Combing the worlds of rural and urban hydrology

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Introduction

As an industry we are moving quite rapidly into an era when fully integrated catchment models are required as the various stakeholders involved in urban flood risk work together with data sharing and use of a single hydraulic model.

There have been considerable advances in the development of the mechanical aspects of creating models which have both sewers and watercourses and, in some cases, pluvial runoff. At the time of writing this paper the latest version of the "UDG River Data Collection Guide" has not been published but is likely to contain guidance on the physical data to enable watercourses to be modelled.

Combining rural (or fluvial) and urban hydrology methodologies in one hydraulic model is a concept which should also be well advanced and readily used, yet there is little or no guidance on how to approach this. There are well established methodologies for each hydrological approach (rural or urban), and each has their own individual industry standard guidance and best practice documentation, but there is nothing available for situations where there is both rural and urban sections in one catchment model. This may well be because it is an extremely complex subject and because the techniques are so different.

There is a considerable barrier between the realms of "Sewer Modelling" and "Fluvial Modelling" which is not only seen in the frequently confrontational relationships between the Water and Sewerage Companies (WaSCs) and the Environment Agency (EA), Natural Resources Wales (NRW) and the Scottish Environment Protection Agency (SEPA) but also within CIWEM which has separate special interest groups (UDG and Rivers and Coastal Group) for the respective disciplines.

The differences are also evident in the supply chain consultancies; those which supply services to both WaSCs and the EA/NRW/SEPA generally have separate teams usually working in 'silos' at different locations.

The Lead Author of this paper is from a fluvial hydrology background but is now working on integrated catchment models and is therefore able to understand and appreciate the benefits and pitfalls of both hydrological processes in the urban environment.

This paper is intended to provide some insight on how the two hydrological approaches can be employed in an integrated urban drainage model. Whilst this paper is being presented at a UDG conference it is hoped that fluvial modellers and fluvial hydrologists will find it of benefit and will offer a starting point from which guidance and discussions can stem.

This paper will use a case study based on a model Richard Allitt Associates (RAA) created for SEPA[1], to show how the hydrological approaches from the two different hydrological worlds can be combined successfully and

[1] The Royal HaskoningDHV and Richard Allitt Associates partnership was commissioned by SEPA.

used in a single hydraulic model to improve the quality and confidence of SEPA's Flood Hazard and Risk Maps in the town of Alloa in Clackmannanshire, Scotland.

Background

Urban flood risk has for a long time been seen as the province of 'Sewer' Modellers; this has stemmed from the original role of Local Authorities as Sewerage Authorities and then as agents for the Regional Water Authorities. It is worth remembering that the boundaries of the Regional Water Authorities were defined following river basin watersheds and all sewerage aspects within those areas became the responsibility of the Water Authorities but with no expertise, the Local Authority staff continued their role and importantly retained their local knowledge.

The rapid development of simulation software and the associated skill base was largely driven during the era when the Local Authorities acted as Agents for the Water Authorities. With the privatisation of the water industry and the creation of the Water and Sewerage Companies in England and Wales the skill base of urban drainage modelling generally remained with the WaSCs and their consultants. The arrangement in Scotland was slightly different and Scottish Water remains as a public body.

Traditionally, modelling of watercourses followed a different development route and timescale. Many people consider that the development of fluvial modelling and fluvial flood risk assessments originated from a series of reservoir disasters which prompted the development of the Flood Studies Report in 1974. Whilst the Regional Water Authorities created at the same time were given responsibilities for fluvial flood risk, this was generally undertaken by the River Authority Departments which worked as a separate entity from the departments dealing with sewerage. The Regional Water Authorities were required from their inception to keep the departments at arm's length from each other to avoid the potential conflict between 'Poacher' and 'Gamekeeper'. Eventually the River Authority departments were combined into a single entity; the "National Rivers Authority" which then became part of the Environment Agency.

The development of fluvial modelling software and expertise followed from the national and regional, rather than local responsibility for flood defence. This led to the assessment and modelling of longer lengths of watercourses which also led to the need for better hydrological inputs. In 1974 the Flood Studies Report was published which provided ground breaking techniques; this was followed by a series of 18 "Flood Studies Supplementary Reports" dealing with specific topics. In 1999 the "Flood Estimation Handbook" was published which represented another significant step change in fluvial hydrology, followed by the publication of the Revitalised Flood Hydrograph (ReFH) method in 2007 and its updated version (ReFH2) in 2016. In addition, in 2013, the FEH rainfall frequency models were also updated. With each significant change in approach and methodology, corresponding guidance and good practice reports were published for use in fluvial studies.

For sewer modelling the Wallingford Procedure was published in 1981; this was largely on the back of the work to develop the Flood Studies Report. The most important element of this was the ability to define local rainfall for different return periods; the use of FSR rainfall remains in use by some WaSCs. The FEH publication in 1999, and subsequent update in 2013, enabled better rainfall to be defined but this was based on fluvial catchments which does not always correlate with urban areas.

The different hydrology approaches are discussed below but a good over-riding definition of Hydrology is "*a multidisciplinary subject dealing with the occurrence, circulation and distribution of the waters of the earth*" (Shaw, 1983).

Urban Hydrology

The runoff from urban surfaces is generally rapid and only varies slightly between different rainfall events. The urban runoff surfaces are generally divided into three categories; paved areas, roof areas and permeable areas.

It is only the runoff from permeable surfaces which varies with different storms and also during storm events as the soil saturation varies.

The general principle behind sewer modelling was that because there was little variation between storms a model could be 'verified' against data from a short-term flow survey and then the model could be used with confidence for more extreme rainfall events.

It is also worth recognising that generally the WaSCs were only interested in storm events up to usually a 1 in 10 year return period and occasionally up to the 1 in 30 year return period.

There are a number of commonly used runoff methodologies in use in urban areas:

- The **Wallingford** runoff methodology though not widely used any more was introduced in the "Wallingford Procedure" which gave an average percentage runoff initially for the whole model and later for individual contributing areas. The percentage runoff (PR) was given by the "PR Equation" which had variables for soil type, annual rainfall and percentage impermeable (PIMP). At very low PIMP values this methodology gave problems which led to the "10-metre rule" being introduced. The percentage runoff using the Wallingford runoff methodology remains constant throughout the storm event and is identical for all storm events.
- The **Fixed** runoff methodology, as the name implies, has a fixed percentage runoff from all surfaces including the permeable surfaces. The percentage runoff from each surface can be set differently; paved and roof areas are frequently set at between 85% and 100% and permeable surfaces between 0% and approximately 35%. The percentage runoff remains constant throughout the storm event and is identical for all storm events.
- The **NewUK** runoff methodology (don't be fooled by the word 'New' as it was introduced in 1991) is the one most widely used in the UK. This works on the basis of fixed percentage runoff from paved areas and roofs but with a varying percentage runoff from permeable surfaces. There are only a very small number of variables which can be used to alter the runoff from the permeable surfaces both in terms of magnitude and duration. Because of the variable nature of the permeable runoff which can vary between storms the principle of 'model verification' no longer holds good and it becomes more of a 'model calibration' exercise. The common practice of verifying (or calibrating) the model for the whole period of the flow survey goes some way towards ensuring the models' suitability for a range of rainfall events. The principal drawback with this methodology is that when it is used with synthetic design storms it can sometimes lead to exceptionally large and false flooding volumes.
- The phenomenon known as "**Rainfall Induced Infiltration**" (RII) can either be caused by very slow surface runoff or by means of shallow groundwater responding to rainfall and infiltrating into the sewer. The exact process is not known, will never be fully known and varies considerably between catchments. Some catchments have sewers which return to baseflow within 12 hours whilst others can take up to 7 days. Modelling RII can be extremely difficult even when using the **Ground Infiltration Module** (GIM) which can be used in conjunction with the 'Fixed' runoff method or the 'New UK' method. The GIM is essentially a black box process which has multiple variables and it is a matter of juggling the variables until a suitable match is achieved. Using GIM is very much a calibration exercise rather than verification.
- The **UKWIR** runoff methodology was developed to overcome the problems associated with the 'New UK' method when simulating with synthetic design storms. This method uses more variables than the New UK method and using the HOST[2] soil classification rather than the WRAP[3] soil classification. This method has not yet gained widespread use in the UK but is gradually becoming more frequently used.
- The **ReFH**/**ReFH2** runoff methodology is used for large permeable areas either within the urban area (e.g. sports fields) or immediately adjacent to urban areas. The method is suitable for "small" areas (<0.5km^2)

[2] Hydrology of Soil Types
[3] Winter Rainfall Acceptance Potential

draining to small watercourses. It is not a suitable method for large watercourses. The section below on rural hydrology explains more how this method can be used.

Rural (Fluvial) Hydrology

The runoff from "rural" surfaces is generally considerably slower than from urban areas and varies significantly between different rainfall events and the return period of interest can be anywhere from a 2 year up to a 1000 year event.

For fluvial flood studies, industry standards and guidance (EA/DEFRA/SEPA) recommend that in most cases a hydrological analysis should be based on methods in the Flood Estimation Handbook (FEH). However, it is not as easy as just using the straightforward software; fluvial flood estimation is a complex process with many aspects. Which is why the industry guidance clearly states it is essential that "those carrying out the studies have the right knowledge, skills and experience"[4].

The current FEH provides two main approaches to flood frequency estimation:

- Statistical method
- Revitalised Flood Hydrograph (ReFH) rainfall runoff method

Statistical method

The Statistical method involves the construction of a flood frequency curve based on the estimation of the median annual maximum flood (QMED). This is the flood that is exceeded on average every other year and assumed to be the 2 year return period for a subject site. A growth curve is then used to derive design flows for other magnitude events as a function of QMED. It is important to note that the Statistical method only provides a peak flood flow, not a flood hydrograph. Full details of the Statistical method can be found in Volume 3 of the FEH[5].

Flood estimation from the statistical method depends on gauged data. The availability, quality and length of this data will determine whether the growth curve, and in turn the peak flow estimation, is based on a single site or pooling group analysis.

Single site analysis can be applied where there is a good quality gauge at the subject site and the length of record is twice the return period of interest, e.g. for a 100 year return period 200 years of data would be required at the site. Where this is not the case, which is more often than not, and for ungauged catchments, the recommendation is to pool data from groups of catchments, this is known as the *pooling group analysis*. The objective is to select gauged catchments that are hydrological similar to the subject catchment. WINFAP-FEH is the recommended software used for this approach.

ReFH

The ReFH method is a conceptual rainfall-runoff model that enables the user to generate peak flood flows and hydrographs for a given rainfall event on a catchment scale. ReFH can be used to model an observed event or to generate a design event input hydrograph.

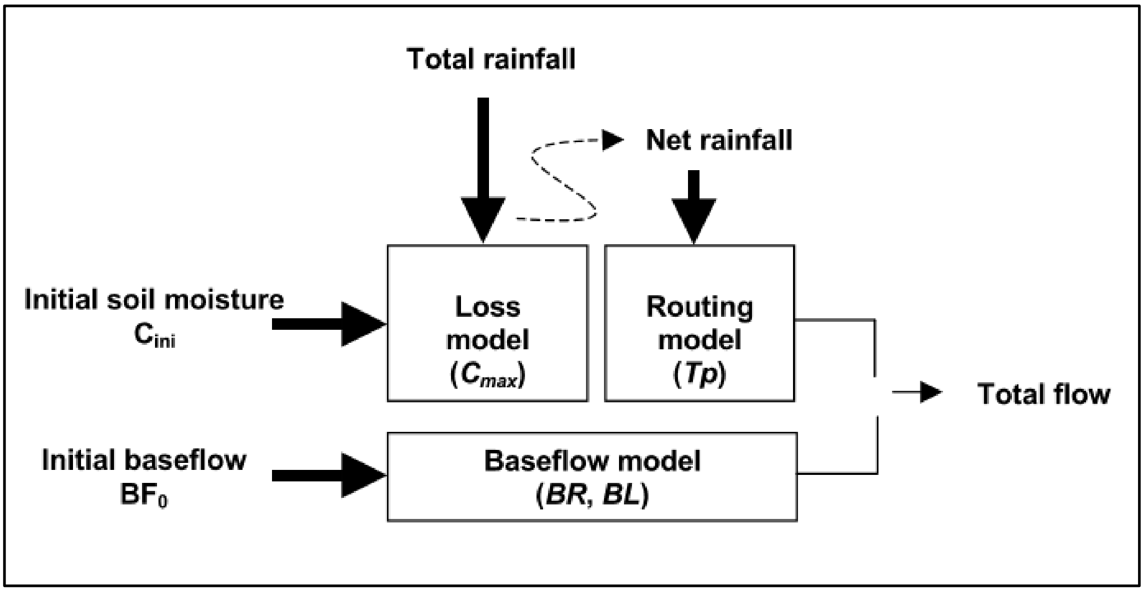
ReFH1 was published in 2005 and superseded the FSR/FEH rainfall-runoff method for majority of cases in England, Wales and Northern Ireland. ReFH1 was not considered suitable for use in Scotland due to the limited number of Scottish gauges and lack of Scottish calibration. In 2016 a new version - ReFH2 - was developed, which included improvements to the method that rendered it applicable for design flow estimation in Scotland and it also included an explicit representation of the influence of urbanisation through a new urban runoff generation module.

[4] Environment Agency (2015). Flood Estimation Guidelines – Technical guidance 197_08
[5] A. Robson & D. Reed (1999). Flood Estimation Handbook (Volume 3) – Statistical procedures for flood frequency estimation

The ReFH/ReFH2 model (see Figure 1) consists of three components:

- A loss model – using a soil moisture accounting approach to define the amount of rainfall occurring over the catchment that is converted to runoff
- Routing model – using a unit hydrograph concept
- Baseflow model – based on a linear reservoir concept

Figure 1 - Schematic representation of the ReFH model



Source: Wallingford HydroSolutions (2016). The Revitalised flood hydrograph Model ReFH2: Technical guidance

The ReFH rainfall runoff models are "lumped" hydrological models, which means they use a single unit to represent a catchment and model parameters values are averaged across the catchment. For a larger or varied catchment, a "distributed" approach may be required, where the catchment is split up and the design flows are routed from each sub-catchment. This is demonstrated in the case study later in the paper.

Catchment descriptors

Both FEH methods (Statistical and ReFH) require quantification of the physical and climatological properties of a catchment, otherwise known as catchment descriptors. The catchment descriptors alone can be used to derive the flood flow estimation at a site, but this would be considered the last resort approach. In an ideal world, hydrometric gauge data (flow and level) with a record length more than twice the target return period would be available for every fluvial flood risk study undertaken. Flood peak data is available at a large number of gauging stations through the UK, but for many of the sites where flood estimation is required there is no such data. Where a site is ungauged a transfer of data from a hydrologically similar site can be applied, using the catchment descriptors as a base.

The catchment descriptors provide useful information about the hydrological characteristics including area, slope, climate, soils, attenuation, length of drainage path and urban cover to name a few. They are digitally derived and either directly or indirectly based on the Institute of Hydrology Digital Terrain Model (IHDTM) and are available via the FEH Web service[6]. Because they are digitally derived, the catchment descriptors may not always be a true representation of the actual catchment. This is particularly true for low-lying or highly permeable catchments where it is often difficult to define the drainage networks. One of the first tasks a hydrologist must undertake is a

[6] https://fehweb.ceh.ac.uk/

check of these digital catchment descriptors against available data (LiDAR, soil and geology maps, OS mapping etc.).

Selecting a method

The choice of method is important and rarely straightforward and will depend on three main factors; the reason for the study, the type of catchment and the type or quality of data available. The choice of method can have a major influence on the results.

There are instances when one method may be preferred over the other, e.g. the Statistical method for catchments larger than 1000km^2 and the ReFH method for low-lying catchments or catchments with significant flood storage. The choice is not always clear cut and becomes more difficult when you might have a catchment greater than 1000km^2 with a reservoir in the upper reaches for example. Often a hydrologist will derive results using both methods and in doing so, additional information may emerge which can help the decision.

In some instances, a hybrid approach may be selected; a combination of both statistically derived peak flows and rainfall-runoff hydrographs. Again, there is no straightforward approach for the hybrid methodology, with at least four ways suggested by FEH guidelines and the choice will depend on several factors.

By its very nature fluvial flood estimation is an uncertain business and the FEH acknowledges that different users will obtain different results, by bringing different data and experiences. It is therefore up to the analyst to judge and justify when a flood estimate is good enough for the needs of the study. It is by no means just a 'click-a-button' exercise.

Critical Storm Durations

The process of identifying the critical storm duration for an urban (sewer system) catchment and that for a fluvial catchment is not too dissimilar. The critical duration is determined by a process of optimisation using a series of model simulations and selecting the duration which gives either the largest flood volume or peak flows at the critical area or area of interest.

The duration for the fluvial hydrology can also be estimated using a statistical equation, which provides a good starting point from which to start the optimisation. The difference in the critical duration for the two hydrological methods lies in the range. For most sewer systems the critical duration is in the range of 30 to 120 minutes. By contrast the critical storm duration in respect of fluvial hydrology is usually measured in hours rather than minutes and durations in excess of 6 hours are not uncommon. When we consider integrated catchment modelling we therefore need to pay particular attention to the critical duration.

The challenge

What happens when you have an integrated catchment study, that has a significant proportion of both urban and rural catchments? Urban and fluvial hydrology methods are clearly different in nearly every way you can think of as identified above. Each are governed by their own guidance and best practice. Should there be a way to unify the two methods? Or should we acknowledge the differences, recognise the amount of research and development that has gone into each and find a way of utilising both methods in one study? The case study below will aim to support the theory that we shouldn't actually be re-inventing the wheel but show how both methods can be utilised successfully in one hydraulic model.

Richard Allitt Associates Ltd
CONSULTING ENGINEERS

Case study – Brothie Burn, Alloa

The Royal HaskoningDHV and Richard Allitt Associates partnership were commissioned by SEPA to undertake the Brothie Burn, Alloa Modelling and Mapping Study.

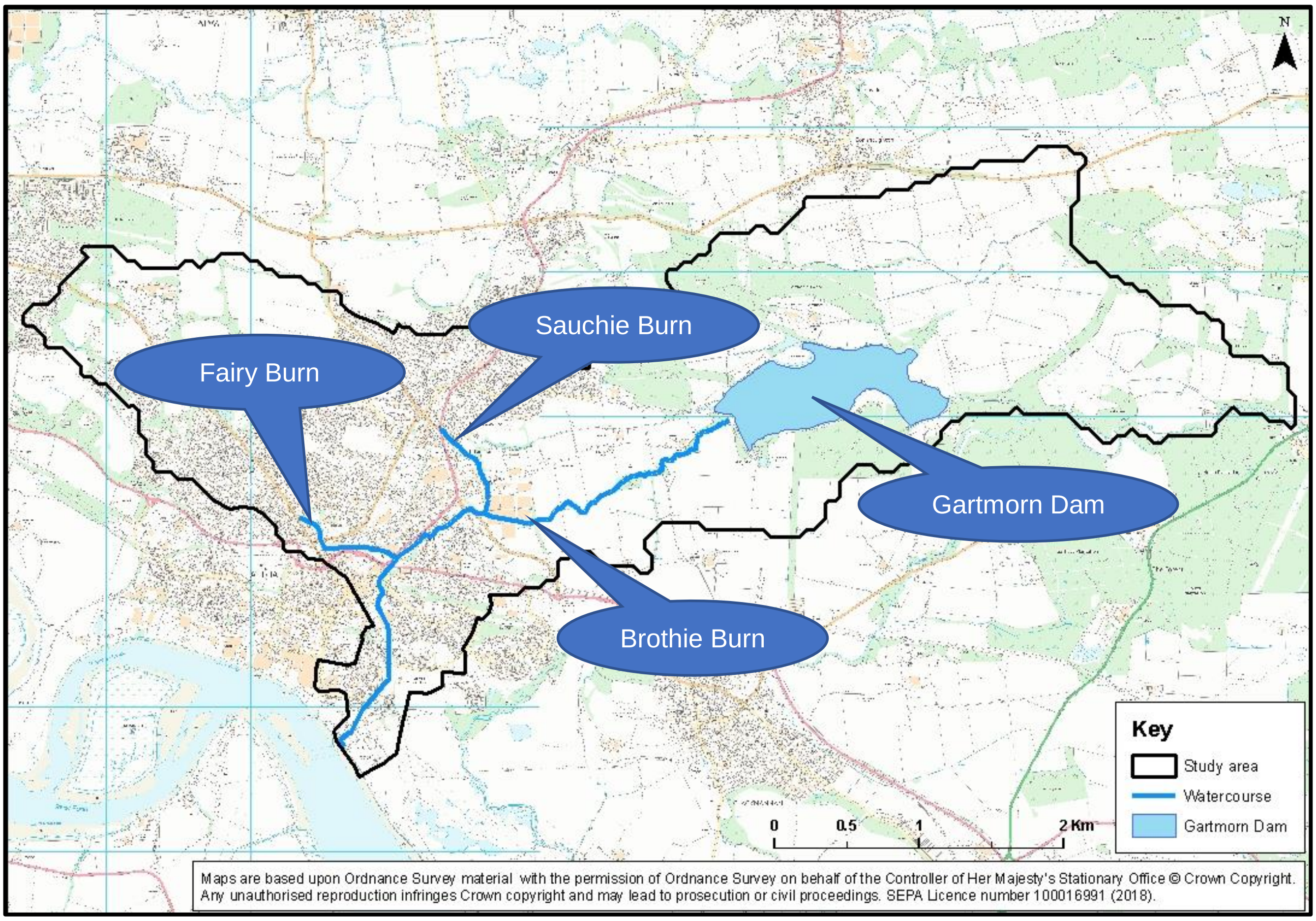
The overall aim of the project was to help improve the confidence in the representation of flood hazard within the Brothie Burn catchment, to gain a further understanding into the flooding mechanisms within Alloa and improve the quality and confidence of SEPA's Flood Hazard and Risk Maps for the Brothie Burn catchment.

Study area

The Brothie Burn catchment is situated in Clackmannanshire in the Central Lowlands of Scotland on the north bank of the River Forth. The burn flows in a generally south westerly direction from the Gartmorn Dam in the upper reaches, down through the town of Alloa before flowing into the River Forth near the sewage treatment works. Figure 2 shows the study area.

The Brothie Burn catchment is predominantly rural until the town of Alloa where the nature of the catchment becomes heavily urbanised. The Brothie Burn is joined by two tributaries, the Sauchie Burn and Fairy Burn, within the urban area, and then it flows in a long culverted section before it outfalls into the River Forth. At the downstream extent of the Brothie Burn the watercourse drains an area of approximately 14.5km^2.

Figure 2 - Brothie Burn study area



There is very little flood history information available for the catchment. There are also no hydrometric monitoring stations (flow, level or rain) within the Brothie Burn catchment.

Model build

The InfoWorks ICM program was used to develop a fully integrated 1D-2D coupled model. The open and culverted sections of the watercourses were modelled in 1D as were the parts of the sewer network within the modelled extents. There is a 2D mesh covering the whole study area and coupling between the 1D and 2D domains is achieved at the manholes (on the sewers and culverted watercourses) and along the bank lines of the open watercourses reaches.

An InfoWorks CS model was received from Scottish Water, converted into InfoWorks ICM and used to include the sewer network in the integrated model for the Brothie catchment. The sewer model covers a larger area than the Brothie Burn study area but includes all the foul and combined sewer network draining to the Alloa Sewage Treatment Works. All of the foul and combined sewers included in the Scottish Water model were retained in the integrated model.

The majority of Alloa is drained on a combined basis and there are several Combined Sewer Overflows (CSOs) throughout the catchment, some of which are a considerable size. The spill pipes from the CSOs are connected into the watercourses (open or culverted).

Although the main reason for the Brothie Burn study was to update the fluvial flood risk maps it was clear that there was a potential for significant inter-action between the watercourse and the sewer system via the CSOs in the network. Several of the CSOs have large diameter spill pipes and could either contribute significant flows into the watercourse or conversely could be inhibited from operating to relieve the surcharge in the sewer system. Both of these potential inter-actions could have a profound effect on the extent and mechanism of flooding. Because of the need to understand this possible inter-action it was decided that the Scottish Water sewer model should be included in a fully integrated model for Alloa.

Hydrological inputs

The hydraulic modelling approach used, which although had its own individual challenges and complexities, was relatively straightforward and followed recognised industry methodologies to develop a fully integrated 1D-2D linked InfoWorks model.

The Brothie Burn required a formal hydrological approach for the study, which needed to be signed off by SEPA prior to commencing the baseline modelling.

Given the nature of the catchment, the modelling approach, the aims and objectives of the study and the hydrological background of the lead author, it became apparent that neither urban or fluvial hydrology methods were appropriate by themselves. The hydrological inflows into the model were therefore estimated using a combination of the urban and fluvial methodologies discussed earlier. Applying the best practice and guidance from each approach as required. Figure 3 and Table 1 below show where the different methodologies have been applied for each of the tributaries modelled.

Figure 3 - Hydrological methodologies

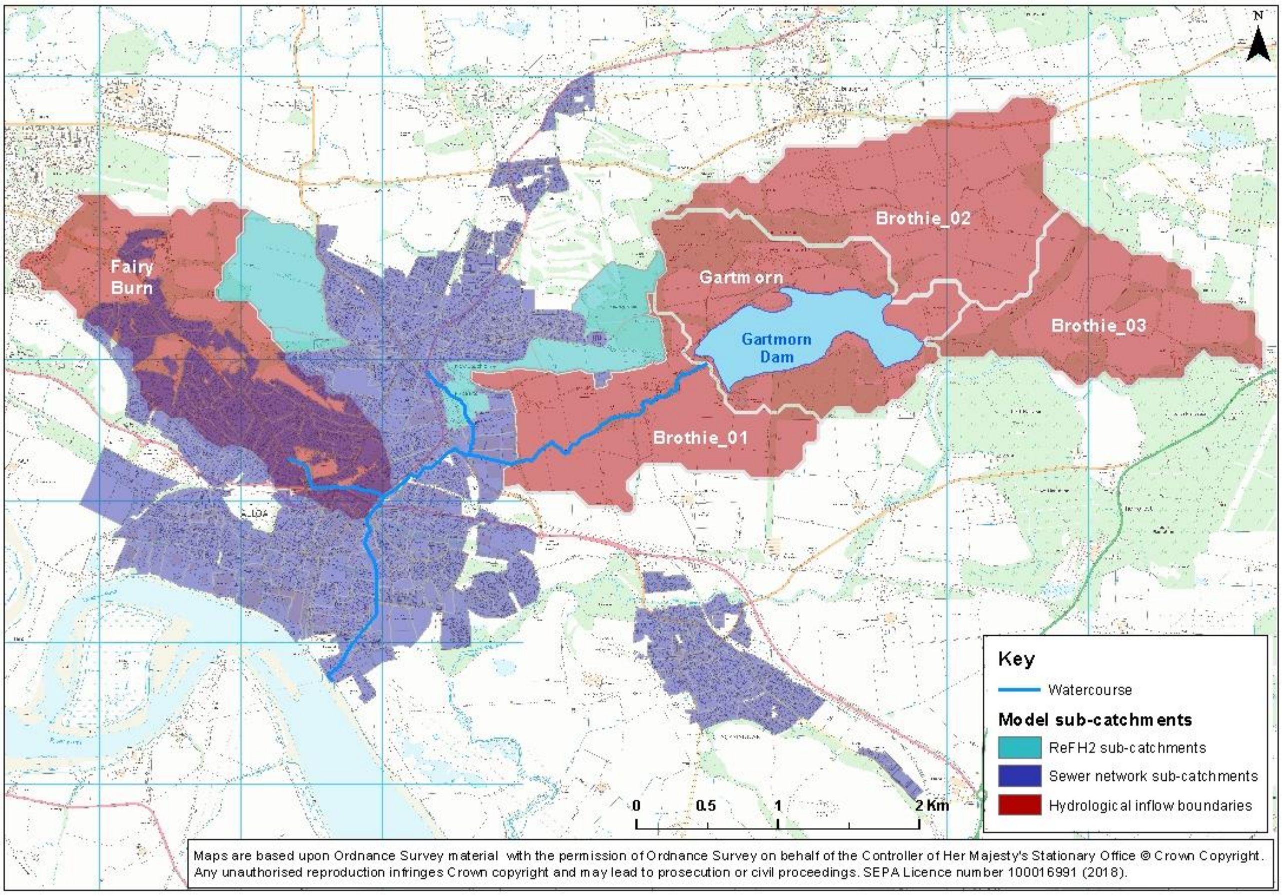


Table 1 - Hydrological method applied

Watercourse/ modelled sub-catchment	Hydrological method applied			
	Urban (fixed/NewUK)	ReFH2 (sub-catchment)	Fluvial inflow hydrographs	2D mesh
Brothie Burn	✓		✓	
Sauchie Burn	✓	✓		
Fairy Burn	✓		✓	
Gartmorn Dam				✓

The Brothie_02, Brothie_03 and Gartmorn fluvial hydrograph inflows were input into the model at the upstream extent of the reservoir and routed through the reservoir in the model. Brothie_01 fluvial hydrograph inflows were input at the downstream extent of the reservoir.

The upstream extents of the Sauchie Burn were modelled using ReFH2 sub-catchments in the InfoWorks model and the remainder modelled through urban rainfall-runoff sub-catchments.

The Fairy Burn tributary used a combination of FEH inflow hydrographs for the rural parts and urban rainfall runoff for the urban sub-catchments (Fixed and NewUK).

Gartmorn Dam

Gartmorn Dam, covering a surface area of approximately 0.6km^2, is located at the upstream extent of the model. The reservoir was included in the InfoWorks model as a 2D mesh zone and an infiltration zone to allow for the potential storage and attenuation offered to be incorporated in the model.

Rainfall on the reservoir waterbody was taken into account in the modelling software by applying 100% runoff. The reservoir (surface area and attenuation) was therefore not included in the fluvial hydrological analysis to avoid double counting of the reservoir effects.

Fluvial hydrology sub-catchments

The choice of method, statistical or ReFH2 rainfall runoff, was not an obvious one for the Brothie Burn catchment. The factors taken into consideration were:

- The presence of the reservoir
- The lack of hydrometric data in the catchment (the catchment is ungauged)
- The size of the catchment (<25km^2)
- Hydrographs were required for the hydraulic model
- Lack of historical flood information
- Catchment geology – impermeable in nature

Neither method stood out as the preferred one in this instance. Brothie Burn was a classic case where both methods should be carried out before a decision is made. This is the approach that was taken.

A pooling group was derived, pooling data from stations with hydrologically similar catchments to the Brothie Burn, and peak flows for all return periods estimated. Hydrographs were produced for each of the locations using the ReFH2 rainfall runoff methodology and a hybrid approach of fitting the hydrographs to the statistical peaks was selected as the preferred approach.

Critical durations

Following several rounds of hydraulic modelling the critical duration identified for the urban areas of the model was found to be substantially shorter than the critical duration identified for the fluvial sections of the model. The hydrological inputs for both durations were run in the model and flood outlines and depths produced for both situations. A simple GIS exercise was used to stamp the two results together to produce the “worst-case” flood risk outline for the Brothie Burn catchment. In this example, and for other integrated catchments with similar characteristics, it did not matter that two durations were identified as ‘critical’. A single flood risk map can still be produced showing the flood risk to a catchment for the range of return periods required (2yr up to and including a 1000 year).

Results

For the Brothie Burn catchment, which included a main river and two tributaries, reservoir, large section of culverted watercourse and an urban area largely drained by a combined sewer system, a complex jigsaw of individually recognised hydrological methods was used across the catchment. This was made possible by using the sophisticated InfoWorks ICM software which allowed the most suitable hydrological method, following the relevant industry guidance, to be selected for each of the sections of the catchment and input to the model where appropriate. The was no need to try and use methods that are deemed unsuitable for certain catchment types.

Conclusions and Recommendations

From our experiences on the Brothie Burn project and others like it, it has been possible to draw some conclusions on the best way forward in respect of the hydrology for integrated catchment studies.

We have concluded that the traditional approaches to urban and fluvial hydrology can satisfactorily be used in the same model as long as the guidance and best practice from each method is followed. The capabilities of the modelling software make this possible and therefore it is not necessary to re-invent the wheel where rural and urban hydrology methods are concerned.

From this work we have made the following recommendations:

1) For models which have a large river (which in England and Wales would be classed as "Main River") the inflows should be in the form of inflow hydrographs which should be derived by (or supervised by) a person who has had formal hydrological training;

2) For models which have one or more smaller watercourses (which in England and Wales would be classed as "Ordinary Watercourses") the inflow can be created within the model by contributing areas using the ReFH2 runoff methodology provided that (a) the contributing area does not exceed $0.5km^2$, (b) there is a reasonable correlation between the shape and extent of the contributing area when compared with the catchment area defined using the FEH web-service [if not the involvement of a trained hydrologist will be required] and (c) the contributing area does not have a high percentage of woodland;

3) Careful consideration needs to be given to the durations of the rainfall and any inflow hydrographs. The relative timing of the peak flows in the sewers and watercourses (when using inflow hydrographs) will be important; coincident peaks will give the worst case but may not be a realistic representation of the flood risk.

Thanks and acknowledgements

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