer at a given time instant) and unsteady (i.e. both flow-rate and depth change with time) and can be considered one-dimensional[5] (1D). Under normal conditions it is free-surface flow, but when urban pluvial flooding occurs the sewers become full and may act as conduits under pressure (this is known as surcharge). There are two general approaches for modelling unsteady flow in sewers: physically-based hydrodynamic models and conceptual models. The former are based on the solution of a complete or a simplified version of the continuity and momentum equations for one-dimensional flow, known as the de Saint-Venant equations. The solution of these equations (whether it is the full version or an approximation) is in general complex and computationally demanding. With the purpose of reducing complexity and run times, a number of simpler conceptual models have been developed to represent flow in sewers. These conceptual models (often referred to as hydrologic models) only satisfy the continuity equation and use conceptual cause-effect relations instead of momentum equations (Vaes et al., 1998, 2002; Achleitner et al., 2007; Wolfs et al., 2013). Although conceptual models are faster and less computationally demanding, they are unable of representing phenomena such as pressurised flow and back water effects, which are common and important features of urban pluvial flooding. Therefore, in urban pluvial flood models physically-based approaches are normally used to simulate sewer flow. The de Saint-Venant equations upon which these approaches are based are next described. These equations were originally developed for free-surface, so a special ‘strategy’ had to be implemented to allow their application under surcharge conditions; such strategy or concept is the ‘Preissman slot’, which is also described in what follows.

The de Saint-Venant equations

The de Saint-Venant equations, first published by A.J.C. Barré de Saint-Venant in 1871, describe one-dimensional unsteady open channel flow, which is applicable to the flow in sewers (except when surcharge occurs). These equations are the one-dimensional form of the “shallow water flow equations”, which in turn are a simplification of the general Navier-Stokes equations for surface flow (where the vertical dimension is much smaller than the horizontal one, thus allowing for a simplification) (Schmitt et al., 2004). A complete derivation of the de Saint-Venant equations and details regarding the assumptions under which they were derived (and therefore under which they are valid) can be found in Chow et al. (1988).

The de Saint-Venant equations are two equations: a mass conservation or continuity equation (Eq. (2-3)) and a momentum conservation or dynamic equation (Eq. (2-4)). In their conservative form, these equations are written in terms of flow rate as follows:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}-q=0 \tag{2-3}$$

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[5] Flow is assumed to be one-dimensional when depth and velocity vary only in the longitudinal direction of the channel, which implies that the velocity is constant and the water surface is horizontal across any section perpendicular to the longitudinal access. In general, this is true for flow in sewers.

$$\underbrace{\frac{1}{A}\frac{\partial Q}{\partial t}}_{\text{T1}} + \underbrace{\frac{\partial}{\partial x}\left(\frac{\beta Q^2}{A^2}\right)}_{\text{T2}} + \underbrace{g\frac{\partial \mathrm{y}}{\partial \mathrm{x}}}_{\text{T3}} - g\left(\underbrace{S_0}_{\text{T4}} - \underbrace{S_f}_{\text{T5}} - \underbrace{S_e}_{\text{T6}}\right) - \underbrace{\frac{\beta \mathrm{v}_x q}{A}}_{\text{T7}} + \underbrace{\frac{W_f B}{A}}_{\text{T8}} = 0 \qquad (2\text{-}4)$$

where:

A: cross-sectionl area

t: time

x: direction parallel to the channel bed

y: flow depth

q: lateral inflow rate

β: momentum coefficient or Bousinesq coefficient, which accounts for the non-uniform distribution of velocity at a channel cross section in computing the momentum (its value ranges from 1.01 for straight prismatic channels, such as sewers, to 1.33 for river valleys with flood plains)

S_0: bed slope

S_f: friction slope. This may be approximated using one of the friction equations for uniform flow (e.g. Gauckler-Manning or Darcy-Weisbach in combination with Colebrook-White) with actual flow velocities and depths.

S_e: eddy loss slope

v_x: flow velocity in the x direction

W_f: wind shear factor

B: surface width (i.e. width of the channel section at the free surface)

The terms indicated in Equation (2-4) represent the different physical processes which govern the flow momentum. These are:

T1: local acceleration, representing the change in momentum due to the change in velocity over time.

T2 and T7: convective acceleration, representing the change in momentum due to change in velocity along the channel caused by inflow entering from the upstream end of the channel (T2) and by lateral inflow (T7). Lateral inflow is seldom present in sewers and T7 is generally neglected, even in models in which the most complete form of the de Saint-Venant equations is adopted (i.e. dynamic wave models, which are next described).

T3: acceleration due to unbalanced pressure force.

T4: acceleration due to gravity force .

T5: acceleration due to frictional forces created by the shear stress along the bottom and sides of the slice of channel.

T6: acceleration due to minor energy losses resulting from eddy motion caused by abrupt contraction or expansion of the channel. Such losses are not always present (and generally neglected) in sewers, as their sections is usually constant.

T8: acceleration due to wind shear force. This term is commonly neglected in sewer flow modelling.

For very special and simple problems, the de Saint-Venant equations can be solved using analytical solutions. However, for more complex problems (which is usually the case), numerical schemes such as finite differences, finite elements or the method of characteristics are used (Zoppou, 2001; Beven, 2012). The most common method of solution of these equations is the finite differences, which entails splitting distance and time into small steps (Butler & Davies, 2011). The finite difference method can be formulated as an implicit or explicit scheme. In explicit schemes (e.g. Rossman (2010)) the equations are rearranged such that a single unknown value is written in terms of known values. This results in a number of simpler linear equations which can be solved directly. Although simple, explicit schemes are conditionally stable under the Courant condition, which establishes a limit on the maximum allowable time step. In implicit schemes (e.g. Jin et al. (2002), Mark et al. (2004), Innovyze (2011), DHI (2011)) the unknown value is not isolated and the resulting set of finite difference equations is therefore more difficult to solve. However, implicit schemes have the advantage of not having any restriction on the time step. Allowing longer time steps may therefore compensate for the additional computational effort required to solve the system of implicit equations. Although implicit schemes are more stable than explicit ones, it is virtually impossible to ensure the complete stability of any of them. Particular instability problems may arise in both schemes when the input data contains rapid changes and in the transition between pressurised and free-surface flow. Such problems may be partially overcome by implementing a range of numerical methods (e.g. automatic adjustment of the time step in order to reach convergence); however, complete stability, especially when urban pluvial flood modelling is being simulated, cannot be ensured.

The solution of the de Saint-Venant equations is computationally demanding. Given the relative importance of the terms of the momentum equation, some of them may be neglected under specific circumstances, thus resulting in simplified models whose solution requires less computational effort. The simplest model is the ‘kinematic wave’ approximation, which neglects local acceleration (T1), convective acceleration (T2 and T7), and pressure terms (T3), in addition to wind shear force, which is generally neglected in all models. This approximation therefore neglects variations with time and distance. A less drastic simplification is the ‘diffusion wave’ approach, which neglects local acceleration and convective acceleration (T1, T2 and T7), but not pressure terms (T3); this implies neglecting changes with time, but not with distance. The ‘dynamic wave’ approach (commonly referred to as ‘full hydrodynamic approach) considers all the terms of the momentum equation, taking into account variations with time and distance. Table 2-5 summarises the hydraulic conditions accounted for in each of these three approaches.

Table 2-5: Conditions accounted for in the complete and simplified versions of the de Saint-Venant equations (Butler & Davies, 2011)

Hydraulic condition accounted for	**Kinematic wave**	**Diffusion wave**	**Dynamic wave**
Wave translation	Yes	Yes	Yes
Backwater effects and flow reversal	No	Yes	Yes
Wave attenuation	No	Yes	Yes
Flow acceleration	No	No	Yes

As has been mentioned, the de Saint-Venant equations were developed for free-surface flow, which is normally the case in sewer systems. However, extreme rainfall may cause the sewers to surcharge; it is, sewers may become full and run as full pipes under pressure, instead of as open channels. In order to allow the application of the de Saint-Venant equations in pressurised flow, the concept of the Preissmann slot was introduced (Preissmann, 1961). The Preissmann slot is a conceptual vertical and narrow slot into the pipe soffit, which allows conceptual free surface condition for the flow when the water level is above the top of a closed conduit. The width of the slot is estimated such that it does not have a significant effect on continuity; the resulting slot width is around 2 % of the conduit width (Butler & Davies, 2011; Innovyze, 2011). In order to avoid abrupt changes in surface width and wave celerity, a transition between the pipe geometry and the width of the slot is frequently included within models.

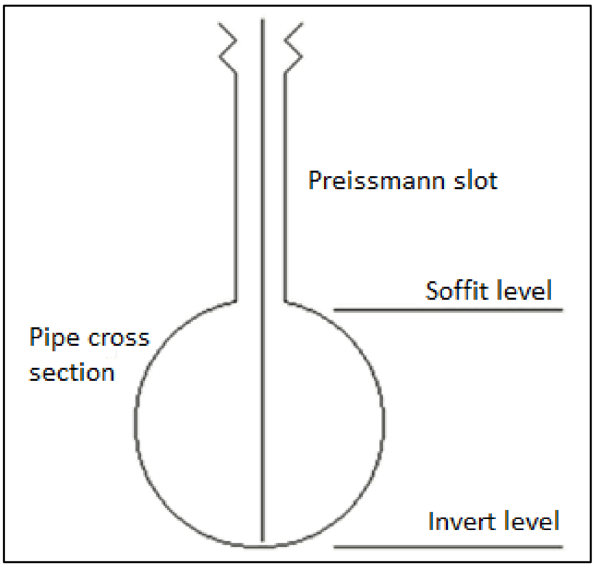

Figure 2-10: Preissmann slot (Innovyze, 2011)

3. SOFTWARE PACKAGES AND MODELLING APPROACHES ADOPTED FOR THE RAINGAIN PROJECT PILOT LOCATIONS

Within the RainGain project a total of 12 pilot sites located in the 4 participating countries (i.e. UK, The Netherlands, France and Belgium) have been adopted for testing the urban pluvial flood modelling and forecasting methodologies that are being developed. Details of the pilot locations can be found on the project website.

Depending on the modelling software most commonly used at each country, on the data that are available and on the purpose of the modelling exercise (e.g. whether it is for urban planning or real time applications, such as flood forecasting and warning), different software packages and modelling approaches were adopted for each pilot location. This will enable comparison and drawing of conclusions regarding the suitability, advantages and disadvantages of the different software packages and modelling approaches.

Table 3-1 summarises the main characteristics, software and modelling approach adopted for each pilot location. Moreover, a brief description of the software packages that will be used in the project is provided afterwards.

Table 3-1: Characteristics, software package and modelling approach adopted at RainGain pilot locations

COUNTRY	PILOT SITE	DRAINAGE AREA	MAIN CHARACTERISTICS	SOFTWARE	MODELLING APPROACH	RAINFALL DATA	MAIN MODELLING OBJECTIVES
NL	Spaanse Polder (Rotterdam District 12)	1.9 km^2	Industrial area, highly impervious	Sobek-Urban	Semi-distributed, sewer system only, simplified modelling of exceedance flow	Raingauges, new polarimetric X-band radar	Mainly urban planning (analysis of water storage tank, water squares, further optimisation of real time control elements, green roofs)
NL	Kralinger – Crooswijk (Rotterdam District 10)	8 km^2	Residential & industrial	Sobek-Urban	Semi-distributed, sewer system only, simplified modelling of exceedance flow	Raingauges, new polarimetric X-band radar	Mainly urban planning (analysis of water storage tank, water squares, further optimisation of real time control elements, green roofs)
NL	Rotterdam - Centre (Rotterdam District 9)	3.7 km^2	Residential area with 2 urban parks	Sobek-Urban	Semi-distributed, sewer system only, simplified modelling of exceedance flow	Raingauges, new polarimetric X-band radar	Mainly urban planning (analysis of water storage tank, water squares, further optimisation of real time control elements, green roofs)
FR	Morée-Sausset, of which Kodak is a subcatchment (Seine-Saint-Denis, Paris)	Morée-Sausset: 34 km^2 Kodak: 1.44 km^2	Highly urbanised, rather flat. Several retention basins for flood control.	Canoe for whole catchment; Multi-Hydro for Kodak subcatchment	For whole catchment: Semi-distributed, sewer system only, simplified modelling of exceedance flow For Kodak: Fully distributed, 1D-2D dual-drainage (with rainfall applied directly on 2D model of surface)	Raingauges, C-band and new polarimetric X-band radar	Optimisation of real time control elements

COUNTRY	PILOT SITE	DRAINAGE AREA	MAIN CHARACTERISTICS	SOFTWARE	MODELLING APPROACH	RAINFALL DATA	MAIN MODELLING OBJECTIVES
FR	Jouy-en-Josas (Seine-Saint-Denis County, Paris)	2.5 km^2	Steep slopes, combination of land uses. Several storm water retention basins	Multi-Hydro	Fully distributed, 1D-2D dual-drainage (with rainfall applied directly on 2D model of surface)	Raingauges, C-band and new polarimetric X-band radar	Optimisation of real time control elements
FR	Sucy-en-Brie (Val de Marne County, Paris)	2.69 km^2	New retention basin (interest on RT control of it)	Currently: Canoe; Multi-Hydro will be implemented during the project	Currently: Semi-distributed, sewer system only, simplified modelling of exceedance flow. During project: Fully-distributed, 1D-2D dual-drainage (with rainfall applied directly on 2D model of surface)	Raingauges, C-band and new polarimetric X-band radar	Optimisation of real time control elements
BE	Northern part of Leuven (Herent)	30 km^2	Occasional pluvial flooding in centre of Herent	Started with InfoWorks CS (2D), moved to InfoWorks ICM towards the end of the project.	Existing model (pre Raingain): semi-distributed, sewer system only, simplified modelling of exceedance flow During project: semi-distributed, 1D-2D dual-drainage (with rainfall applied through subcatchments)	Previously acquired X-band radar and 8 operational raingauges, C-band radar from RMI Belgium.	Flood modelling, RT flood forecasting and warning. Optimisation of pumping stations and CSOs Solve problems of rural overland inflow to sewers

BE	Gent: area Oostakker - Sint-Amandsberg	20 km^2	Regular flooding	Currently : InfoWorks CS; During project : InfoWorks ICM	Currently: semi-distributed, sewer system only, simplified modelling of exceedance flow During project: Fully-distributed dual-drainage model, with rainfall applied on 2D surface model	Rain gauge data to be collected; additional gauges will be installed by TMVW (sewer system manager)	Climate adaptation planning Flood nowcasting system (RainGain & PLURISK projects)
UK	Cranbrook catchment, London Borough of Redbridge	9 km^2	Highly urbanised, coincidental fluvial and pluvial flooding	Currently : InfoWorks CS-2D; During project : InfoWorks ICM	Currently: Semi-distributed dual-drainage (both 1D-1D and 1D-2D models available - with rainfall applied through subcatchments) During project: Fully-distributed dual-drainage model, with rainfall applied on 2D surface model	Polarimetric C-band radar, raingauges and X-band radar	Urban planning and RT urban pluvial flood forecasting and warning
UK	Torquay Town Centre, Devon Borough of Torbay	14.6 km^2	Coastal city, steep slopes drain to natural depression, flooding worsened by high tides.	InfoWorks CS-2D	Semi-distributed, 1D-2D dual-drainage (with rainfall applied through subcatchments)	C-band radar and raingauges	Optimisation of real time control elements
UK	Purley Area, London Borough of Croydon	6.5 km^2	Highly urbanised, great density of receptors, slopes drain to natural depression	InfoWorks CS-2D	Semi-distributed, sewer system only, simplified modelling of exceedance flow	Polarimetric C-band radar, raingauges and X-band radar	Urban planning and RT urban pluvial flood forecasting and warning

Software packages used within the RainGain project

The following software packages have been adopted for modelling of urban pluvial flooding in the RainGain pilot locations:

- **InfoWorks CS® (Innovyze, 2012b):** InfoWorks Collection Systems (CS) is a commercial software package widely used in the UK, Belgium and in many other countries around the world for modelling of urban drainage systems. It is a semi-distributed modelling package, meaning that rainfall is applied to the model through subcatchments associated with manholes or inflow nodes. The total area of each subcatchment can be sub-divided into several different surface types, each of which can have different runoff parameters, rainfall-runoff model and runoff concentration (routing) model. The rainfall-runoff and runoff concentration (routing) models supported by InfoWorks CS are summarised in Table 3-2. The total runoff generated at a subcatchment at a given time corresponds to the sum of the runoff volume generated at each of the individual surface types contained in the subcatchment at that time. In this software package the performance of manholes and gullies can be simulated as a weir (with a user defined discharge coefficient), as an orifice (with a user defined discharge coefficient), or the modeller can define his/her own head-discharge curve. The flow in the sewers is simulated using the dynamic wave approximation of the de Saint-Venant equations, which is solved through a finite implicit differencial scheme. Sewer surcharge (i.e. pressurised flow) is modelled using the Preissman slot and exceedance flow or overflow can be represented using any of the simplified approaches illustrated in Figure 2-7 (i.e. lost volume, virtual reservoir and virtual water column). Alternatively, InfoWorks CS allows 1D modelling of the urban surface (as described in Section 2.3.3), which uses the same principles and modelling tools as the 1D model of the sewer system. Using InfoWorks CS, the 1D model of the surface can be linked to the model of the sewer system, thus resulting in a 1D-1D dual drainage model (instead of using the simplified methods for modelling of exceedance flow). More information about this software package can be found in its help file and at Innovyze's website (http://www.innovyze.com/).

Table 3-2: Runoff volume estimation and runoff concentration (routing) models supported by InfoWorks CS (for details of each of these models the reader is referred to InfoWorks CS's help file (Innovyze, 2011))

Runoff volume estimation models	**Runoff concentration (routing) models**
• Fixed runoff coefficient • Wallingford procedure • NewUK • US Soil Conservation Service • Horton • Green-Ampt • Constant Infiltration • Curve Number • Horner	• Wallingford (double linear reservoir) • Large catchment (double linear reservoir) • US Soil Conservation Service unity hydrograph • Snyder unit hydrograph • SPRINT (single linear reservoir) • Desbordes (single linear reservoir) • SWMM (single non-linear reservoir) • User-defined unit hydrograph

- **InfoWorks CS-2D®(Innovyze, 2012b):** this software package has the same functionalities as InfoWorks CS, with the difference that the 2D version includes a module for 2D simulation of overland flow using a triangular mesh and an implicit solution of the full shallow water equations. Hence, InfoWorks CS-2D allows 1D-2D dual-drainage modelling, with the interaction between the sewer and surface systems occurring at manholes and gullies. When using InfoWorks CS-2D, it is possible to apply rainfall either through subcatchments (as described in Section 2.3.1) or directly on the 2D model of the surface. Nonetheless, this software package does not allow rainfall-runoff modelling (i.e. estimation of runoff, as described in Section 2.2) when rainfall is applied directly on the 2D model of the surface. To circumvent this problem, the modeller must calculate runoff externally and subtract it from the rainfall hyetograph before applying it to the model. In order to account for the difference in roughness across the urban surface, the 2D module of InfoWorks CS-2D allows the definition of different roughness zones, each of which can be assigned a different Manning roughness coefficient. More information about this software package can be found in its help file and in Innovyze's website (http://www.innovyze.com/).

- **InfoWorks ICM® (Innovyze, 2014):** InfoWorks ICM (Integrated Catchment Modelling) is the successor of InfoWorks CS and InfoWorks RS (river systems) which were both commercially abandoned in late 2014. The main novelties in terms of hydraulic simulations are the standard integration of the 2D surface flood modelling engine, and the integration of urban drainage and river elements. Many of the limitations of InfoWorks CS-2D (described above) have been improved in InfoWorks ICM and as a result of recent hardware developments (e.g. graphics cards processing units), the possibilities for 2D mesh creation are much higher than in InfoWorks CS-2D. Standard 1D modelling including semi-distributed rainfall runoff through subcatchments has not substantially changed in comparison with InfoWorks CS, but it is clear that future developments will focus more on fully-distributed direct rainfall runoff modelling via the 2D surface. More information about this software package can be found in its help file and in Innovyze's website (http://www.innovyze.com/).

- **Sobek®** (Bolle et al., 2006; Deltares, 2013)**:** Sobek is a commercial suite for modelling of hydrological and hydraulic processes both in rural and urban areas. It comprises a number of modules for specific applications; one of them is Sobek-Urban, which can be used for modelling of urban drainage systems and urban pluvial flooding. Sobek-Urban offers both 1D and 2D modelling capabilities. Similar to InfoWorks CS, Sobek-Urban-1D is a semi-distributed modelling package, with rainfall applied to the model through subcatchments, each of which can comprise different surface types with different runoff parameters. In Sobek-Urban-1D dry weather flows and the transformation in time of rainfall into runoff entering the sewer system are simulated based on the NWRW (Nationale Werkgroep Riolering en Waterkwaliteit) model. The processes included in this model are: surface storage, evaporation, infiltration (only for pervious or open impervious areas), and runoff delay. Surface storage occurs as a result of moistening and puddle forming and its maximum depth is specified as a fixed value (in mm), following the recommended values presented in Table 2-1. Evaporation and infiltration will reduce the surface storage. The former must be specified by the user as a fixed rate (see average evaporation rates for The Netherlands in Table 2-3), while the latter is estimated based on Horton's equation. When the rainfall volume exceeds surface storage, runoff towards the sewer system occurs. The delay in the runoff (i.e. runoff concentration-routing) is described by the Runoff Delay Rational Method, which incorporates a runoff delay coefficient whose value depends on the average distance to the inflow location in sewer system, the slope and roughness of the area. Different runoff delay coefficients can be assigned to different areas. More details on the NWRW model and the recommended parameter values can be found in the 'Dutch guidelines for sewer systems computations and hydraulic functioning' (Stichting RIONED, 2004). In Sobek-Urban-1D the flow in the sewers is simulated using the dynamic wave approximation of the de Saint-Venant equations. When only the sewer system is modelled using Sobek-Urban-1D, sewer surcharge is simulated using the Preissman slot and exceedance flow or overflow is simulated using the simplified approaches described in 2.3.2. Alternatively, in Sobek-Urban-1D it is also possible to model the urban surface in 1-dimension and couple it with the 1D model of the sewer system, as explained in Section 2.3.3. In addition, Sobek-Urban-2D module offers the possibility of implementing a 2D model of the surface which can be linked to the 1D model of the sewer system, thus resulting in a 1D-2D dual drainage model. Sobek-Urban-2D simulates overland flow using a rectangular grid (which allows nested grids of smaller resolution) and solving the full shallow water equations. When a 2D model of the surface is implemented in Sobek, it is possible to apply the rainfall to the model through sub-catchments or directly on the surface. Nevertheless, similar to InfoWorks CS-2D, Sobek-Urban-2D does not allow rainfall-runoff modelling (i.e. estimation of runoff) when rainfall is applied directly on the 2D model of the surface. More information about this software package can be found in http://www.deltares.nl/en/software/108282/sobek-suite. Sobek was developed by Dutch company Deltares and, as such, it is the most commonly used software in The Netherlands. In addition, it is also used operationally in other countries around the world (e.g. Taiwan, Vietnam).

- **Canoe® (Allison et al., 2005):** Canoe® is a commercial software package dedicated to urban hydrology commonly used in France. It is a semi-distributed modelling package, similar to InfoWorks CS. Same as in InfoWorks CS, subcatchments can comprise different surface types, each of which has different runoff parameters and response times. The runoff generation and runoff concentration (routing) models supported by Canoe are summarised in Table 3-3. In Canoe the flow in the sewer system is modelled with the help of a numerical approximation of the most complete form of the de Saint-Venant equations (i.e. dynamic wave approach, resolved with an implicit numerical scheme). Canoe does not allow for 2D modelling of the urban surface; however, it does allow for 1D modelling of the surface (which, as was explained before, uses the same modelling concepts and functionalities as the 1D model of the sewer system). More details on this software package can be found in the user manual.

Table 3-3: Runoff volume estimation and runoff concentration (routing) models supported by CANOE (Allison et al., 2005)

Runoff volume estimation models	**Runoff concentration (routing) models**
• Fixed runoff coefficient • Standard canoe model (runoff coefficient depends on the rainfall intensity) • Horton	• Linear reservoir • Nash (multiple linear reservoirs)

- **Multi-Hydro:** Multi-Hydro is a fully-distributed physically-based research-oriented urban drainage modelling software which aims at representing in more detail the interactions between surface, sub-surface and sewer flows. This software is currently being developed at the Ecole des Ponts ParisTech (a partner in RainGain) and has initially been tested during the EU FP7 SMARTesT project (www.floodresilience.eu). Multi-hydro is basically a numerical platform that connects and allows interactions between four modules, each of which represents a portion of the water cycle in the urban environment. The general structure of the model is illustrated in Figure 3-1. This type of modular structures have recently received growing interest (Hsu et al., 2000; Rodriguez et al., 2008; Leandro et al., 2009; Maksimović et al., 2009; Jankowsky, 2011). Each of the Multi-Hydro modules relies on widely used and validated open source software packages. The **surface module** is based on the TREX model developed by Colorado State University (Two dimensional Runoff, Erosion and eXport model (Velleux et al., 2011)). It deals with surface flow (through a diffusive wave approximation of the 2D de Saint-Venant equations), interception and surface storage (simulated as equivalent depths), and infiltration (simulated through a simplification of the Green and Ampt equation). A regular square grid is used and a single land use and soil type is assigned to each pixel or grid element. The typical size of pixels used in the modelling of urban and peri-urban areas ranges from 1 m to 20 m. A special land use class which is worth describing is the “gully” class. This class is used to handle the interactions between the overland and the sewer systems. Pixels of gully class are connected to a node of the sewer system through which water can either go into or out of the sewer system, depending on the flow regime. When water goes out of the sewer system, the gully pixel does no longer allow water into the sewer and instead the gully becomes a temporary water source of the TREX model. The **sewer or drainage module** is based on SWMM (Storm Water Management Model (Rossman, 2010)), which is a popular 1D model developed by the US Environmental Agency. In SWMM a dynamical wave approximation of the de Saint-Venant equations is used to compute sewer flows. The **ground module** which deals with sub-surface flow in the unsaturated zone is based on the VS2DT software package developed by the U.S. Geological Survey (Lappala et al., 1987). The simulated flows, which are mainly vertical in the unsaturated portion of the soil, are computed with the help of the law of conservation of fluid mass and a non-linear form of the Darcy equation. The infiltration capacity of the soil at the ground level is continuously computed and used as updated parameter in the surface module. In addition, there is a **rainfall module** which enables to perform downscaling of spatially distributed radar data from the observation scale (usually 1 km in space and 5 min in time with the C-band radars commonly operated by western meteorological services) down to the chosen pixel size. This module relies on stochastic discrete Universal Multifractal cascades (see Auguste Gires et al. (2012) and A. Gires et al. (2013) for examples of applications).

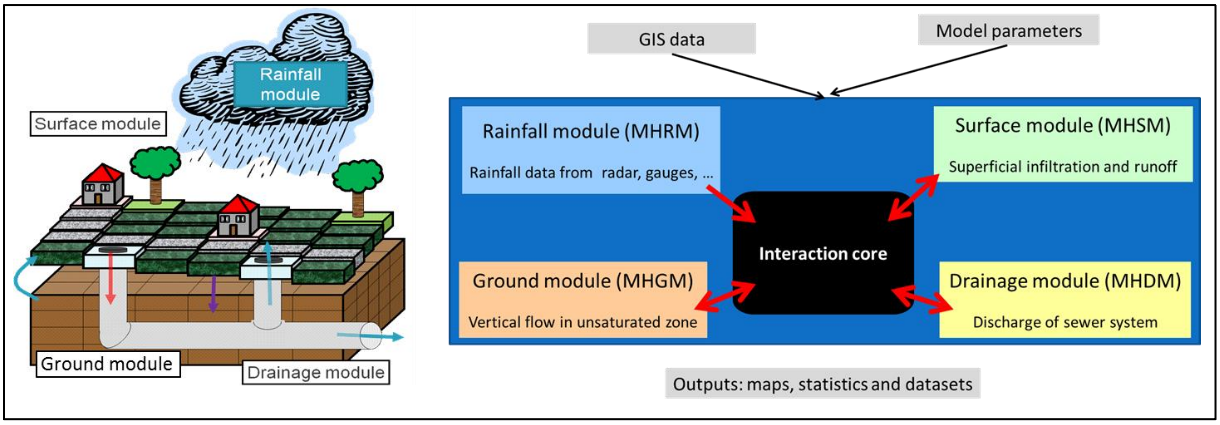

Figure 3-1: Structure of Multi-Hydro platform: physical description (left) and modular structure (right)

The input data required for implementing and running a model in Multi-Hydro include detailed description of the sewer network, the topography of the area (i.e. DTM/DEM) and the land use distribution. Each land use type must be characterised by its hydraulic conductivity (m/s), capillary suction (m), moisture deficit (dimensionless – ranging from 0 to 1), Manning coefficient ($s.m^{-1/3}$) and depth of interception (mm). The modeller can choose whether to use the ground module or not. If this module is used, additional parameters are needed for each land use type, including specific storage, porosity and initial conditions (i.e. pressure head, moisture content, and relative hydraulic conductivity corresponding to the pressure head). If the topographic data available for the area under consideration does not include anthropogenic elevation (e.g. elevation of buildings and streets), there is an option in Multi-Hydro for decreasing the elevation of road pixels by 15 cm (to reflect the fact that roads are preferential paths for surface water) and increasing the elevation of building pixels by 5 m (to prevent water from running through these pixels). Moreover, in order to prepare the inputs required for building and running a Multi-Hydro model, a dedicated user friendly software called MH AssimTool was developed (Richard et al., 2012). The AssimTool takes data in common formats, such as those provided by national geographic services, and converts it into formats compatible with Multi-Hydro. This facilitates implementation and transferring of models to Multi-Hydro. More details about the Multi-Hydro model can be found in Giangola-Murzyn et al. (2012b).

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