CRUE
FLOODING ERA-NET

Integrate, Consolidate and Disseminate

European Flood Risk Management Research

2nd ERA-NET CRUE Research Funding Initiative
Flood Resilient Communities – Managing the Consequences of Flooding
"Guidelines for Novel Risk Quantification and Communication"

CRUE Research Report No 2.4:

Guidelines for Informatics Support to Awareness Raising and Resilience Enhancement Activities (Deliverable 2.4 of the DIANE-CM Project)

Authors

Susana Ochoa Rodriguez (Imperial College London)
NunoSimões (Imperial College London, Universidade de Coimbra)
Li-Pen Wang (Imperial College London)
AkliluDinknehTeklesadik (Leuphana University of Lueneburg)

Funded by

Federal Ministry of Education and Research (BundesministeriumfürBildung und Forschung – BMBF) (Germany) (Contract number: 02WH1040)
Environment Agency (EA) (England and Wales) (Contract number: PO 30262748)
Ministry of Transport, Public Works and Water Management (Ministerie van Verkeer en Waterstaat – MinVenW) (Contract number: 31031919)

Bundesministerium für Bildung und Forschung
Environment Agency
Rijkswaterstaat
Ministerie van Infrastructuur en Milieu

Project Website: www.crue-eranet.net and http://hikm.ihe.nl/cm/
Project Contact: evers@uni.leuphana.de

DISCLAIMER

Flood risk management strategies in European Member States: Flood resilient communities – managing the consequences of flooding

CRUE Research Report No 2.4

This report was prepared with the support of the CRUE Funding Initiative on Flood Risk Management Research. While reasonable care has been taken in preparing this publication to ensure that information is appropriate and valid it has to be considered that the views, conclusions and recommendations expressed herein are those of the authors and most not necessarily endorse the views of the CRUE ERA-NET or the respective Funding bodies involved.

The intent of the research reports is to provide relevant information and to stimulate discussion of those having an interest in flood risk management. The results and conclusions of all reports produced under the **CRUE Funding Initiative on Flood Risk Management Research** are made available to policy-makers and stakeholders at all levels, research funding bodies, universities, industries, practitioners, and the general public by way of the CRUE website (**http://www.crue-eranet.net**).

This publication is copyright, but wide dissemination is encouraged. Information on copyright will be provided by the authors. Content reproduction is allowed only with full citation as follows:

Ochoa, S. *et al*., 2011: Guidelines for Informatics Support to Awareness Raising and Resilience Enhancement Activities. Deliverable 2.4, DIANE-CM Project (Decentralised Integrated Analysis and Enhancement of Awareness through Collaborative Modelling and Management of Flood Risk), Era-Net CRUE Funding Initiative on Flood Resilience.

Researcher's Contact Details

S. Ochoa[1*], N. Simões[1,2], L. Wang[1], A. Dinkneh[3]

[1]Imperial College London, Urban Water Research Group, United Kingdom
[2]Universidade de Coimbra, Portugal
3Leuphana Universität Lüneburg, Germany
*Correspondingauthor, e-mail s.ochoa-rodriguez@imperial.ac.uk

In submitting this report, the researchers have agreed to CRUE publishing this material in its edited form.

Era Net-CRUE Contact Details

Email: info@crue-eranet.net
Web: http://www.crue-eranet.net/

Published in September 2011

ERA-NET CRUE is funded by the ERA-NET Scheme under the 6th Framework Programme
General Directorate for Research in the European Commission
Contract number: ERAC-CT-2004-515742

ERA-NET CRUE Funding Initiative onFlood Risk Management Research

ERA-Net CRUE was funded within the Sixth EU Framework Programme and introduced structure within the area of European research on flood risk management (FRM). Its vision was to support and develop an extensive co-ordination and integration of regional, national, and European research programmes, projects and policies in the field of Flood Risk Management. Within the CRUE ERA-Net two funding initiatives were introduced.

The second ERA-Net CRUE Research Funding Initiative**"Flood resilient communities – managing the consequences of flooding"** was launched in support of the EU Floods Directive 2007/60/EC, which was introduced as a result of several severe flood events causing loss of life and property. Within this initiative seven joint research projects with test sites all over Europe are funded and focus on a broad spectrum of issues related to the enhancement of resilience. Besides, the scientific coordination project CORE CRUE is funded within this second call, to support the implement of the call and to disseminate its results.

Decentralised Integrated ANalysis and Enhancement of Awareness through Collaborative Modelling and Management of Flood Risk (DIANE-CM)

Work Package 2: Data, Modelling, Mapping and Near Real Time forecasting for stronger involvement of the local champions, and providing links with the topic 2 (Event Management) of the CRUE programme

Deliverable 2.4: Guidelines for informatics support to awareness raising and resilience enhancement

CRUE Research Final Report No 2. 4

Funded by

Federal Ministry of Education and Research (BundesministeriumfürBildung und Forschung)	Bundesministerium für Bildung und Forschung **BMBF (DE)**
Environment Agency	Environment Agency **EA (UK)**
Ministry of Transport, Public Works and Water Management (Ministerie van Verkeer en Waterstaat)	Rijkswaterstaat Ministerie van Infrastructuur en Milieu **MinVenW (NL)**

Contents

1 INTRODUCTION

The kernel of the DIANE-CM project is the **collaborative modelling**[1], which aims at bringing stakeholders together to jointly select the most appropriate alternatives for managing flood risk in a certain area. The participatory nature of the proposed approach enhances learning, transparency of information and results, confidence in the process and acceptance of selected negotiated measures.

This collaborative modelling approach is strongly supported by informatics tools: the development and implementation of the collaborative modelling tools and methodologies is an iterative process in which stakeholder engagement and communication activities are constantly complemented and supported by modelling and development of informatics tools and vice versa. For this reason, one of the objectives of the DIANE-CM project is to improve flood modelling, mapping and forecasting techniques and to understand how they could be used to effectively support the collaborative modelling activities and ultimately to enhance flood resilience.

The present guidelines focus on the flood modelling tools which have been developed and implemented throughout the DIANE-CM project. Firstly, a summary of the modelling approach implemented in each case study is presented and afterwards detailed guidelines are given for the set up and use of 1D-1D pluvial flood models, which are key for near real-time pluvial flood forecast and constitute the most innovative modelling tool implemented throughout the project. These guidelines cover the concept behind and the use of the in-house *AOFD* (Automatic Overland Flood Delineation) tool and also the steps that must be followed to set up the dual-drainage 1D-1D pluvial flood models in *InfoWorks CS*.

[1] The *Collaborative Modelling Exercise* (*CME*) constitutes the final stage of the collaborative modelling approach implemented throughout the DIANE-CM project. The purpose of the *CME* was to jointly rank the alternatives for flood risk management in each case study area according to a set of objectives defined through guided discussion and negotiation amongst stakeholders. The web platforms implemented to carry out the CME in each case study can be accessed in the following links:

- UK case study (Cranbrook catchment): http://hikm.ihe.nl/diane_cm/internal/cranbrook/exercise/
- Germany case study (river Alster catchment): http://hikm.ihe.nl/diane_cm/internal/alster/exercise/

2 MODELLING APPROACH IMPLEMENTED IN EACH CASE STUDY

2.1 MODELLING APPROACH IMPLEMENTED IN THE RIVER ALSTER CATCHMENT (GERMANY)

2.1.1 Main characteristics of the study area

- **Major Type of Flood:** fluvial
- **Size of catchment area:** 578 km²
- **Past flood events:** Several flood events during the last 10 years, with the most recent event on 6th February 2011
- **Environmental Setting:** The Alster catchment is situated in Northern Germany. Approximately 47 % of the catchment is located within the Hamburg Metropolitan Region and the remaining 53 % lies within the state of Schleswig-Holstein. The upper part of the catchment (located in Schleswig-Holstein) is predominantly rural, whereas the lower part (located in Hamburg) is highly urbanised, with impervious surfaces covering approximately 80 % of the area.

In the city centre of Hamburg the Alster River is dammed by a sluicegate (Rathausschleuse), forming two lakes (Binnenalster and Außenalster) which have the same water level, ranging from 2.85 m to 3.25 m. Another lock (Schaartorschleuse) is located 1 km downstream of the Rathausschleuse (see **Error! eference source not found.**), where the Alster joins the River Elbe. This sluice protects the inner city of Hamburg from high tides in the Elbe River. A pumping station at the Schaartorschleuse (with a pumping capacity of 36 l/s) protects the city centre from flooding. In the Hamburg city centre the Alster is famous for its charm and for the recreational activities that take place in it, rather than for its flooding history. Approximately 10 km upstream of the Rathausschleuse there is another sluice called Fuhlsbüttler Schleuse (see Figure 1), with an upstream-downstream water level difference of 3 m. Upstream of this sluice the Alster and its tributaries cause frequent flooding, with the most recent event in February 2011 (during the development of the DIANE-CM project).

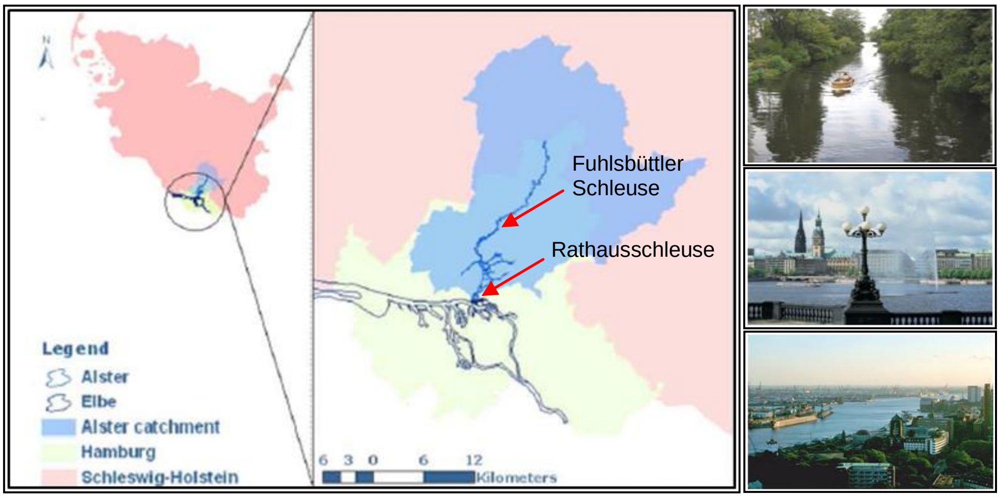


Figure 1. River Alster catchment

2.1.2 Hydrological and hydraulic modelling of the Alster catchment

2.1.2.1 Existing models

A hydrological model of the river Alster catchment was built and calibrated by an engineering company using Calypso software. In addition to the hydrological model, a hydraulic model for the upper part of the river Alster (until Fuhlsbüttler sluice) was built and calibrated using MIKE 11. These models are owned by the LSBG (Agency for Streets, Bridge and Water), which was a technical partner in the DIANE-CM project. Simulations of different events, including extreme events, were carried out by the engineering company and these results were used in the DIANE-CM project as a boundary condition for the model that was built for the river section between Fuhlsbüttler sluice and Schaartorschleuse.

2.1.2.2 New models developed throughout the DIANE-CM project

Throughout the DIANE-CM project a model was built for the section of the river between Fuhlsbüttler sluice and Schaartorschleuse (point at which the Alster River flows into the Elbe); this part of the river had not been modelled before.

HEC-RAS software was used to build the 1D model of this section of the river Alster and the output from the MIKE 11 model (described in Section 2.1.2.1) was used as upstream boundary condition. Moreover, tidal data of the river Elbe was used as downstream boundary condition.

In what follows a description is provided of the information used for the construction of the model and also of the steps followed in the construction process.

Data used in the set-up of the 1D model of the river Alster (between Fuhlsbüttler sluice and Schaartorschleuse):

- High resolution elevation data: elevation data with at least 3 points in a 1 m grid was provided by LSBG. This dataset was used to determine the geometry of the river.

- River bed elevation data (bathymetry) of the river Alster and its tributaries was provided by LSBG.
- Flow output from MIKE 11 model (provided by LSG) was used as upstream boundary condition.
- Measurements from level gauges along the river Alster and its tributaries were provided by LSBG. These data were used for calibration of the model.
- Tidal data of the Elbe River, which was used as downstream boundary condition.

Steps followed for construction and calibration of the 1D river model with HEC-RAS:

i. ***Preparation of geometrical data:*** the high resolution elevation data and bathymetry data were processed in ArcGIS to create a Digital Elevation Model (DEM). Using the HEC-GeoRAS extension tool in ArcGIS river cross sections, bank lines and structures across the river were extracted. These geometrical data was exported to HEC-RAS afterwards. Figure 2 illustrates this process.

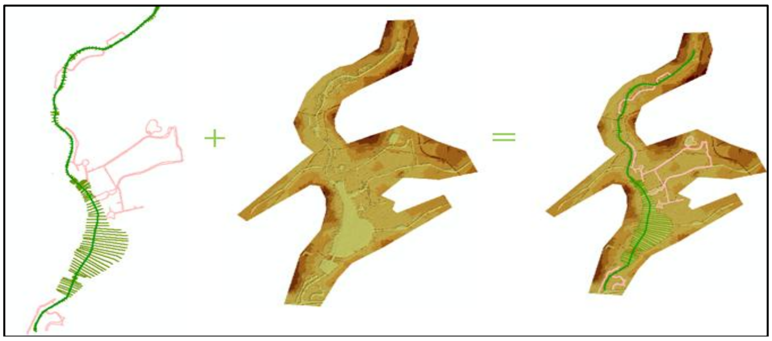


Figure 2. Extraction of geometrical data from DEM

ii. ***Import of geometrical data to HEC-RAS and setting of model parameters:*** after processing the geometrical data in ArcGIS, it was imported to HEC-RAS. Afterwards, model parameters (e.g. manning, expansion and contraction coefficients) were set and information of bridges, pumps and inline structures was incorporated in the HEC-RAS model. An example of this process is shown in Figure 3.

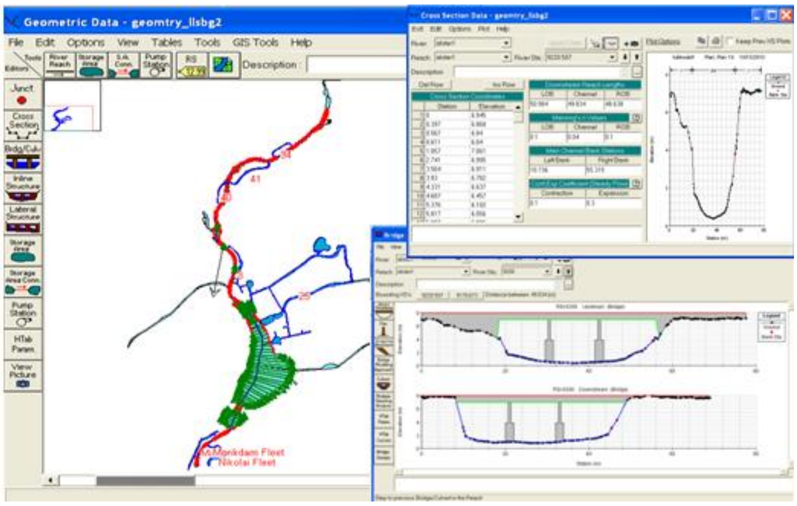


Figure 3. Example of cross section and bridges definition in HEC-RAS

iii. ***Calibration***: the model was calibrated using data from December 2007 to April 2010. During the calibration process the only parameter that was adjusted was the manning coefficient and the only data available for calibration was water level at different locations. Having flow data, in addition to level data, would have enabled having a more robust model; however, the quality of the model obtained after calibrating with level data only was enough for reliably simulating extreme events for flood mapping purposes. Some results of the calibration process are shown in Table 1. It can be observed that the results obtained from the model match with the observations.

Table 1. Calibration results (comparison of simulated and observed water level at different locations)

Location	Simulated	Measured
Krugkoppelbrücke	3.07 m	3.18 m
Upstream of Rathausschleuse	3.05 m	3.12 m
Downstream of Rathausschleuse	1.7 m	1.63 m

After calibration, the model was used for simulation of different flood scenarios and flood risk management alternatives. The scenarios and alternatives considered for the river Alster catchment are described in the next sections. In addition, the results of the model were used for generation of flood hazard maps.

2.1.3 *Flood scenarios considered in the Alster catchment*

A scenario is a set of conditions that are out of the decision maker choice; it is something that could happen, but we cannot control.

In order to estimate the effects of different flood events and conditions in the Alster catchment, the following flood scenarios were simulated and analysed:

- Scenario 1: 100 years return period event
- Scenario 2: 200 years return period event
- Scenario 3: 100 years return period event + pump failure at Schaartorschleuse
- Scenario 4: 100 years return period event + gate failure at Schaartorschleuse + high tide at river Elbe

Scenario 2 was chosen as the base case for the CME: it was used as reference to evaluate the performance of the different alternatives for flood risk management. Scenarios 3 and 4 are very extreme scenarios with very low probability of occurrence; that is why they were not considered as base case in the CME.

2.1.4 *Fluvial flood risk management measures considered in the Alster catchment*

As explained in Section 1 (Introduction), the final aim of the *Collaborative Modelling Exercise* developed throughout the DIANE-CM project was to jointly select the most appropriate alternatives for managing flood risk in the study areas. In order to do this, a decision support system was implemented. However, before carrying out the exercise a set of possible measures for managing flood risk in the study areas was defined. A preliminary set of alternatives was initially proposed based on its feasibility of implementation and the potential benefits they could bring to each study area. The proposed alternatives were discussed amongst stakeholders during a collaborative workshop and based on the discussion the final set of alternatives to be considered in the *Collaborative Modelling Exercise* was defined.

The flood risk management alternatives considered in the Alster catchment are summarised in Table 2. As can be seen, some of the alternatives correspond to a combination of individual measures.

Table 2. Proposed alternatives for flood risk management in the Alster catchment

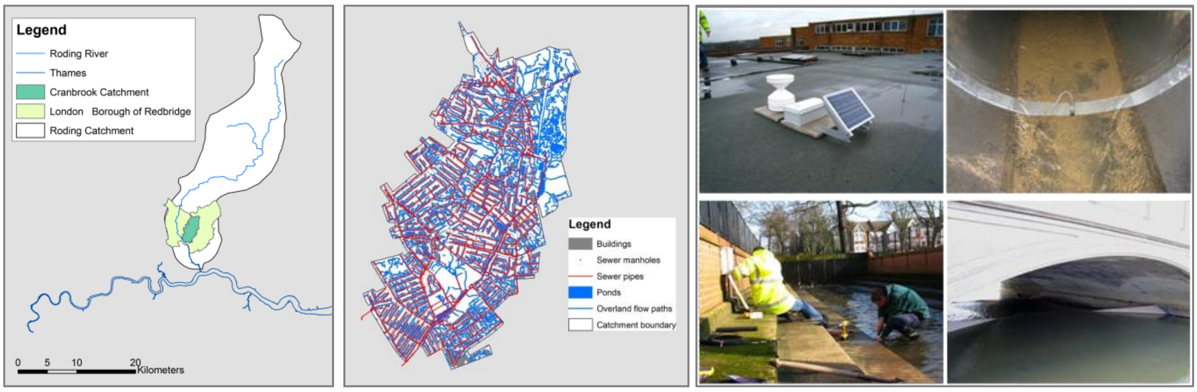
Alternative	Modelling example / Description of the alternative
Alternative 1: Doing nothing (base case)	Current situation, no measures are implemented
Alternative 2: Technical measures	
Modification of hydraulic structures	• Lowering crest level of weir at Fuhlsbüttler Schleuse • Lowering crest level of weir at Wohldorfer Scheuse
Construction of reservoirs	Building dike around Hoopwishen village
Alternative 3: Management of the catchment area	
Sustainable and careful maintenance of water systems	Clearing trees from Ammersbeck River, a tributary of the Alster
Alternative 4: Prevention	
Improved coordination	Coordination of responsibilities between authorities and other stakeholders
(Private) property protection	Flood protection measures at the household level
Forecast / Information	Installation / improvement of predictive mechanisms, information of local residents

The potential measures for flood risk management were defined through live discussion with workshop participants and also based on the feedback provided via the collaborative platform and e-mail.

2.2 MODELLING APPROACH IMPLEMENTED IN THE CRANBROOK CATCHMENT (UK)

2.2.1 *Main characteristics of the study area*

- **Major type of flooding**: pluvial and fluvial. Although the study area is subject to these two types of flooding, more attention has been given to fluvial flooding in the past and the associated models, forecasting and warning systems have been well established. In contrast, little attention has been given to pluvial flooding in this area and its management however has been identified as a missing gap both at the planning and at the emergency management stages. For this reason, the focus in the Cranbrook catchment case study was on pluvial flood risk management.
- **Size of catchment area:** 9 km²
- **Past flood events**: Several flood events reported since 1926, most recent events in October 2000 and February 2009.
- **Environmental Setting:** The Cranbrook catchment is located within the London Borough of Redbridge. It is predominantly urbanised; the main water course is 5.75 km long, of which 5.69 km are culverted. The Cran Brook is a tributary of the Roding River, which in turn is a tributary of the River Thames.



(a) (b) (c)

Figure 4. Cranbrook catchment. (a) location of Cranbrook catchment in relation to the Roding River catchment; (b) dual-drainage networks of the Cranbrook catchment; (c) monitoring system installed in the study area.

2.2.2 *Pluvial flood modelling in the Cranbrook catchment*

Pluvial flooding is caused by intense rainfall whose volume exceeds the capacity of the sewer network and of the surface drainage system. This type of flooding is typically localised and happens very quickly after the rain has fallen, making it difficult to predict, pinpoint and give reliable warning. The speed and the scale at which this type of flooding takes places make it necessary to have fast flood models which can provide accurate information at small spatial and temporal scales. However, the modelling and forecasting of this type of flooding is still in its “infancy”; this is why new modelling approaches are needed and are currently under development.

In order to model and forecast urban pluvial flooding, two main “modules” are required: (1) rainfall data and (2) hydraulic flood modelling. The first module constitutes the main input for the second one.

Depending on the application purposes of the pluvial flood models, the two modules mentioned above have different characteristics in order to comply with different requirements:

- Characteristics and requirements of pluvial flood models used for **planning purposes or other off-line applications:**
    - *Computational time:* not critical
    - *Rainfall data:* design storms or data from previous rain events can be used as inputs for the corresponding hydraulic flood models.
    - *Hydraulic flood models:* these models must be detailed and must take into account the complexity of the urban environment and of the phenomena that take place when pluvial flooding occurs (including the interaction between the overland and the sewer network). Since computational time is not critical for these applications, the hydraulic flood models do not necessarily have to be fast. For this type of applications 1D-2D[2] hydraulic models are in general more suitable than 1D-1D[3] models, given that the 2D model of the surface provides more detail and allows for better visualisation of the results (a detailed description of the 1D-1D and 1D-2D hydraulic models is given in Section 2.2.5. Furthermore, a comparison of the main features of both models can be found in Appendix 0).
    - *Use in the DIANE-CM project:* this is the case of the models developed and used to generate the information required for the collaborative modelling activities. For these activities fine-scale hydraulic models were run off-line using FEH (Flood Estimation Handbook) design storms of different return periods and including various modifications in the hydraulic models in order to simulate different flood scenarios as well as the effect of different flood risk management measures.

- Characteristics and requirements of pluvial flood models used for **real-time applications (i.e. real-time forecasting)**:
    - *Computational time:* critical. These models have to be fast in order to provide enough lead time which allows issuing early warnings and timely triggering structural and non-structural measures. This will ultimately allow the prevention and reduction of the negative consequences of pluvial flooding.
    - *Rainfall data:* fine-scale short-term rainfall forecast is required. Given the scale and speed at which surface flooding occurs, the rainfall forecast needs to be fast and must also have fine spatial (i.e. street scales, approx. 250 – 500 m) and temporal (i.e. 5 min) resolution.
    - *Hydraulic flood models*: given the criticality of time and the rapid onset of pluvial flooding, these models must be fast, but at the same time detailed and accurate enough to minimise the occurrence of false alarms and missed alerts. Given the requirements of real-time surface flood forecasting, 1D-1D hydraulic flood models must be used for this type of applications (the different types of hydraulic flood models are described in Section 2.2.5).

[2] A 1D-2D pluvial flood hydraulic model is made up of a one dimensional (1D) model of the sewer system coupled with a two dimensional (2D) model of the surface or overland network.
[3] A 1D-1D pluvial flood hydraulic model is made up of a one dimensional (1D) model of the sewer system coupled with a one dimensional (1D) model of the surface or overland network.

- *Use in the DIANE-CM project*: urban pluvial flood forecasting is a more challenging, uncertain and "unexplored" problem, as compared to its modelling for off-line applications (e.g. for planning and design purposes).Throughout the DIANE-CM project great effort was put into improving the rainfall forecast and the hydraulic pluvial flood models with the final purpose of enabling short-term, real-time, street-scale forecasting of these events. Although the forecasting methodologies were not used to generate the flood hazard maps included in the *Collaborative Modelling Exercise,* the progress made in this direction was constantly communicated to the stakeholders in order to inform them about the feasibility and accessibility of pluvial flood forecasting and warnings. Furthermore, one of the flood risk management alternatives considered in the *Collaborative Modelling Exercise* was the access to surface flood warnings before these events actually take place.

Table 3 summarises the characteristics and requirements of the flood models according to its final purpose or application.

Table 3. Characteristics / requirements of flood models according to its purpose or application

	PURPOSE OR APPLICATION OF SURFACE FLOOD MODELS	
REQUIREMENT / CHARACTERISTIC	**PLANNING / OFF-LINE APPLICATIONS**	**REAL-TIME (*RT*) FORECASTING / OTHER *RT* APPLICATIONS**
COMPUTATIONAL TIME	Not critical	Critical (lead time is critical for triggering alarms and reducing negative impacts of surface flooding)
RAINFALL INPUT	Design rainfall events (e.g. FEH) or data from previous rain events	Short-term fine-scale rainfall forecast
HYDRAULIC FLOOD MODEL	Fine-scale models, which represents the complexity of the urban environment and of the processes involved in urban pluvial flooding (1D-2D models are more suitable)	Short-term fine-scale models which are fast but accurate enough to keep false alarms and missed alerts to a minimum. (1D-1D models)

Next, a brief explanation is provided on the rainfall inputs, the rainfall forecast and the pluvial flood hydraulic models developed and used throughout the DIANE-CM project. Afterwards, a description is given on the different flood scenarios and flood management alternatives considered in the *Collaborative Modelling Exercise*.

2.2.3 Rainfall inputs for pluvial surface flood modelling and forecasting

In the DIANE-CM project the following sources of rainfall data were used for the Cranbrook catchment:

- **Rain gauge data from the monitoring system installed in the Cranbrook catchment:** 3 tipping bucket raingauges were individually installed in the roofs of 3 high schools within the Cranbrook catchment in April 2010. The gauges are equipped with wireless communication devices which provide real time access to rainfall data in the study area. Furthermore, the system also archives historical data. The data collected by these raingauges, along with level data obtained from level gauges installed throughout the sewer system, has mainly been used for calibration and validation of the hydraulic model. Some of the collected data has also been used for testing the rainfall forecast and downscaling methodologies developed throughout the DIANE-CM project (these methodologies are described in Section 2.2.4).
- **Raingauge data from the London Grid for Learning:** 42 raingauges in the Greater London, which provide real-time access to 1 minute resolution data and access to historical data since 06/06/2006. The historical data obtained from this network of raingauges has been used for testing the rainfall forecast and downscaling methodologies developed throughout the DIANE-CM project (these methodologies are described in Section 2.2.4)
- **Flood Estimation Handbook (FEH) design storms:** the FEH provides advanced means of producing design storms for any given return period and duration for UK catchments. It utilises digital terrain modelling and possesses data for over 4 million catchments in the UK from 0.5 km^2 upwards. The FEH includes a CD-ROM with which it is possible to identify the descriptors of a certain catchment, which can in turn be used to generate the corresponding rainfall depth-duration-frequency graphs. The FEH was published in January 2000 by the Centre for Ecology and Hydrology and the work was based on rainfall data from 6,106 daily raingauges and 375 hourly raingauges (Allit, 2001). In the DIANE-CM project FEH design storms were used to create flood scenarios for storms of different return periods. Moreover, the base case of the *Collaborative Modelling Exercise* was defined using a FEH design storm (the base case corresponds to a 200-year return period FEH design storm with summer rainfall profile).
- **Radar data:** the Cranbrook catchment is within the coverage of two weather radars operated by the UK Met Office: the Chenies radar (single-polarisation) and the Thurnham radar (dual-polarisation). The radar data collected was used to assess the rainfall forecasting and downscaling methodologies developed throughout the DIANE-CM project (these methodologies are described in Section 2.2.4).
- **Nimrod data:** it corresponds to radar data which has been calibrated using raingauges and further merged with satellite images and Numerical Weather Prediction (NWP).This data was used to evaluate the rainfall forecasting and downscaling methodologies developed throughout the DIANE-CM project (these methodologies are described in Section 2.2.4).

2.2.4 Fine-scale short-term rainfall prediction methodologies

Urban pluvial flood forecasting requires short term rainfall prediction with high spatial and temporal resolution (given that the modelling needs to be carried out at the scale of urban catchments, which are significantly smaller and more complex than rural catchments). The state-of-the-art methods for high-resolution rainfall prediction are mainly based upon radar techniques; however, the lead time of these methods (approx. 45–60 minutes) and the spatial and temporal resolutions of the rainfall forecast obtained with them are insufficient for the corresponding pluvial flood hydraulic models to carry out an accurate and timely estimation. To overcome these shortcomings, an integrated methodology consisting of radar-based nowcasting[4] techniques and enhanced statistically-based downscaling methods is being developed in order to obtain longer lead-time rainfall forecasting with high spatial and temporal resolutions. The research currently under development includes improvements in the operational Short Term Ensemble Prediction System (STEPS) of the UK Met Office. The STEPS is a post-processing system composed of the information from radar-based nowcasting, Numerical Weather Prediction (NWP) model (UM model: 4 km), and randomly/statistically generated noise (for local areas). In the nowcasting part, improved data merging techniques, which aim at optimally combining different rainfall data sources to provide more accurate rainfall estimates, are under development. Moreover, statistically based downscaling techniques are also under development aiming at obtaining rainfall forecasts with finer spatial and temporal resolutions. These improved data will be applied to the operational STEPS and the nowcasting-only-version STEPS*. Furthermore, the improved rainfall forecast will be applied to the hydraulic models in order to assess its effects on the final urban pluvial flood forecast. More information about the on-going work regarding radar-based rainfall nowcasting can be found in Wang *et al*. (2011).

In addition to the improvement in the radar-based rainfall forecasting methodologies, rainfall forecasting techniques based on networks of raingauges only are also being developed and have provided promising estimates. These techniques combine an artificial intelligence algorithm (Support Vector Machine) and Single Spectrum Analysis (a combination of time series analysis, multivariate statistics and geometry, and signal processing) in order to forecast the rainfall time series at each raingauge site. After doing so, spatial interpolation techniques are applied in order to generate a continuous rain field; different spatial interpolation techniques are being analysed at the moment (e.g. Kriging, block Kriging, inverse squared distance method, Thiessen polygons). More information about the raingauge-based forecast can be found in Simões *et al*. (2011a).

Figure 5 presents a summary of the short-term fine-scale rainfall forecasting techniques that are currently under development at Imperial College London. This scheme shows how the different modules of the rainfall forecasting methodology are connected and how it ultimately feeds the hydraulic pluvial flood models.

As previously mentioned, the rainfall forecast was not used to generate material for the collaborative modelling activities; however, great effort was throughout the DIANE-CM project in order to improve the rainfall forecasting methodologies. In addition, the progress made in this direction was constantly communicated to the stakeholders in order to make them aware of the feasibility and importance of having pluvial flood forecast and warnings. Furthermore, one of the flood risk management alternatives considered in the *Collaborative Modelling Exercise* was the access to surface flood warnings before these events actually take place.

The forecasting methodologies described herein are currently in the final phase of development. However, further testing (including operational testing) must be carried out before these techniques can actually be implemented. Moreover, in order for these techniques to be properly implemented and used, a legal and operational framework for pluvial flood forecasting and warning must be first developed (this is not yet available in the UK, although progress is being done in this direction).

[4]Nowcasting is a technique for very short-range forecasting that maps the current weather and uses an estimate of its speed and direction of movement to forecast the weather a short period ahead (only few hours ahead), assuming that the weather will move without significant changes (The UK Meteorological Office, 2011).

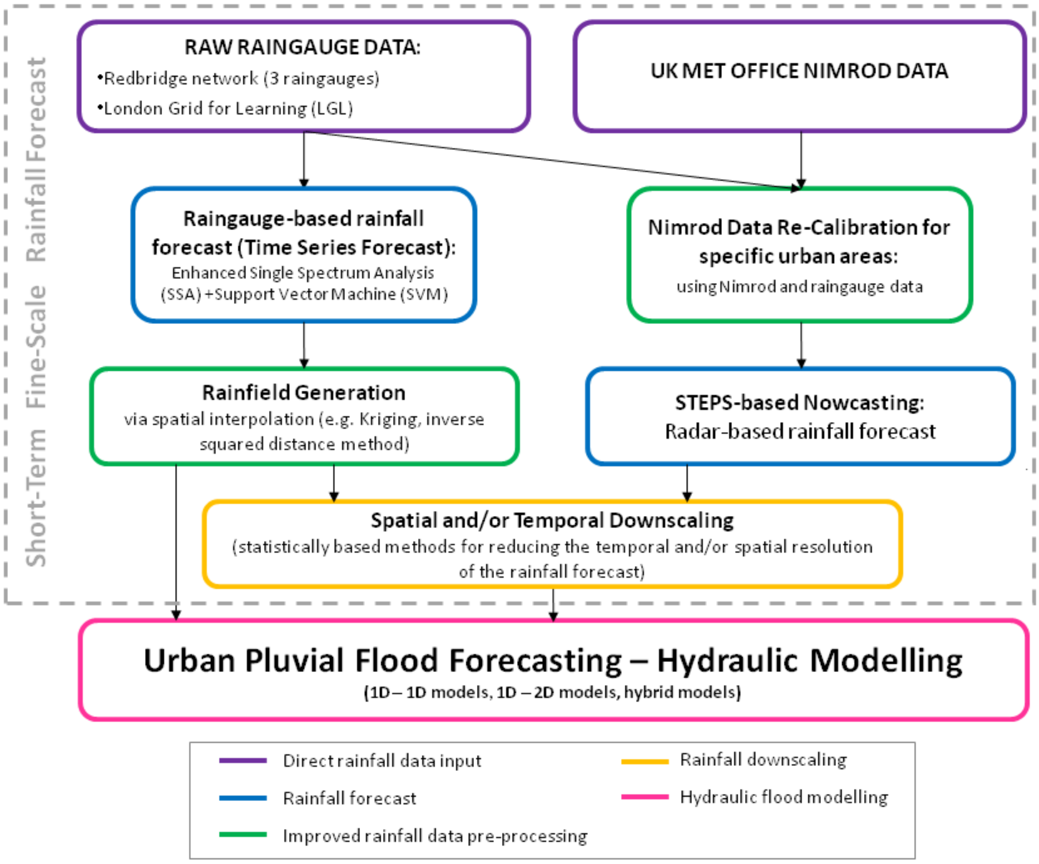


Figure 5. Summary of proposed techniques for fine-scale short-term rainfall forecast as input for urban pluvial flood forecast.

2.2.5 Hydraulic pluvial flood models

In order to reliably model urban pluvial flooding, it is necessary to realistically represent the urban fabric in its complexity, taking into account the local topography and the interactions between the overland and sewer networks, as well as the boundary conditions that determine the performance of the system.

The models of the Cranbrook catchment developed throughout the DIANE-CM project are physically based[5] and take into account the interaction between the overland (surface) and the sewer network; this is known as the "dual-drainage concept" (Djordjević *et al*., 2005) (a detailed explanation of this concept is given in Appendix 0).

In what follows, a description is given of the overland and sewer network models implemented for the Cranbrook catchment. In addition, the way in which these two models are coupled in order to account for the dual-drainage concept is also described.

[5]In physically based models, water movement over the surface and in the sewers is modelled by solving the appropriate approximation of mass and momentum conservation equations. This enables simulating the features of urban areas more realistically. The main advantage of physically based approaches is that once the model has been calibrated, any changes in physical characteristics of the catchment (e.g. increased imperviousness due to urbanization), change of network topology, or addition / modification of pipes can be reliably described by updating the subcatchment characteristics but without the need for re-calibration of surface run-off model parameters as it would be necessary with conceptual models (Maksimović *et al*., 2009).

2.2.5.1 Surface network model:

In the last few years different approaches have been implemented to represent the flow on the urban surface (e.g. virtual reservoir, lost volume, rapid flood spreading models); however, none of these can realistically represent the hydraulic behaviour of the flow on the surface (Butler and Davies, 2011).

More recently, two ways of realistically modelling the surface or overland network of an urban catchment have been developed:

- As a 2-dimensional (2D) surface, using a mesh of triangular elements, or
- As a 1-dimensional (1D) system made up of ponds (modelled as storage nodes) and pathways (modelled as conduits with specific geometry computed from the Digital Terrain Model –DTM–).

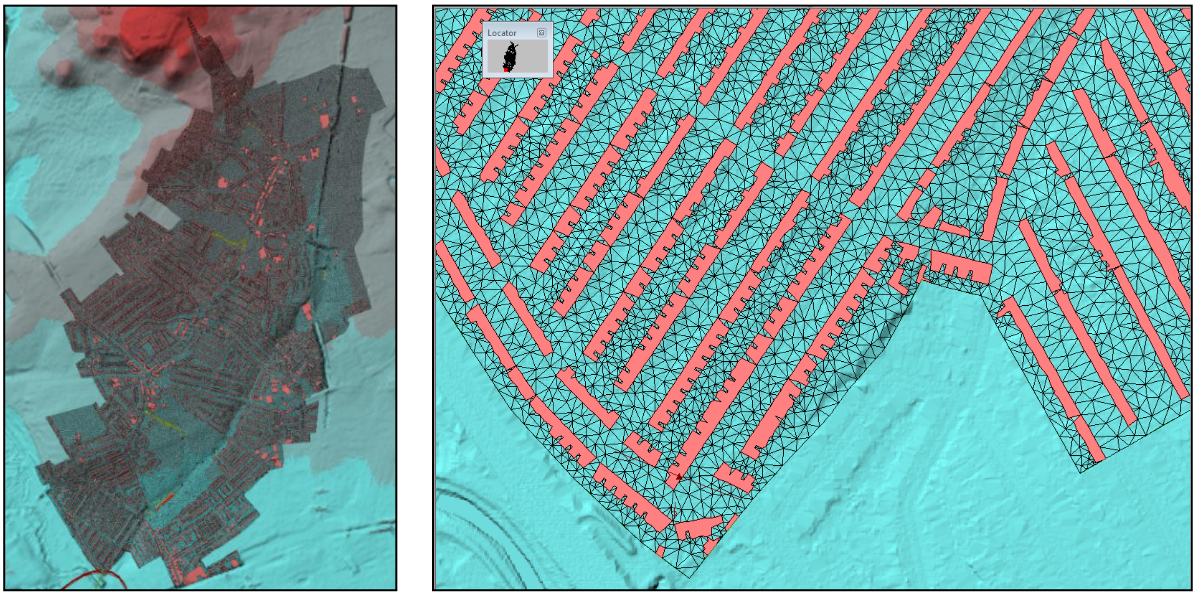
Both models can reliably represent the overland network and the flow on it, but each of them has advantages and disadvantages. The 2D models provide a more detailed representation of the overland flow and allow for a better visualisation of the results; however, they are computationally demanding and their running time makes them unsuitable for short-term real-time forecasting of urban pluvial flooding (given that short computational time is essential for this purpose). In contrast, the 1D models are significantly faster and therefore suitable for short-term real-time forecasting; however, they provide less detail and poorer visualisation of results, although they can still represent the overland flow reliably.

In the DIANE-CM project both kind of models were implemented for different purposes: the 1D model was used for forecasting purposes, whereas the 2D model was used for the mapping and improved visualisation of flood scenarios (included in the *Collaborative Modelling Exercise*). Both models were implemented in *InfoWorks CS*.

The 2D model of the surface network was created from the catchment DTM, using the tools provided in *InfoWorks CS* 11.0 to generate a 2D mesh of triangular elements, which is then used to model 2D flows. The DTM used for this purpose corresponds to 1 m resolution LiDAR data, obtained from Infoterra. In *InfoWorks CS* 11.0, the 2D mesh is generated using the Shewchuk Triangle meshing functionality. Heights at the vertices of the generated mesh elements are calculated by interpolation from the DTM. In order for meshing to be carried out, a bounding polygon must be defined (this generally corresponds to the catchment boundary). Furthermore, voids (i.e. regions that will not be meshed, such as buildings), break lines and areas of varying roughness and mesh resolution may also be defined (MWH Soft, 2011). Figure 6 shows the 2D model of the surface network of the Cranbrook catchment (modelled in *InfoWorks CS 11.5*).

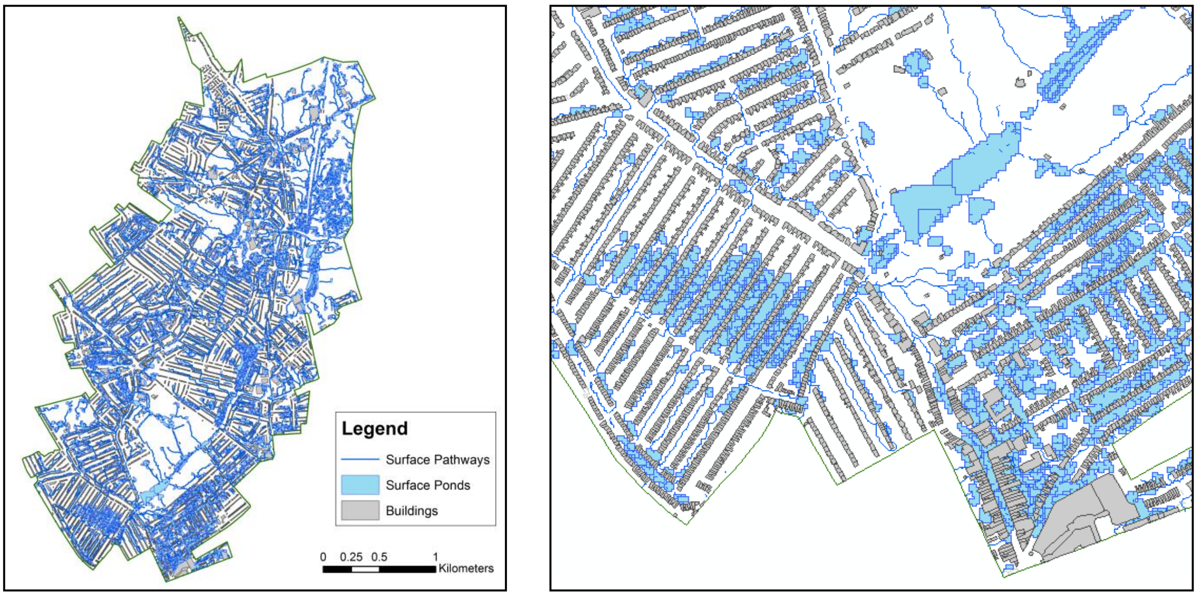
The 1D model of the surface was produced from the same set of 1 m resolution LiDAR data obtained from Infoterra. The tool used to create the 1D model of the overland network is the Automatic Overland Flow Delineation –*AOFD*– (Maksimovć *et al*., 2009). Based on the DTM of the area, the *AOFD* tool generates the overland network model and quantifies hydraulic parameters for simulation of pluvial urban flooding. The output of the *AOFD* tool is a series of shapefiles, which can be imported into *InfoWorks CS* (or also into SIPSON) in order to create the 1D model of the surface. More details about the *AOFD* tool, including user instructions, are provided in Chapter 3. Figure 7 shows the 1D model of the surface network of the Cranbrook catchment.

It is worth mentioning that several software packages (e.g. InfoWorks, SIPSON/UIM, SOBEK) (Leandro, 2008) allow for 2D simulation of the overland network and have special tools to create such models (i.e. to create the 2D mesh based on the DTM). Regarding 1D models of the surface, there are also several software packages (e.g. InfoWorks CS, MOUSE, SOBEK, SWMM) which are capable of simulating the 1D flow over the surface; however, their methodology to estimate the overland flow assumes manual (hence subjective) definition of the surface flow paths, which is laborious and might lead to unreliable representations of surface flow processes (Maksimović *et al*., 2009). This is why the *AOFD* tool constitutes a useful innovation.



(a) (b)

Figure 6. 2D model of the overland network of the Cranbrook catchment: (a) entire catchment; (b) detail.



(a) (b)

Figure 7. 1D model of the overland network of the Cranbrook catchment: (a) entire catchment; (b) detail.

Both types of surface models (1D and 2D) can be coupled with the model of the sewer network, thus originating a dual drainage model. The connection between the two systems (i.e. overland and sewer network) takes place at the manholes, gullies or inlets.

2.2.5.2 Sewer network model:

All sewer network models are made up of nodes and conduits. Given that in these elements the flow direction is very well defined and the section within each conduit is constant, 1-dimensional (1D) models can be used to represent its behaviour (in fact, sewer networks are always modelled as 1D models). An *InfoWorks CS* model of the sewer network of the Cranbrook catchment was obtained from Thames Water. However, this model was missing some details, which had to be completed from information provided by various local authorities of the London Borough of Redbridge or by means of different data mining tools. A map of the sewer network of Cranbrook is shown in Figure 8.

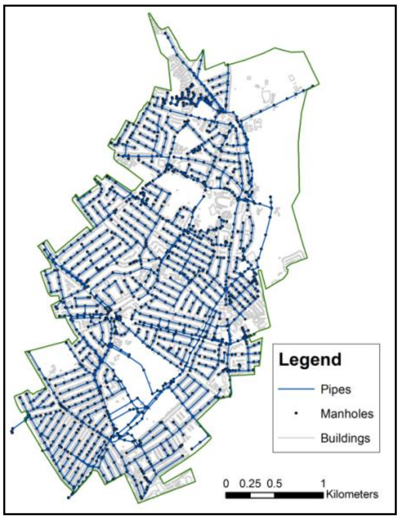


Figure 8. Sewer network of the Cranbrook catchment.

2.2.5.3 Dual-drainage model: overland network model + sewer network model

After coupling the overland and the sewer network models (in *InfoWorks CS*), a dual-drainage model of the study area is obtained. The interaction between these two systems takes place at the manholes, where water can either go in or out depending on the regime of flow in both systems.

According to the type of surface model used, the dual-drainage models can be of two types:

- **1D-2D:** 1D model of the sewer system + 2D model of the surface
- **1D-1D:** 1D model of the sewer system + 1D model of the surface. In Section 3 instructions are provided on the use of the *AOFD* tool and creation of 1D-1D models.

A summary of the differences between the 1D-1D and 1D-2D pluvial flood models is presented in Appendix A.4.

Depending on the type of model, the manholes must be assigned different properties. The main difference of the modelling aspects of the manholes in 1D-2D and 1D-1D models in InfoWorks CS is their flood type:

In 1D-2D models the manholes are assigned a "2D" flood type. In this case the discharge between the surface storage (on the 2D mesh) and the manhole is calculated using standard weir equations, where the weir width is taken as the circumference of the manhole and the user may define the flooding discharge coefficient (MWH Soft, 2011).

In 1D-1D models the manholes are assigned a "Stored" flood type. In this case the flood water on the catchment surface is retained in the storage volume defined by the flood levels and areas (specified for each manhole). When the flood level is reached, the water flows from the manholes to the surface pathways (towards another manhole or a surface pond; thus originating surface flow). The flood water returns to the drainage system as the levels drop.

As explained before, in the DIANE-CM project both 1D-1D and 1D-2D were implemented. In addition, with the purpose of combining the advantages of each type of model and to overcome their drawbacks, a new type of model called "hybrid" was developed. In the hybrid model most of the surface is modelled in 1D, except for those areas which have been identified as critical (i.e. as being more prone to pluvial flooding). In the critical areas a 2D mesh is generated in order to represent the hydraulic behaviour of the overland network more accurately and with greater detail. The 1D model, which covers most of the catchment, is connected with the 2D area in such a way that interaction between the two overland models is enabled and water can flow continuously from 1D areas to 2D areas and vice versa. An example of the interaction between the two surface models is shown in Figure 9; it can be seen that the overland pathways (of the 1D model) enter the 2D area and discharge there (through 2D outfalls).

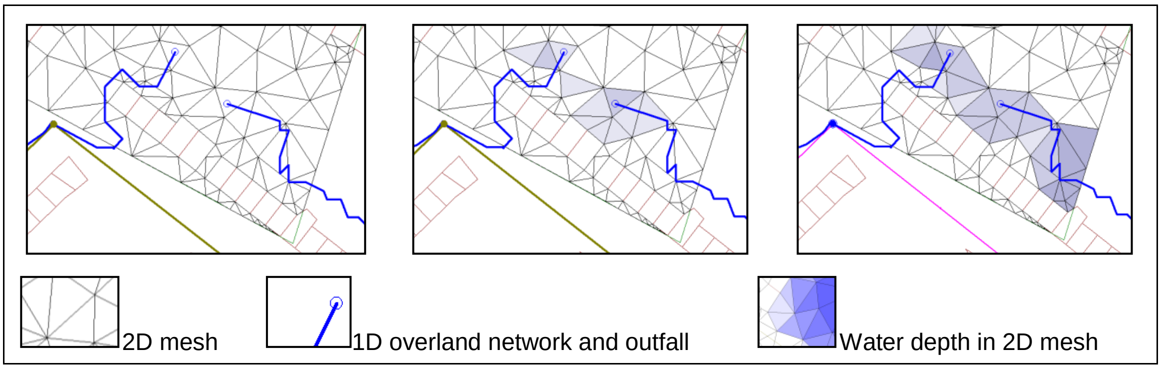
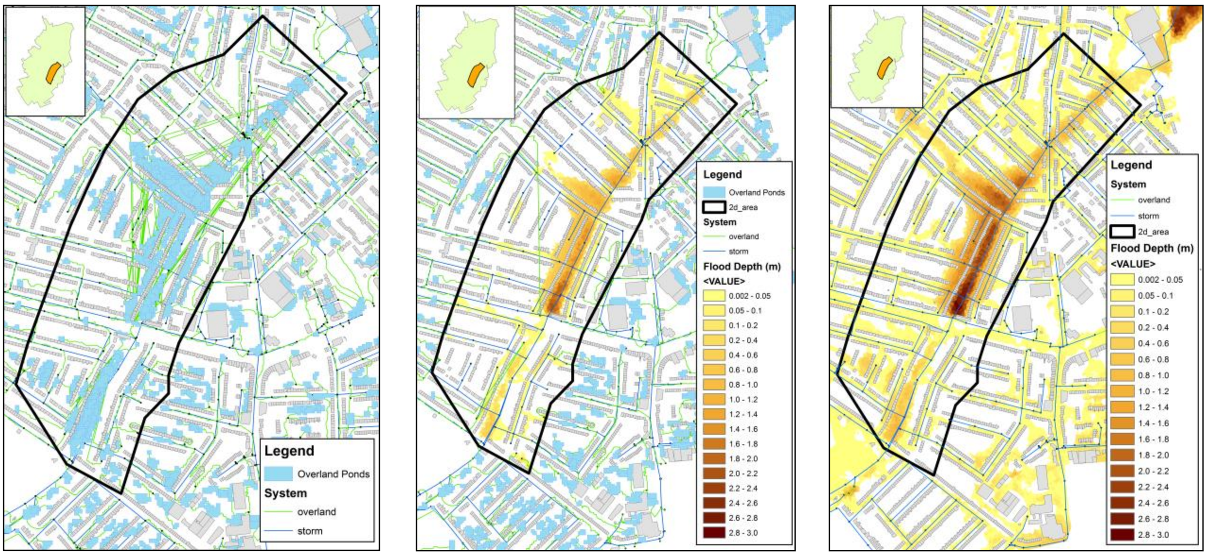


Figure 9. Interaction between the 1D-1D network and 1D-2D network in the hybrid model

The results obtained with the hybrid model show good agreement with the full 1D-2D model. Figure 10 shows a detail of the pond delineation of the 1D-1D model and the water depths in the 1D-2D and hybrid models (the results correspond to a 200-year return period rainfall event). It can be seen that the results of all models match and that the water depth in the 2D areas of both the hybrid and the 1D-2D model are very similar (slightly higher water depths are observed in the 1D-2D model, which can be explained by the lower retention capacity of this model).



a) b) c)

Figure 10. Flood extent in: a) 1D-1D model; b) Hybrid model; c) 1D-2D model.

In addition, the computational time of the hybrid model is short, making it suitable for real-time applications.

Table 4 shows the computational time of the 1D-1D, 1D-2D and hybrid models for different flood events. It can be seen that the 1D-1D and the hybrid models are significantly faster than the 1D-2D model.

Table 4. Simulation time of the 1D-1D, hybrid and 1D-2D models for FEH rainfall events of different return periods.

Flood Event (return period)	Duration	Model	Simulation time [hh:mm:ss]	Difference (compared to 1D/1D model)
30-yr	300min	1D/1D	00:01:46	
		Hybrid	00:04:31	+156%
		1D/2D	00:45:23	+2469%
100 yr	300min	1D/1D	00:02:11	
		Hybrid	00:05:20	+144%
		1D/2D	01:11:10	+3160%
200 yr	300min	1D/1D	00:04:40	
		Hybrid	00:05:49	+25%
		1D/2D	01:16:05	+1530%

2.2.6 Flood scenarios considered in the Cranbrook catchment

In order to understand the effects of different flood events and conditions in the Cranbrook area, different flood scenarios were modelled and analysed. The scenarios that were considered are the following:

- Scenario 1: 30 years return period event + low level at the Roding River
- Scenario 2: 30 years return period event + high level at the Roding River

- Scenario 3: 200 years return period event + low level at the Roding River
- Scenario 4: 200 years return period event + high level at the Roding River

The design rainfall events were taken from the Flood Estimation Handbook (FEH). Furthermore, for all of the scenarios the summer rain profile specified in the FEH was used, given that the summer storms are more intense and are more likely to generate surface flooding, as compared to winter storms.

Scenario 4 was chosen as the base case in the Collaborative Modelling Exercise: i.e., it was used as reference to evaluate the performance of the different alternatives for flood risk management.

Table 5 provides a short explanation about the parameters chosen to create the above scenarios.

Table 5. Parameters chosen to create flood scenarios for the Cranbrook catchment.

PARAMETER	ADOPTED VALUE	RATIONALE
Return period or probability of occurrence	30 years (the probability of occurrence in any year is approximately 3 %) 200 years (the probability of occurrence in any year is approximately 3 %)	These are the return periods used for the “Flood Maps for Surface Water” (FMfSF), which have been recently produced by the Environment Agency. We wanted our scenarios to be comparable and compatible with the most recent UK regulations. The reason why these return periods were chosen to generate the new FMsSF is the following: The 30 year return period event is a more probable event, which is likely to produce inundation in the majority of urban areas of England and Wales. Furthermore, this return period is commonly used as standard for urban drainage design. The 200 year return period event corresponds to a rarer event, which enables testing a more critical condition.
Rain profile	Summer rain profile	Summer storms are more intense than winter storms and are more likely to generate surface flooding, which is the focus of this project.
Water level at the Roding River (at the downstream end of the Cranbrook catchment)	Low water level (0.00 m) High water level (5.86 m)	The Roding River is located in the downstream end of the Cranbrook catchment. When the water level at the Roding River is high, a backwater effect (water from the River entering the sewer system of the Cranbrook catchment) can take place, thus reducing the capacity of the drainage system and causing more critical surface flood events in Cranbrook. We picked two different water levels at the Roding River in order to understand the effect of the river on the behaviour of storm drainage system of the Cranbrook catchment. The high water level (5.86 m) was the level recorded during a major flood event in 2000.

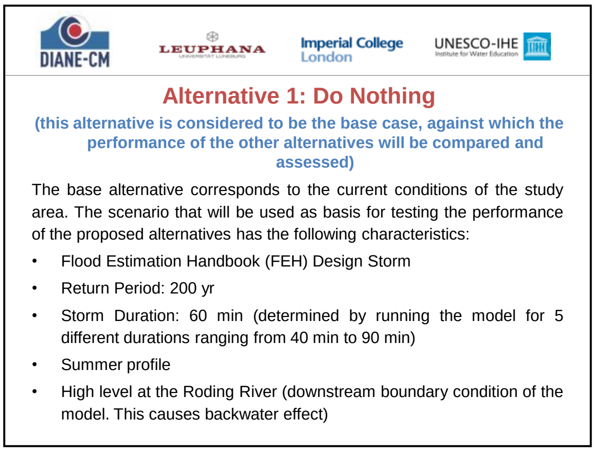
2.2.7 *Pluvial flood risk management measures considered in the Cranbrook catchment*

In the same way as was done for the Alster catchment, a set of potential alternatives for flood risk management was defined for the Cranbrook catchment. A preliminary set of alternatives was initially proposed based on its feasibility of implementation and the potential benefits they could bring to the Cranbrook area. The initially proposed alternatives were discussed amongst stakeholders during a collaborative workshop and based on the discussion the final set of alternatives to be considered in the *Collaborative Modelling Exercise* was defined. The total number of alternatives was kept to 5, in order to facilitate the execution of the *Collaborative Modelling Exercise*. It is worth mentioning that this is a first approach to the problem and that there are many more possible alternatives that could be implemented in the Cranbrook catchment. An overview of all the different measures that can be implemented to mitigate pluvial flood risk can be found in Annex F of the Surface Water Management Plan Technical Guidance (Defra, 2010).

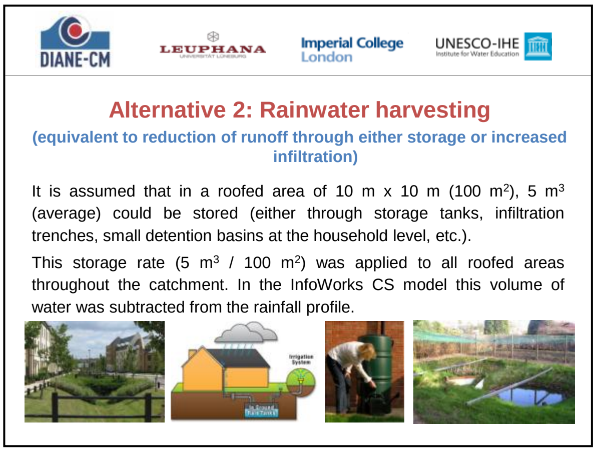
The selected alternatives for the Cranbrook catchment are summarised in Table 6. In addition, more details about the modelling aspects of each of the alternatives can be seen in Figure 11 (a) to (e).

Table 6. Proposed alternatives for flood risk management in the Cranbrook catchment.

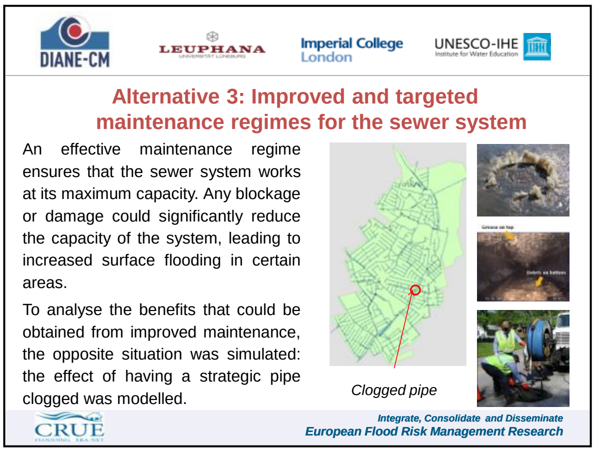
RISK MANAGEMENT MEASURE	TYPE OF MEASURE	DESCRIPTION
1- Do nothing	• Base case	Current situation. This will be used as base point for comparing and assessing the performance of the proposed measures.
2- Rainwater harvesting	• Mitigation measure at source level • Structural measure	It reduces runoff or flow entering the system. Rainwater harvesting has been selected as one of the few SUDS that can be retrofitted into the existing built-up area.
3- Improved and targeted maintenance regimes for the sewer system	• Mitigation measure at pathway level • Non-structural measure	After identifying locations which are at greatest risk of flooding, targeted maintenance at the critical points can be carried out.
4- Improved resistance for preventing water from entering properties	• Mitigation measure at receptor level • Non-structural measure	Resistance measures prevent water from entering the property. It is useful for managing residual risk. In this case, the effect of sandbags or *floodsaxs* placed at the household level was modelled and analysed.
5- Improved rainfall and flood forecasting and warning	• Mitigation measure at receptor level • Non-structural measure	With the technology we are currently developing, it will be possible to provide site-specific real-time rainfall and surface water flood forecast. This could be integrated with the Environment Agency warning system, so that improved warnings for surface flooding can be timely issued.



(a). Alternative 1 – Base Case

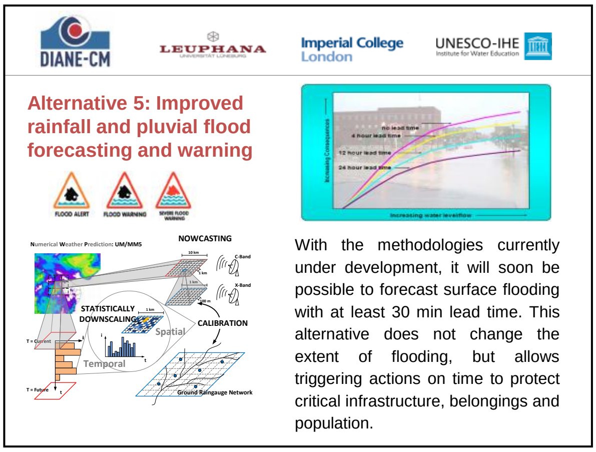


(b). Alternative 2 – Rainwater harvesting



(c). Alternative 3 – Improved maintenance

(d). Alternative 4 – Improved resistance at properties



(e). Alternative 5 – Improved pluvial rainfall forecasting and warning

Figure 11. Description of proposed alternatives for flood risk management in the Cranbrook catchment.

3 CREATION OF 1D-1D URBAN PLUVIAL FLOOD MODELS

As explained in Section 2.2.5, 1D-1D pluvial flood models comprise a 1D model of the overland network coupled with a 1D model of the sewer system. Although commercial software packages are capable of simulating the 1D flow over the surface, their methodology to estimate the overland flow assumes manual (hence subjective) definition of the surface flow paths, which is laborious and might lead to unreliable representations of surface flow processes (Maksimović *et al*., 2009). This is why the *AOFD* tool developed at Imperial College London constitutes a useful innovation.

In this section, the algorithm behind the *AOFD* tool is explained and basic instructions on the use of the tool are provided. Furthermore, the way in which the generated 1D model of the surface is imported into a hydraulic simulation software (in this case InfoWorks CS) and coupled with the 1D model of the sewer system is also described.

The information presented in this section is mainly a compilation of information included in the following documents, which were previously produced at the Urban Water Research Group:

- Maksimović Č. et al. (2009). Overland flow and pathway analysis for modelling of urban pluvial flooding. Journal of Hydraulic Research, 47 (4), 512-523.
- Leitão J.P. (2009). Automatic Overland Flow Delineation Tool – User's Manual (v1.0). Technical Report – Imperial College London.
- Boonya-aroonnet S., Leitão J.P. and Maksimović Č. (2007). UKWIR IUD Demonstration Project – Task 4: Produce 1D Surface Model. Technical report of the Flood Risk Management Research Consortium.

3.1 *AOFD* TOOL FOR CREATION OF 1D MODELS OF THE OVERLAND NETWORK

AOFD stands for Automatic Overland Flow Delineation. The *AOFD* tool is a GIS (Geographic Information Systems) tool which automatically analyses and generates 1D models of the overland network based on an accurate DEM (digital elevation model) of the study area. The 1D models generated with the *AOFD* tool 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) and can be easily coupled with 1D models of the sewer system, thus allowing for the creation of 1D-1D dual drainage models.

3.1.1 *Internal routines of the AOFD tool*

The steps that are internally executed within the *AOFD* tool in order to produce the 1D model of the overland network are illustrated in Figure 12. An explanation of each of the main steps of the algorithm is next provided.

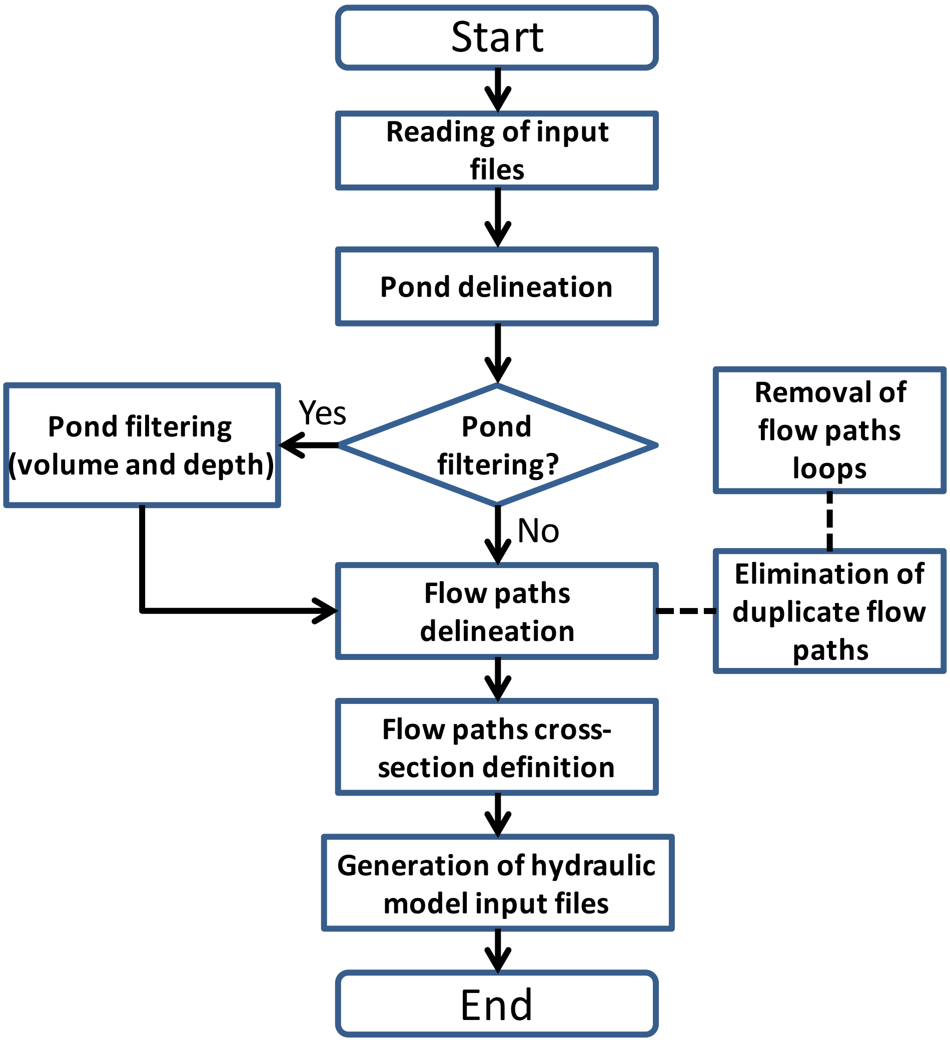


Figure 12. Internal routine of the *AOFD* tool (Leitão, 2009).

1. Reading of input files:

The first step of the algorithm is the reading of input files, which contain the information required to generate the 1D model of the overland network. The input files include: DEM, terrain slope and aspect, catchment boundary, buildings and manholes.

All files must be in IDRISI 16bit vector and/or raster format. Besides, a project file is also required, which summarises key characteristics of the area and of the input files to be used in the analysis. More information about the input files and instructions to prepare them are provided in Section **Error! eference source not found.**.

2. Pond delineation and filtering

Ponds correspond to local depressions where water is likely to be stored during a pluvial flood event.

Based on the DEM of the catchment, the ponds are identified and its storage capacity (i.e. depth-volume relationship) is quantified. The algorithm developed for this purpose searches the entire DEM and identifies the local points whose elevation is lower than that of the surrounding area. Based on the DEM, the pond boundary and storage volume for each low point is determined using an iterative "grow-up" routine. The "natural exit point" is identified as the termination criterion for the pond delineation (Figure 13). The "natural exit point" is the lowest point along the pond boundary and is the first location from which the water stored inside the pond would start to overflow. It acts as the starting point for the flood pathway over the catchment surface (Maksimović *et al*., 2009).

In most cases (even in small catchments), the initial number of identified ponds is huge and it is advisable to reduce the number of ponds (computational nodes) to an acceptable level. For this purpose, volume and depth thresholds can be defined by the user in order to filter out small depressions. This filtering routine removes some little ponds from the analysis (which satisfy both the depth and volume thresholds set by the user), but the DEM remains unchanged, thus preserving slope features required for the pathway delineation procedure. This approach is different from the standard "fill" method of the ArcGIS Toolbox, which fills all sinks (regardless of their size) with a user specified depth. In this way, little ponds (or pits) are removed, but the big ones also loose part of their storage capacity and the DEM is modified.

Moreover, at this stage it is also possible to remove those ponds located inside buildings. This particular case occurs if there are garden or roof storage features constructed inside the building perimeter. These storages can be removed and modelled instead as initial losses, but in this modelling approach these storages have no surface linkage to the overland drainage network. The location of the buildings is given by the building layer, which is part of the input data required to run the *AOFD* tool. The tool enables the user to choose whether to remove the ponds inside buildings or not.

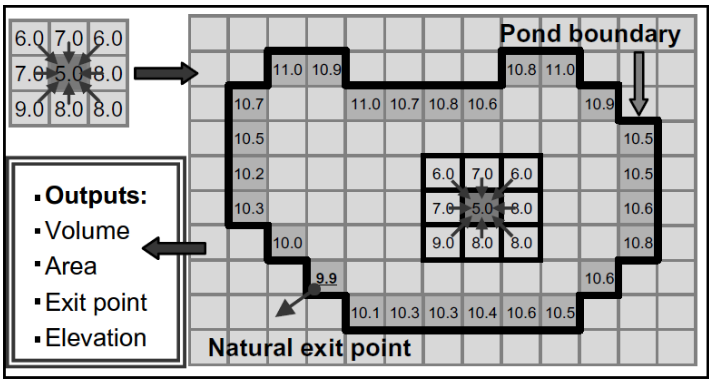


Figure 13. Pond delineation (numbers in cells correspond to elevations) - (Maksimović *et al*., 2009).

3. Flow path delineation (connectivity analysis)

In this step the connection between nodes (ponds previously delineated and manholes) is identified and the model of the overland network is completed by linking the nodes throughout the DEM.

The urban surface is a complex array of different types of permeable and impermeable surfaces, which typically include elements such as roadways and footpaths. These features are generally lower than the surrounding areas and can convey flow over significant distances, thus causing flooding to occur at locations that are far away from the source of the flood water. Overland flow accumulates in depressions and, once the depression is filled, it overtops and creates a surface flow. This flow may overflow directly to an adjacent depression (adjacent pond) or it may also flow along a connecting pathway until it enters another depression or the sewer network via a gully inlet or manhole. Alternatively, the flow could also leave the catchment, in which case the volume of water must be subtracted from the water balance of the catchment.

The connectivity algorithm used to delineate pathways was first developed by Prodanović within the AUDACIOUS project (Ashley *et al*., 2007). This algorithm is known as the “rolling ball” technique; it uses flow direction image to determine flow path to the next surrounding cell, thus tracing water path and delineating pathways. Starting at the natural exit points of the identified ponds or surcharged manholes, the algorithm determines pathways by preferential flow direction based on terrain slope, taking into account the presence of buildings and other features that are included in the DEM. In cases where the low resolution of the DEM prevents the rolling ball algorithm from capturing all relevant small features on the surface, the generated network of pathways may have to be enhanced manually.

The types of surface pathways that can be identified in this stage are the following:

- **i.** from pond to downstream pond (via pond link);
- **ii.** from pond to downstream manhole or gully;
- **iii.** from pond to out of the catchment;
- **iv.** spillway between two mutually connected ponds;
- **v.** from surcharged manhole to downstream manhole;
- **vi.** from surcharged manhole to downstream pond; and
- **vii.** from surcharged manhole to out of the catchment.

Figure 14 illustrates the concept of pathway delineation.

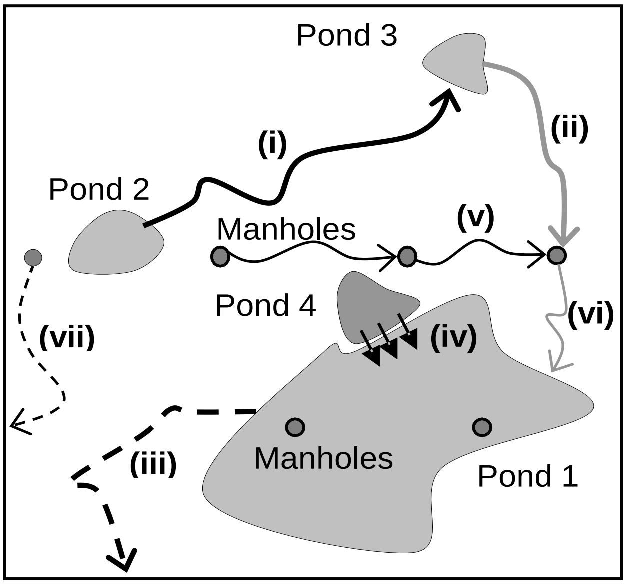


Figure 14. Concept of flow path delineation (Maksimović *et al*., 2009)

4. Estimation of pathway geometry and drainage capacity

In order to model surface flow through overland pathways (using 1D modelling approach), the following information is required:

- Geometry of the open channel
- Upstream/downstream elevations
- Roughness of the channel
- Actual length of the pathway (i.e. distance between two ponds or surface nodes).

The algorithm with which the above information is obtained is illustrated in Figure 15. This algorithm uses the previously extracted pathways (step 2 of the *AOFD* tool) and draws equi-distant cross-sections along each pathway length (Figure 15(b)). It then uses the surrounding DEM to estimate and average the areas of each cross-section (Figure 15(c)). Finally, the algorithm allows users to select the shape of the channel cross-section which can be either an arbitrary set of points (irregular shape) or trapezoidal (Figure 15(d)). If an arbitrary shape is selected, the algorithm will determine the average elevation of the entire pathway at each offset distance from the centreline (Figure 15(c)). If the trapezoidal shape is selected, the algorithm will compute the average flow areas at different depths along the length of each pathway (so called "stage-flow area" curve) and then will find the geometry of a trapezoidal shape that fits the stage-flow area curve. The calculation is done by recognising that the relation between flow area A and depth H of trapezoidal shape is quadratic. The channel's bottom width B and the slope of channel's sides 1/m are the unknowns to be calculated. Least-square for the polynomial regression is used to find these two unknown variables.

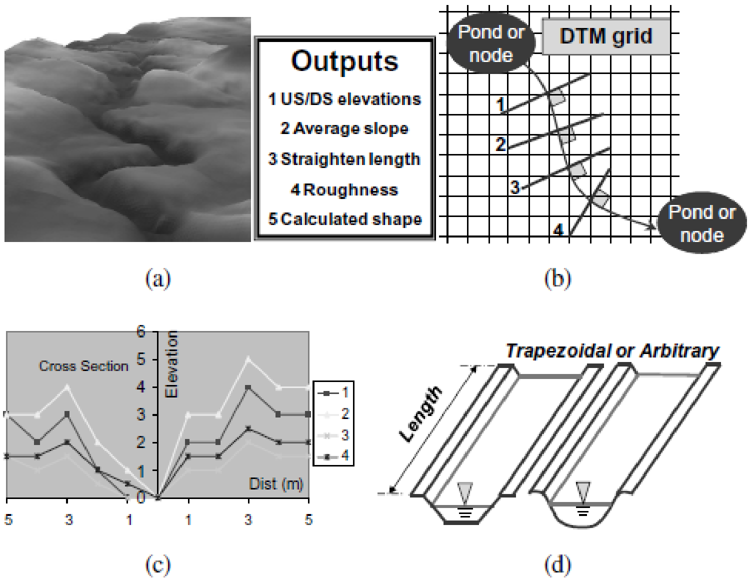


Figure 15. Estimation of pathway geometry and drainage capacity (a) 3D DEM showing identified flow path, (b) number of cross-section lines drawn perpendicularly to path, (c) arbitrary shapes of cross sections plotted as estimated from the DEM, and (d) averaged output with two choices: trapezoidal or arbitrary shapes. (Maksimović *et al*., 2009)

5. Creation of output files

After the aforementioned steps have been completed, the *AOFD* tool generates a set of ArcGIS shapefiles which comprise the elements required to set up the one-dimensional model of the surface flow network, including location, geometry and other hydraulic characteristics of the overland ponds and pathways. The shapefile format was chosen given that common software packages can interpret and import this file format.

3.1.2 *Preparation of input files for the AOFD tool*

The layers of information required to run the *AOFD* include:

- DEM (Digital Elevation Model)
- Terrain slope
- Terrain aspect
- Catchment boundary
- Cover layer
- Buildings
- Manholes

Each of the layers above may comprise more than one file. All files must be in IDRISI 16bit vector and/or raster format. The *AOFD* tool includes an interface to convert ESRI ASCii format files to IDRISI 16bit raster format files, and vice-versa. Also, it includes a tool to convert ESRI shapefile format to IDRISI 16bit vector format, and vice versa. Figure 16 shows the *AOFD* interface for format conversion.

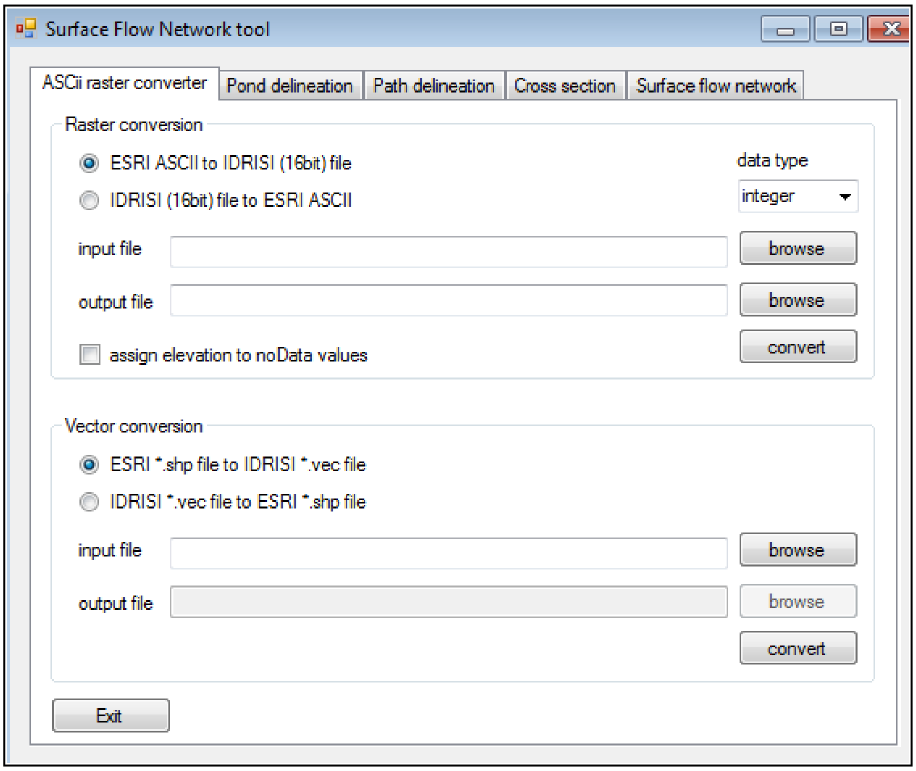


Figure 16. *AOFD* interface for file format conversion

In addition to these layers, a **project file** must be provided, which summarises key characteristics of the study area and of the input files to be used in the analysis. This file provides the main instructions required to run the *AOFD* tool.

Table 7 provides a summary of the input files, including their format, data type and a brief description.

Table 7. Summary of input files for the *AOFD* tool

INPUT DATA	FILE FORMAT (REQUIRED FILES)		DATA TYPE	DESCRIPTION/EXPLANATORY NOTES
DEM	IDRISI 16 bit Raster	*.doc, *.img	Double	Digital Elevation Model. It is important to represent the buildings in this file: the buildings must be given an elevation significantly higher than that of the boundary cells (this can be done by processing the DEM or DTM in a GIS software package)
SLOPE	IDRISI 16 bit Raster	*.doc, *.img	Double	Derived from the DTM. Can be generated with a GIS software package. The slope must be given in [m/m] (dimensionless)
ASPECT	IDRISI 16 bit Raster	*.doc, *.img	Double	Aspect is the direction in which a slop faces. It can be derived from the DTM and can be generated with a GIS software package
MANHOLES	IDRISI 16 bit Raster	*.doc, *.img	Integer	Manholes are represented by their ID. Cells representing catchment boundary = 0, outside catchment boundary = -1
	IDRISI 16 bit Vector	*.vec, *.dvc		
	Text	*.csv, *.ntt	Text (string)	Creates correspondance between the integer manhole IDs in the raster format file and the manhole IDs in the hydraulic model.
CATCHMENT BOUNDARY	IDRISI 16 bit Raster	*.doc, *.img	Integer	Cells outside catchment = 0, inside = 1
	IDRISI 16 bit Vector	*.vec, *.dvc		Polygon type, polygon ID = 1
COVER	IDRISI 16 bit Raster	*.doc, *.img	Integer	Copy of catchment boundary
	IDRISI 16 bit Vector	*.vec, *.dvc		
BUILDINGS	IDRISI 16 bit Raster	*.doc, *.img	Integer	Value inside buildings = 1, outside = 0
	IDRISI 16 bit Vector	*.vec, *.dvc		
PROJECT FILE	Text format	*.pro	Text	A template of this file must be provided by the AOFD developers. The user must edit this file manually in order to show the following: - Names of input files - Extent (coordinates, left, right, top and bottom) of study area - Elevation range (maximum and minimum "z" values) - Number of rows and columns of the input raster files - Cell size of the final grid (to match that of the raster layers)

NOTE 1: All raster files must have the same extent and cell size
NOTE 2: The structure of the manhole *.csv and *.ntt files is shown in Figure 17.

*.csv file

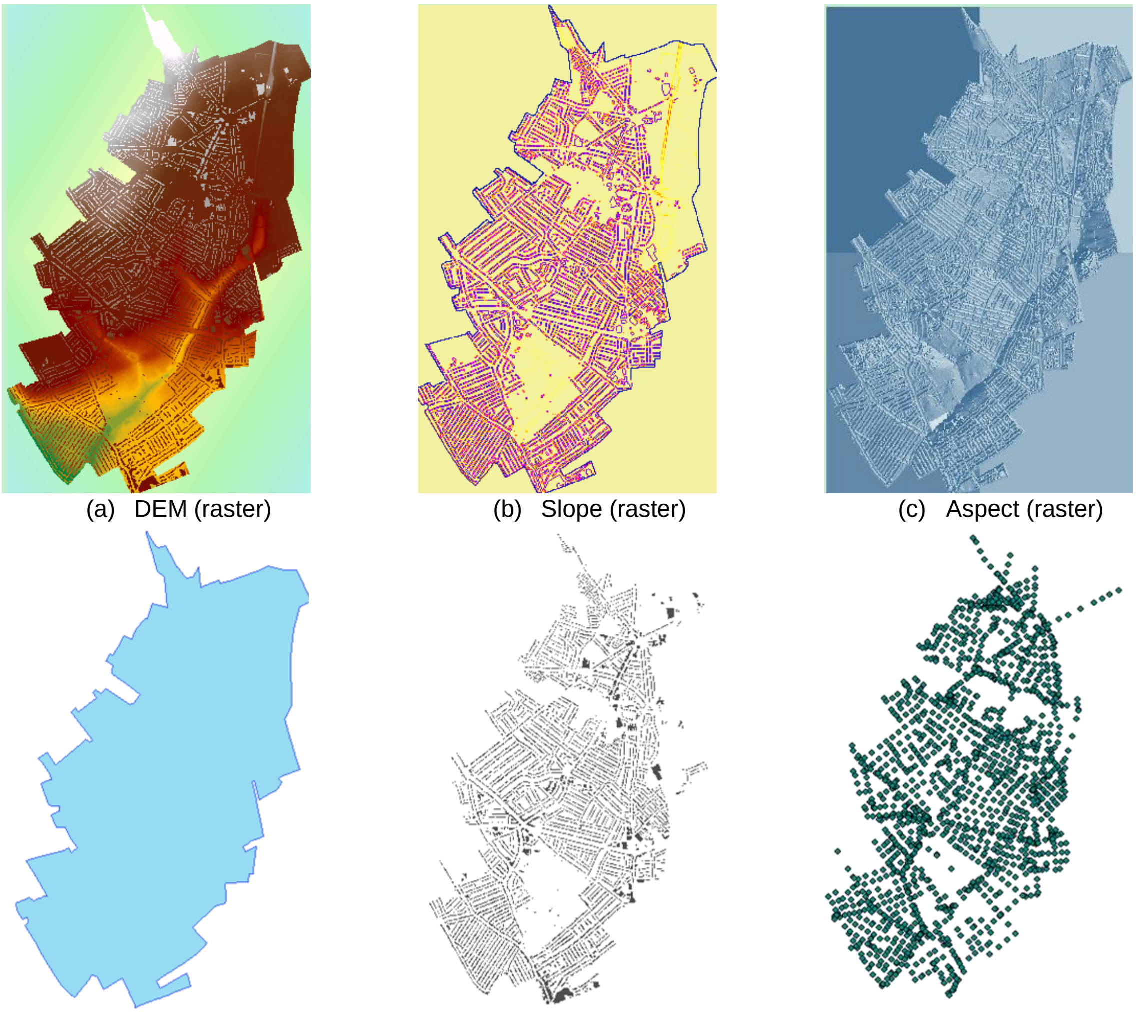
R_1	M_1
R_2	M_2
R_3	M_3
.	.
.	.
.	.
.	.
R_n	M_n

*.ntt file

R_1	M_1	FFFF	1
R_2	M_2	FFFF	1
R_3	M_3	FFFF	1
.	.	.	.
.	.	.	.
.	.	.	.
.	.	.	.
R_n	M_n	FFFF	1

Figure 17. Structure of *.csv and *.ntt manhole files (see file description in Table 7). R_i corresponds to the manhole ID in the raster and vector files and M_i is the corresponding manhole ID in the hydraulic model (e.g. InfoWorks CS). "n" is the number of manholes in the model.

Examples of some of the input files required to run the *AOFD* tool are shown in Figure 18. These examples correspond to the Cranbrook catchment (UK).



(a) DEM (raster) (b) Slope (raster) (c) Aspect (raster)

(d) Catchment boundary & cover (vector) (e) Buildings (vector) (f) Manholes (vector)

Figure 18. Examples of input files for *AOFD* tool

Once the aforementioned files have been prepared, they must be organised as follows:

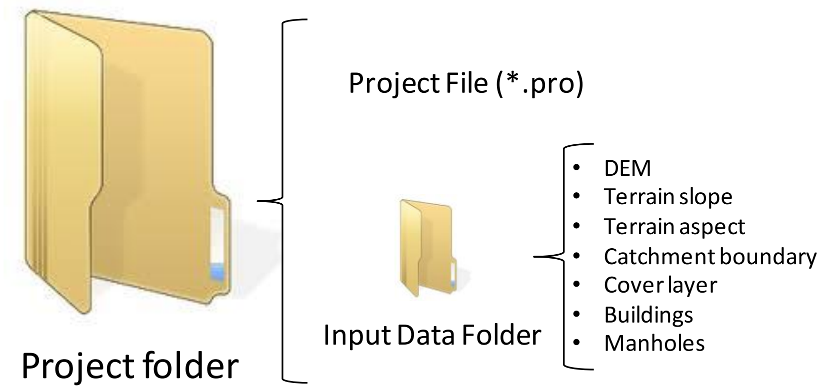


Figure 19. Organisation of input files

An example of the organisation of *AOFD* input files is shown in Figure 20.

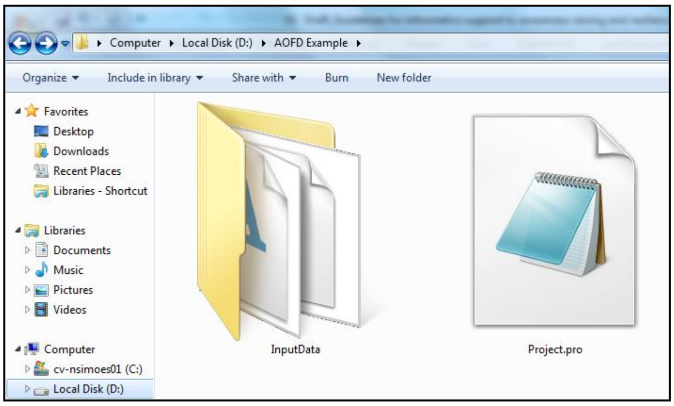


Figure 20. Example of organisation of *AOFD* input files

After preparing and organising the files, the *AOFD* tool can be executed.

3.1.3 Running the AOFD tool

The execution of the *AOFD* comprises 4 stages, for which of each there is a special tab where the user can select the parameters to be considered in the analysis. These 4 stages correspond to the internal routines described in section 3.1.1. The interfaces used for each stage are shown below.

It is worth noting that these stages must be completed in strict order, otherwise the execution of the tool may fail.

1. Pond delineation and filtering

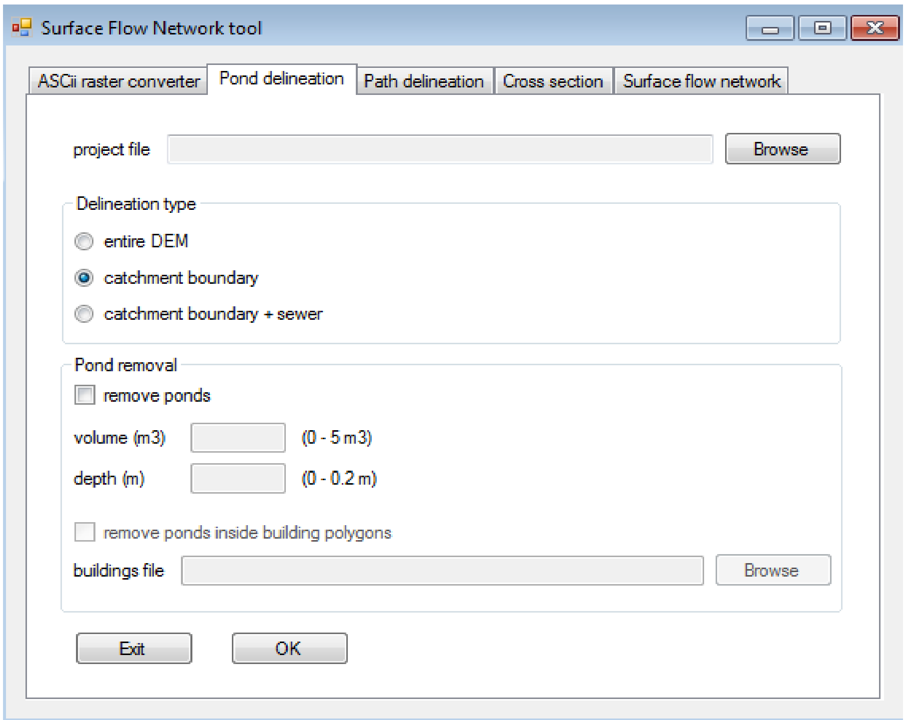


Figure 21. *AOFD* tab for pond delineation and filtering

2. Flow path delineation (connectivity analysis)

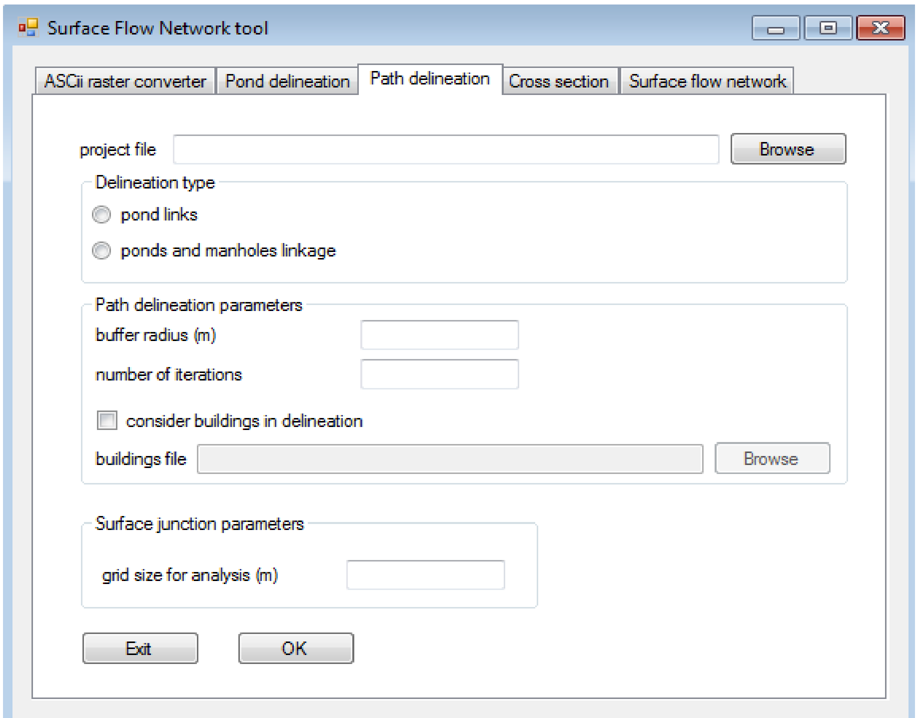


Figure 22. *AOFD* tab for flow path delineation

3. Estimation of pathway geometry and drainage capacity

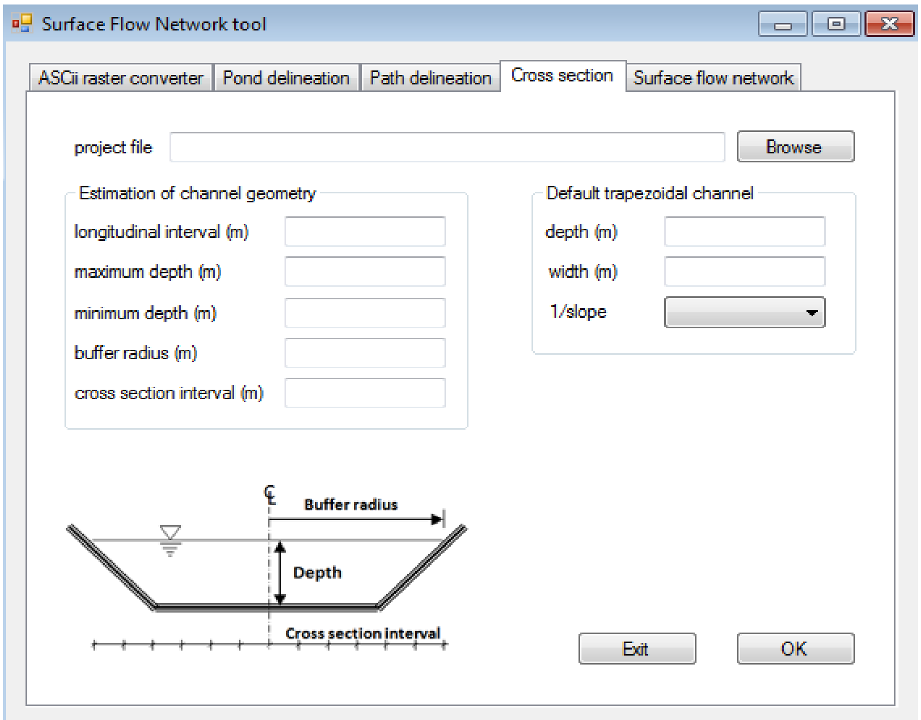


Figure 23. *AOFD* tab for cross section analysis

4. Creation of output files – generation of surface flow network

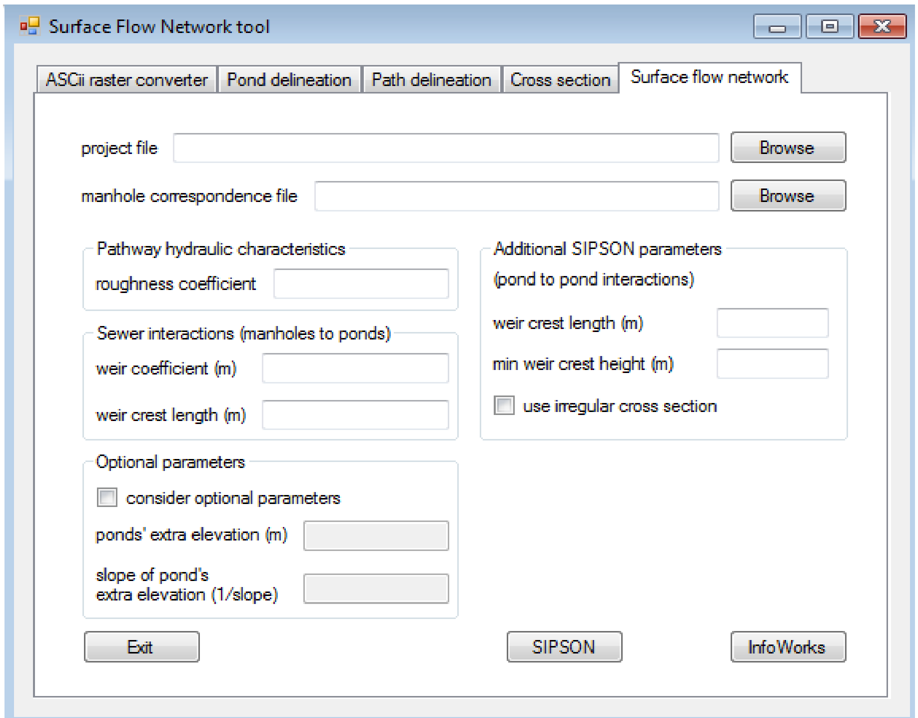


Figure 24. *AOFD* tab for creation of surface flow network

3.1.4 *Output files of the AOFD tool*

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) and can be easily coupled with 1D models of the sewer system, thus allowing for the creation of 1D-1D dual drainage models.

Figures 25-28 show examples of the output files generated by the *AOFD* tool. These examples correspond to the Cranbrook catchment (UK).

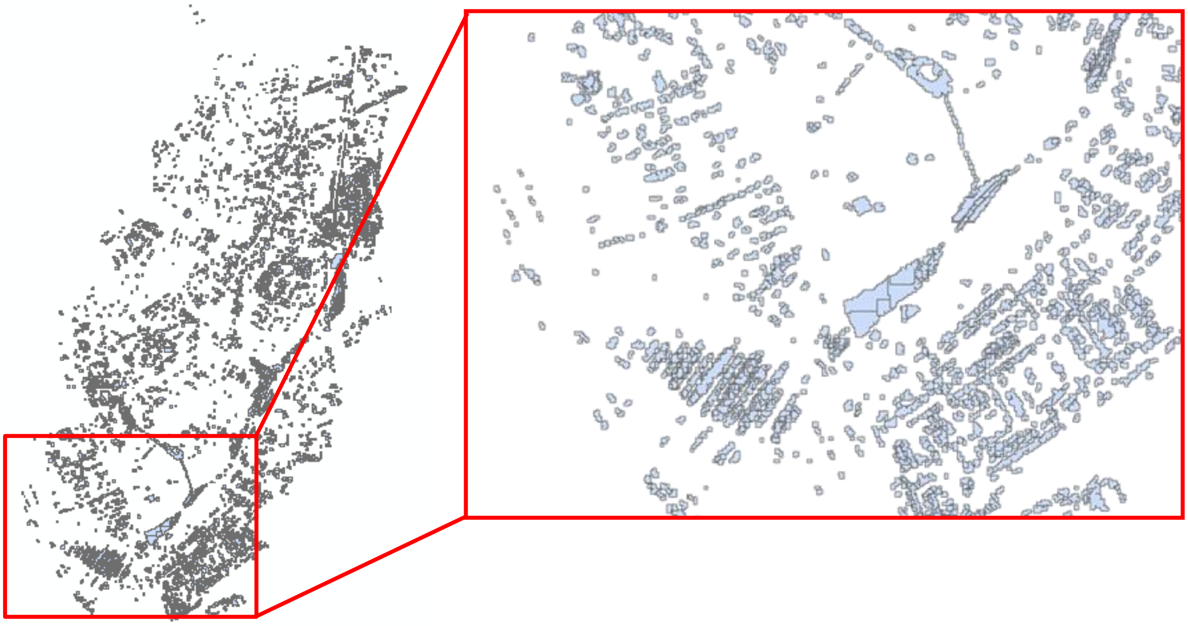


Figure 25. Surface ponds shapefile (polygon)

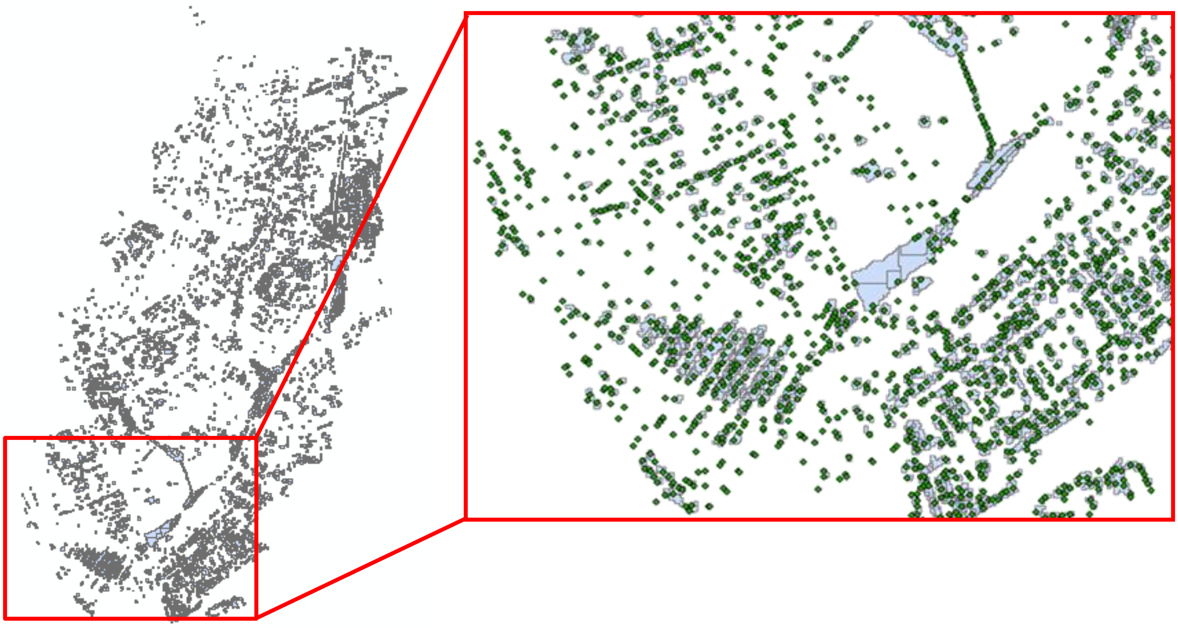


Figure 26. Surface nodes shapefile (point)

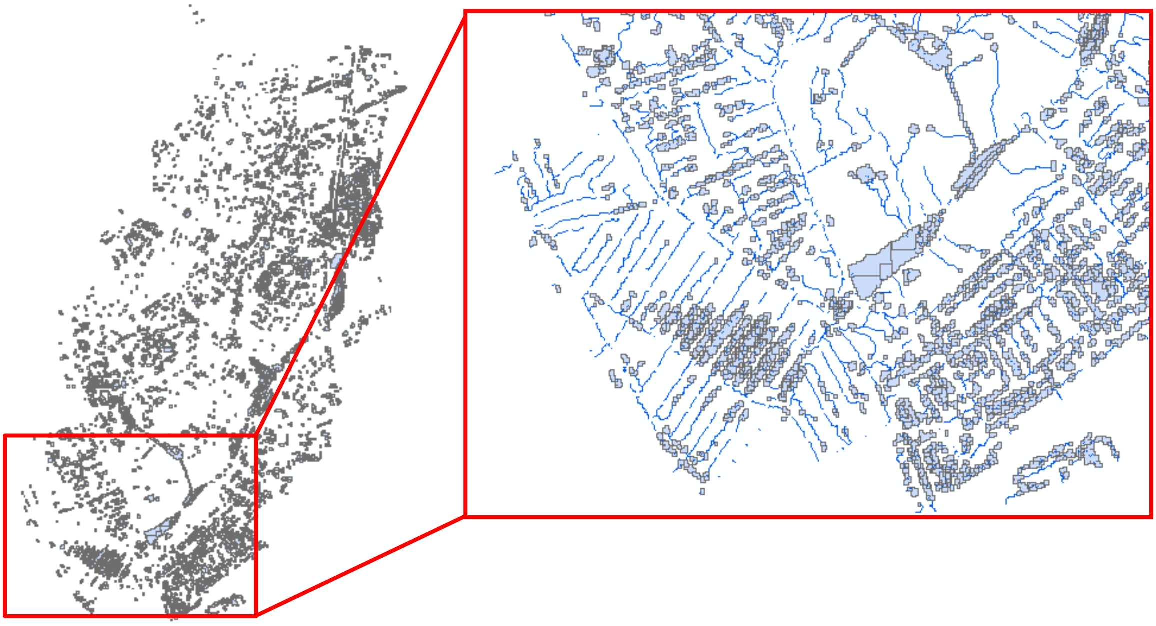
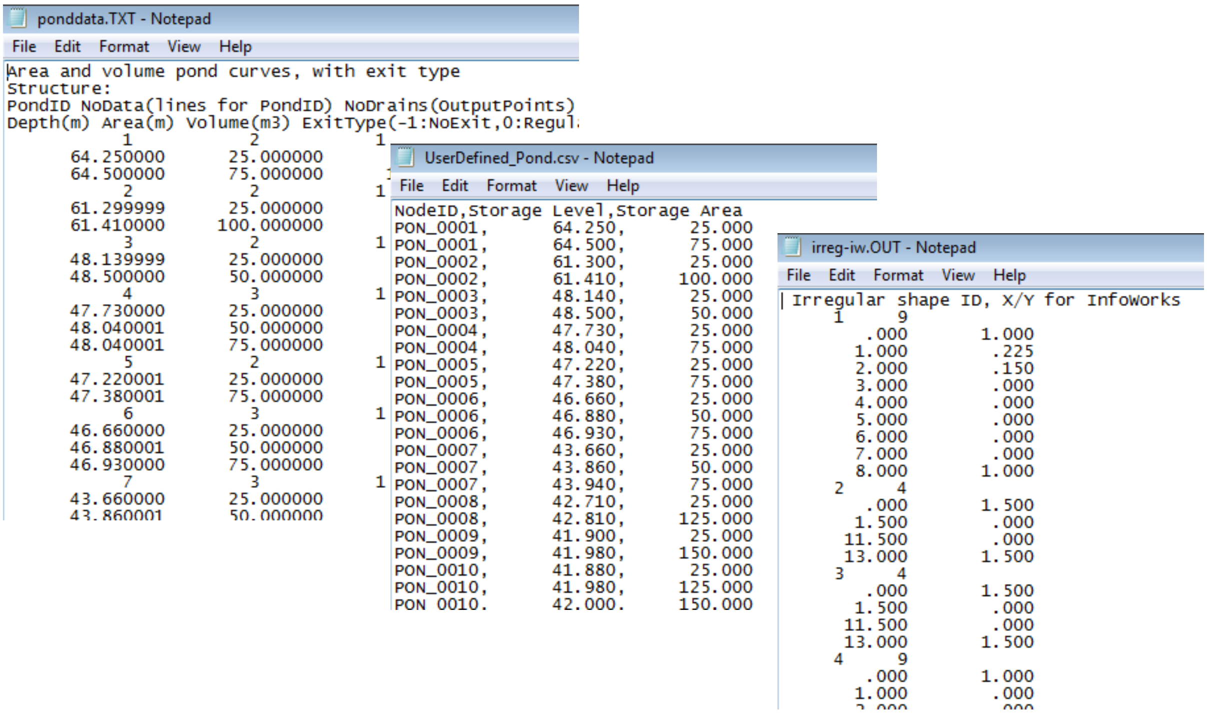


Figure 27. Overland pathways shapefile (line)



ponddata.TXT - Notepad

```
Area and volume pond curves, with exit type
Structure:
PondID NoData(lines for PondID) NoDrains(OutputPoints)
Depth(m) Area(m) Volume(m3) ExitType(-1:NoExit,0:Regul
       1          2          1
  64.250000   25.000000
  64.500000   75.000000
       2          2          1
  61.299999   25.000000
  61.410000  100.000000
       3          2          1
  48.139999   25.000000
  48.500000   50.000000
       4          3          1
  47.730000   25.000000
  48.040001   50.000000
  48.040001   75.000000
       5          2          1
  47.220001   25.000000
  47.380001   75.000000
       6          3          1
  46.660000   25.000000
  46.880001   50.000000
  46.930000   75.000000
       7          3          1
  43.660000   25.000000
  43.860001   50.000000
```

UserDefined_Pond.csv - Notepad

```
NodeID,Storage Level,Storage Area
PON_0001,     64.250,     25.000
PON_0001,     64.500,     75.000
PON_0002,     61.300,     25.000
PON_0002,     61.410,    100.000
PON_0003,     48.140,     25.000
PON_0003,     48.500,     50.000
PON_0004,     47.730,     25.000
PON_0004,     48.040,     75.000
PON_0005,     47.220,     25.000
PON_0005,     47.380,     75.000
PON_0006,     46.660,     25.000
PON_0006,     46.880,     50.000
PON_0006,     46.930,     75.000
PON_0007,     43.660,     25.000
PON_0007,     43.860,     50.000
PON_0007,     43.940,     75.000
PON_0008,     42.710,     25.000
PON_0008,     42.810,    125.000
PON_0009,     41.900,     25.000
PON_0009,     41.980,    150.000
PON_0010,     41.880,     25.000
PON_0010,     41.980,    125.000
PON_0010,     42.000,    150.000
```

irreg-iw.OUT - Notepad

```
| Irregular shape ID, X/Y for Infoworks
    1     9
       .000      1.000
      1.000       .225
      2.000       .150
      3.000       .000
      4.000       .000
      5.000       .000
      6.000       .000
      7.000       .000
      8.000      1.000
    2     4
       .000      1.500
      1.500       .000
     11.500       .000
     13.000      1.500
    3     4
       .000      1.500
      1.500       .000
     11.500       .000
     13.000      1.500
    4     9
       .000      1.000
      1.000       .000
```

Figure 28. Text files containing information about overland ponds and pathways

3.2 IMPORT OF 1D OVERLAND NETWORK MODEL INTO InfoWorks CS AND COUPLING WITH 1D MODEL OF THE SEWER NETWORK

In order to import the 1D model of the overland network (generated with the *AOFD* tool) into InfoWorks CS and couple it with a 1D model of the sewer network, the following steps must be followed:

1. Open and check out the model of the sewer network

2. Open the Data Import Centre (under the *Network* menu) (see Figure 29)

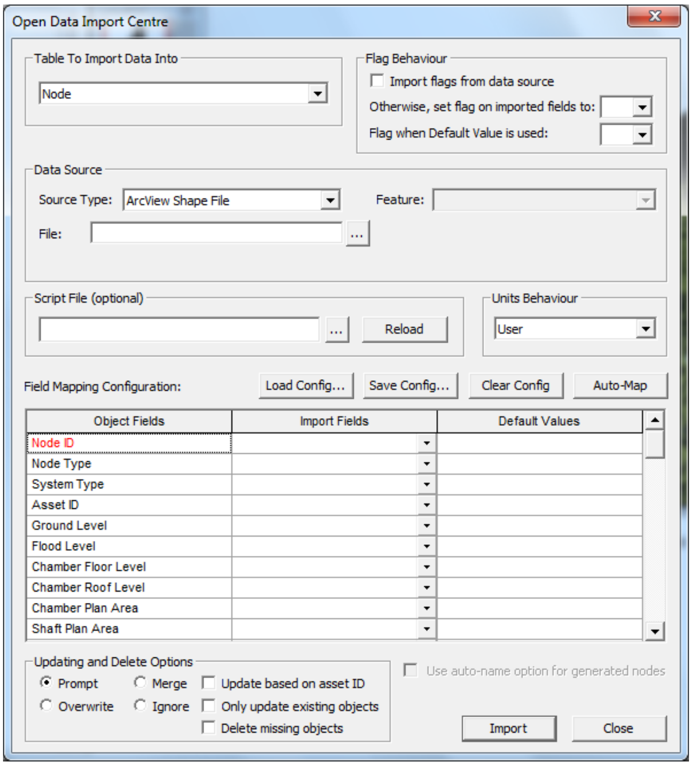


Figure 29. Data Import Centre – InfoWorks CS

3. Import the output files of the *AOFD* tool taking into account the tables and associated object fields indicated below:

i. Nodes (*.shp):

- NodeID
- Node type
- System type
- Ground level
- Flood level

ii. Conduit (*.shp):

- US nodeID
- Link suffix
- DS nodeID
- Link type
- System type
- Length
- Shape_ID
- Width
- Height
- Roughness type
- Bottom roughness
- Top roughness
- US invert level
- DS invert level

iii. Weir (*.shp):

- US nodeID
- Link suffix
- DS nodeID
- Link type
- System type
- Crest
- Width
- Height
- Discharge coefficient

iv. Storage level (*.csv)

v. Storage area (*.csv)

NOTES:

- The linkage between the overland and the sewer system takes place at the manholes. Provided that correct manhole files (see Table 7) were used in the execution of the AOFD tool, the connection between the two systems should be done automatically after importing the 1D shapefiles into InfoWorks CS, given that the overland pathways are connected to the manholes.
- The overland pathways and ponds (storage nodes) must be assigned an "overland system" type in InfoWorks CS. The distinguishing aspects of the overland system type are the following (MWH Soft, 2011):
  - Links are not included in the default calculation of manhole chamber and shaft sizes. This feature is important because if overland flow links are added to a previously verified model, manhole sizes should not change.
  - There is no numerical correction for overland flow links. Numerical correction is the InfoWorks CS utility for decreasing the size of manholes to account for the fact that the volume of storage in a model is greater than that which exists in reality due to the inclusion of the

'Preissmann slot'. Overland flow links are assumed to exist above the ground surface and therefore have no influence on manhole storage.

- The validation warning 'invert or soffit higher than ground level' does not apply to overland flow links.

- The DEM/DTM is the main input for the generation of the 1D model of the surface. Therefore, before the AOFD tool is executed, it is worth verifying the quality of the DTM/DEM and enhancing it. Details on this topic can be found in Leitão *et al*. (2009).
- Once the model has been setup, it must be checked by the modeller. If possible, existing flood records should be used to validate the performance of the resulting model and, when necessary, manual editing must be carried out. As with any other model, adequate catchment knowledge is crucial.
- For more details on the use of the AOFD tool and information about the performance of 1D/1D models, the user is refered to: Maksimović *et al*. (2009), Allit *et al*. (2009), Leandro *et al*. (2009), Simões *et al*. (2011b).

4 REFERENCES

Allit, R. (2001). Modelling FEH Storms. WaPUG Spring Meeting, 1st May 2001, UK.

Allitt, R. *et al*. (2009). Investigations into 1D-1D and 1D-2D urban flood modelling. WaPUG Autumn Conference. Blackpool, UK.

Ashley, R. *et al*. (2007). Adaptable Urban Drainage: Addressing Change in Intensity, Occurrence and Uncertainty of Stormwater (AUDACIOUS). Built Environment, 33(1): 70-84.

Boonya-aroonnet S., Leitão J.P. and Maksimović Č. (2007). UKWIR IUD Demonstration Project – Task 4: Produce 1D Surface Model. Technical report of the Flood Risk Management Research Consortium.

Butler, D. and Davies, J. (2011). Urban Drainage. Third Edition. Spon Press, UK.

Centre for Ecology and Hydrology (formerly the Institute of Hydrology). (1999). Flood Estimation Handbook. Wallingford, Oxfordshire, UK.

Defra. (2010). Surface Water Management Plan Technical Guidance, UK.

Djordjević, S. *et al*. (2005). SIPSON - Simulation of interaction between pipe flow and surface overland flow in networks. Water Sci. Technol., 52(5): 275-283.

MWH Soft (2011). Help File – InfoWorks CS V11.5. Wallingford, UK.

Leandro, J. (2008). Advanced Modelling of Flooding in Urban Areas - Integrated 1D/1D and 1D/2D Models. PhD Thesis, University of Exeter, Exeter, UK.

Leandro, J., *et al*. (2009). Comparison of 1D/1D and 1D/2D Coupled (Sewer/Surface) Hydraulic Models for Urban Flood Simulation. Journal of Hydraulic Engineering-Asce, 135(6): p. 495-504.

Leitão J.P. (2009). Automatic Overland Flow Delineation Tool – User's Manual (v1.0). Technical Report – Imperial College London.

Leitão, J.P., *et al*. (2009). The influence of digital elevation model resolution on overland flow networks for modelling urban pluvial flooding. Water Sci Technol 60(12): 3137-3149

Maksimović Č. *et al*. (2009). Overland flow and pathway analysis for modelling of urban pluvial flooding. Journal of Hydraulic Research, 47 (4), 512-523.

Simões, N.E. *et al*. (2011a). A methodology for urban flood forecast based on a network of raingauges, 12th International Conference on Urban Drainage, Porto Alegre, Brazil.

Simões, N.E. *et al*. (2011b). Urban drainage models for flood forecasting: 1D/1D, 1D/2D and hybrid models. International Conference on Urban Drainage. Porto Alegre, Brazil.

The UK Meteorological Office (2011). "Weather nowcasting" Retrieved June, 2011, from http://www.metoffice.gov.uk/learning/science/hours-ahead/nowcasting

Wang L. *et al*. (2011). Applications of high-resolution rainfall nowcasts to flood forecasting over urban areas. 12thInternational Conference on Environmental Science and Technology, 8-10 September 2011, Rhodes Island, Greece.

APPENDIX. Basic facts about pluvial flooding, 1D-1D models and the AOFD (Automatic Overland Flow Delineation) tool

A1. What is pluvial flooding?

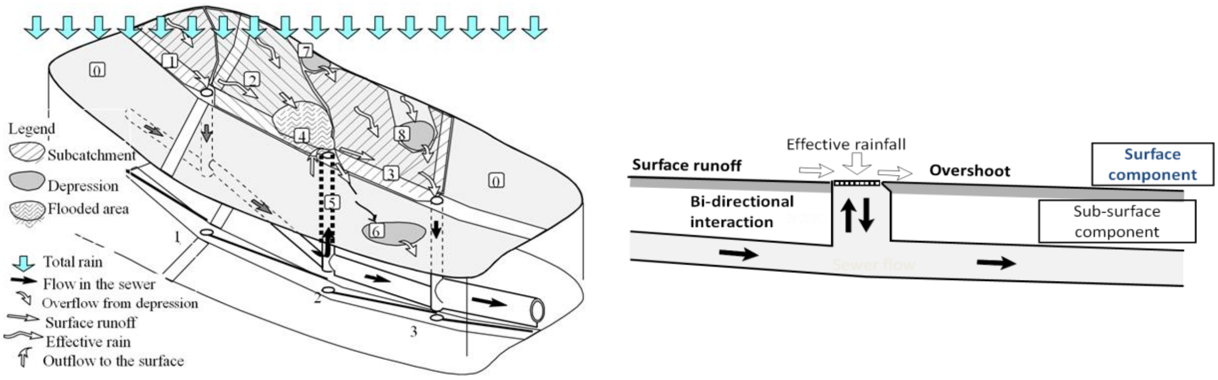
Flooding caused by intense rainfall, which exceeds the capacity of the installed drainage system. This type of flooding is typically localised and happens very quickly after the rain has fallen, making it difficult to give any warning. Predicting and pinpointing this type of flooding is much more difficult than doing so for river or coastal flooding.

A2. What is dual-drainage?

Dual-drainage refers to the interaction that takes place between the overland and the sewer networks when urban pluvial flooding occurs.

When extreme rain events take place over urban areas, rain initially falls on the surface (on the streets, roofs, parks, curbs, etc.) and flows along surface pathways until reaching a manhole or gully, from where it enters the sewer system. Water continues to enter the sewer system until the pipes reach their maximum capacity and the system surcharges (which happens quickly when extreme rainstorms take place). Once the sewers surcharge, water may eventually flow from the sewer system to the surface, thus becoming part of the surface or overland flow. After the end of the storm, pipes continue to drain water, they are not surcharged anymore and water from the surface can enter the sewer system again (through gullies).

This interaction between the overland and the sewer system is known as “dual-drainage concept” and it needs to be taken into account in the urban pluvial flood models. It is in fact the basis of the physically based models implemented throughout the DIANE-CM project. The “dual-drainage concept” is illustrated in Figure 30.



(a) (b)

Figure 30. Schematic representation of the process that take place in the overland and sewer network when surface flooding occurs. (a) showing all processes that take place on the surface; (b) simplified representation of the interaction between the overland and the sewer network.

A3. What is a 1D-1D pluvial flood model?

A 1D-1D pluvial flood model is a dual-drainage model in which both, the overland and the sewer networks are modelled in one dimension (1D). 1D models are made up of two basic types of elements: nodes and conduits, to which geometric and hydraulic properties are associated.

In the 1D model of the sewer system, manholes, outfalls, etc. are modelled as nodes and the pipes are modelled as conduits. In the case of the 1D model of the overland network, the ponds (i.e. depressions where water is likely to be stored during a flood event) are modelled as storage nodes and the pathways (i.e. the paths through which the water is likely to flow during a flood event) are modelled as conduits with specific geometry computed from the DTM. After coupling the 1D models of the overland and sewer networks, a 1D-1D dual drainage model is obtained (the interaction between the two systems takes place at the manholes).

A4. What is the difference between 1D-1D and 1D-2D pluvial flood models?

The table below summarises the main differences between the 1D-1D and the 1D-2D pluvial flood models.

Table 8. Summary of differences between 1D-1D and 1D-2D pluvial flood models

MODEL / PROPERTY	1D – 1D MODELS	1D – 2D MODELS
Models Structure	1D model of the sewer network + 1D model of the overland network	1D model of the sewer network + 2D model of the overland network
Detail and accuracy	Fairly accurate representation of the hydraulic processes that take place during pluvial flood events. However, less detail in the representation of flood extent.	Accurate representation of the hydraulic processes that take place during pluvial flood events. Greater detail in the representation of flood extent.
Computational time	Very short, suitable for real-time forecasting applications. ***For example:*** for a 9 km^2 catchment, the simulation of a 200 yr return period, 300 minute event takes 00:04:40.	Very long. Non suitable for real-time forecasting applications. ***For example:*** for a 9 km^2 catchment, the simulation of a 200 yr return period, 300 minute event takes 01:16:05.
Visualization of results	Poor, hard to understand for the general public	Good, easy to understand for the general public

A5. What is AOFD?

AOFD stands for Automatic Overland Flow Delineation. The *AOFD* is a GIS (Geographic Information Systems) tool which automatically analyses and generates 1D models of the overland network based on an accurate DEM (digital elevation model) of the study area. The 1D models generated with the *AOFD* tool 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.

The output of the *AOFD* tools is a set of shapefiles which constitute the 1D model of the overland network. These files can be imported into several hydraulic simulation software and can be easily coupled with 1D models of the sewer system, thus allowing for the creation of 1D-1D dual drainage models.

A6. Is the AOFD tool a hydraulic simulation software?

No. The *AODF* tool simply generates the 1D model of the overland network, but it does not carry out hydraulic simulations. This tool works independently from urban drainage models.