Integrated catchment modelling: an application of the ReFH2 runoff model

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1 Introduction

Integrated urban drainage can be defined as "an approach to planning or managing an urban drainage system which leads to an understanding of how different physical components interact and how different organisations must work together for it to operate effectively" (WaPUG, 2009). This highlights the importance of analysing how different components of urban drainage, such as the sewerage network, watercourses, sea and groundwater, interact and how they should be carefully considered for understanding the risk of flooding.

In this context, Scottish Water appointed RPS as part of their ARC Joint Venture to undertake an Integrated Catchment Study (ICS) for the Inverness catchment. The major aim of the project was to improve the knowledge regarding the interactions between the below ground and above ground drainage networks (sewers and watercourses) and provide a fuller understanding of the flooding sources and mechanisms across the catchment. The aim was to create an appropriate modelling tool that can be used in the development of solutions to reduce flood risk from the urban drainage systems, including where there are interactions.

2 Catchment overview

The Inverness catchment area is comprised of the City of Inverness and the surrounding residential areas. The catchment lies on the coast of Beauly Firth and Moray Firth which discharge to the North Sea and encompasses an area of approximately 3,075ha, with a modelled population of 72,570.

The major watercourse within the catchment is the River Ness which flows through the city centre and has several tributaries that vary in size and contribute flow over this length, the largest being the Ault na Skiah located in the southern side of the catchment.

The modelling approach followed for this project was to upgrade the existing sewer model to the current catchment conditions, including integration of the ground model, local watercourses and coastal stretches with the sewer network where required. The model was built using InfoWorks ICM 8.5 and was updated with manhole, outfall, ancillary and watercourse surveys undertaken as part of the study at key locations.

Surveys had been selected in strategic areas of the network. The verification was undertaken against 27 flow and 26 depth monitors installed at both sewer and watercourse locations as part of a three months flow survey. A total of 18 depth only monitors were installed in watercourses.

3 Modelling methodology

Within integrated models, watercourses and associated rural hydrology can be represented within the 1D environment, whereby the watercourses are represented by river reaches which can be subsequently linked to the 2D environment. Alternatively, watercourses can be represented solely within the 2D environment, involving the local improvement of the DTM based on topographical watercourse cross-sectional surveys. In the case of Inverness ICS, the watercourses were represented as 1D river reaches, with the contribution from rural areas represented via subcatchments that were point loaded along the reaches utilising the ReFH2 runoff model.

Using river reaches has the potential to create instabilities within the model, in particular when oscillating flow to and from the river banks is generated. However, using 1D river reaches and ReFH2 subcatchments reduced the overall number of 2D elements and in particular the number of wet elements. This generally improves the simulation times and reduces the need for long 2D meshing times. Furthermore, the 1D approach allowed for a better calibration of the generated rural runoff via the ReFH2 model, whereas similar calibrations could not be achieved in a fully 2D environment, with rainfall applied directly onto the mesh.

Another drawback when representing the watercourses as purely 2D features is the need for a high-resolution DTM which is not always available. Additionally, there is often the need to manually adjust areas with poor DTM data, which otherwise would cause unrealistic cross-section restrictions and consequent flooding. The 2D approach can also generate instabilities at the transition from the 2D to the 1D environment (and vice versa), for instance around culverts and bridges which are represented as 1D links. These instabilities are usually associated with the 2D element assigned to the outfall 2D not being big enough to transfer the required volumes between the two environments.

Within the Inverness model, the river reaches were built using data from cross-section surveys undertaken at strategic points throughout the catchment. Previous HEC-RAS and ISIS river models were also analysed to identify all suitable data to be incorporated in the ICM model. River reaches were subsequently connected to other reaches as well as to the sewer network outfalls via break nodes. In some instances, open trapezoidal channels were used to represent small ditches connecting storm outfalls to the main watercourses. Manning's roughness values were assigned to the cross-sections after Chow (1959) based on the ground coverage evident in the area.

River structures were represented using 1D links. Culvert inlet and outlet links were utilised on large culverts to model inlet and outlet headlosses, with characterising parameters based on Innovyze guidance. For all other minor structures, the headlosses were applied directly to the conduit using a headloss type of 'fixed', with the entrance and exit coefficients based on UDFCD (2016). For all river structures and culverts, the bottom roughness was increased as compared to the sewer network to represent gravel, stones, rocks and other obstructions.

The full representation of the River Ness was not required, therefore the boundary condition for it was represented via level files applied to all outfalls discharging into the river.

3.1 The ReFH2 model

The contribution from rural areas draining into watercourses was represented via subcatchments using the ReFH2 runoff model. This is an updated version of the Revitalised Flood Hydrograph (ReFH) model and it consists essentially of three main components: a loss model, a routing model and a base flow model:

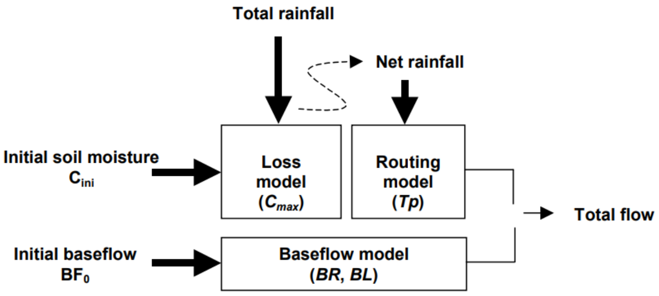

Figure 1. Schematic representation of the ReFH model (from Wallingford HydroSolutions, 2016)

The subcatchments were drawn at the upstream end of each watercourse based on the boundaries from the FEH CD-ROM, which has subsequently been superseded by the FEH Web Service. Subcatchments were also drawn to represent other large contributions generated by green fields within the urban area or rural areas further downstream. The subcatchments were drawn in such a way not to overlap existing storm or combined subcatchments to avoid double counting of runoff.

For large rural subcatchment areas, spatial rainfall variability is expected, and thus rain gauge data was supplemented with 1km grid RADAR rainfall data, provided by Scottish Water. As a consequence, large ReFH2 subcatchments were split into smaller areas to allow for the application of different RADAR rainfall profiles.

As part of verification of the river monitors, the ReFH2 model was calibrated for all relevant subcatchments. First, the initial conditions C_{ini} and B_{F0} were estimated, and subsequently the ReFH2 parameters were calibrated, as described below.

Initial conditions

The soil moisture content C is one of the main parameters of the ReFH2 runoff model and it is used to control the total generated runoff. The estimate of the initial soil moisture content (C_{ini}) is a key component of the ReFH2 model. For a given catchment and rainfall event, a low C_{ini} results in a hydrograph with a smaller peak flow and conversely if C_{ini} is high, the runoff volume and peak flow will be higher (Wallingford HydroSolutions, 2016).

For all ReFH2 subcatchments, estimates of C_{ini} were obtained using the 'ReFH2 Calibration Utility' (https://www.hydrosolutions.co.uk/). Based on available rainfall data, the utility can use up to two years of antecedent rainfall to run a daily moisture model and calculate an estimate of the initial soil moisture content for selected events (Wallingford HydroSolutions, 2016b). For the Inverness project, six months of RADAR rainfall prior to the beginning of the flow survey were used.

The second initial condition for the ReFH2 runoff model is the initial base flow B_{F0}. When flow data are available, B_{F0} can be estimated using the ReFH2 Calibration Utility. For the Inverness ICS project, however, depth only data was available, and therefore design B_{F0} values were used instead. These design values were obtained from the ReFH2 software (https://www.hydrosolutions.co.uk/software/ refh-2/refh2_download/), which can generate ReFH2 hydrographs based on catchment descriptors.

Calibration of the ReFH2 parameters

Upon calibration of the initial conditions, six ReFH2 parameters must be specified to calculate the ReFH2 hydrograph: C_{max}, T_p, U_p, U_k, B_L, B_R. C_{max} represents the maximum soil moisture capacity, and therefore the maximum runoff is generated when the soil moisture content C reaches C_{max}. Lowering the value of C_{max} would lead to increased runoff volumes at lower antecedent conditions. This parameter was not modified as part of the project to avoid altering unrealistically the generated runoff. For clarity, Figure 2 shows the relationships among some of the ReFH2 parameters:

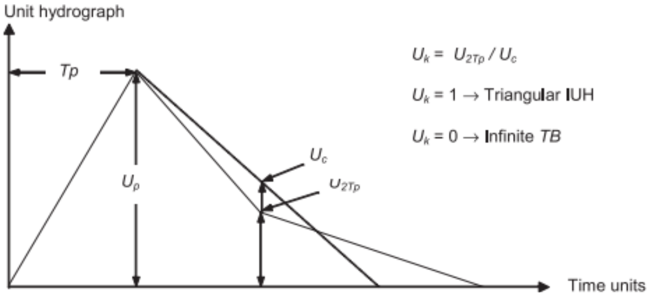

Figure 2. Kinked Unit Hydrograph (from Kjeldsen, 2007).

When flow data are available, the aforementioned parameters can be estimated using the ‘ReFH2 Calibration Utility’. Each parameter can be defined from catchment descriptors, set to design standard, defined by the user or estimated through optimisation procedures. Additionally, the software also has the additional functionality of calibrating B_L and B_R via recession fitting, allowing for a more accurate match to observed data. No flow data was available for this project, therefore a manual calibration for T_p, U_p, U_k, B_L, B_R was undertaken based on observed depth data.

Design set up

For the ReFH runoff model, formulas are available to calculate design values for C_{ini} and B_{F0}. The same formulas, however, are not suitable for the ReFH2 model. Therefore, for this study, a different approach was used to estimate design values for initial soil moisture content and base flow.

The ReFH2 Calibration Utility was used to estimate the variation of the soil moisture content throughout a selected TSR typical year. C_{ini} values at the beginning of each storm event within the typical year were then selected and averaged over winter and summer months to obtain design summer and winter values. Design B_{F0} values were estimated using the ReFH2 software as described in previous sections.

4 Issues and limitations

The river monitors showed a much slower response as opposed to the sewer monitors. Thus, the verification was initially undertaken on the full period, considering six months of preceding RADAR rainfall. The model initially over-predicted flows generated by the ReFH2 subcatchments, particularly in the later end of the flow survey. Therefore, the ReFH2 contributing areas were drastically reduced, which in turn caused a significant under-prediction of flows during design events (Figure 3).

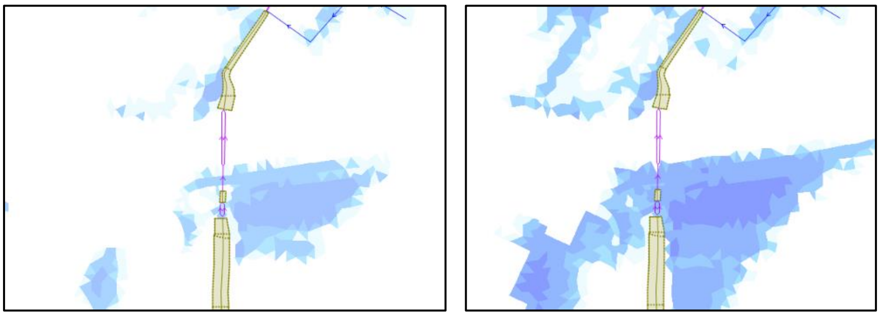

Figure 3. Effects of miscalibration of the ReFH2 model in terms of flood extents. The same rainfall profile was applied in both cases.

After consultations with Innovyze, a major limitation of the ReFH2 model within ICM was identified. The soil moisture content C varies over time and would generally be expected to increase as a result of rainfall and decrease in the inter-event dry-periods. However, it was found that this is not the case within ICM, and the soil moisture instead continues to increase and levels-out during dry-periods (Figure 4):

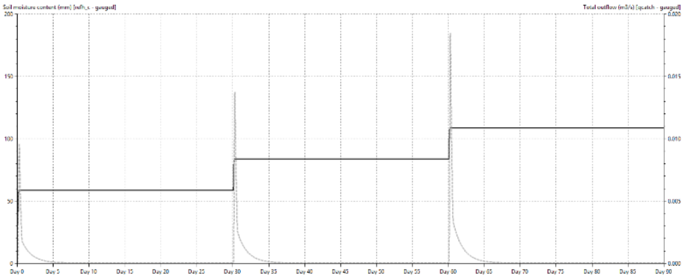

Figure 4. Effects of lack of degradation in the soil moisture store. Grey dashed line indicates the total runoff from a test subcatchment, black line indicates the variation of the soil moisture content.

This being the case, *C* is vastly over-predicted with progression towards the latter events in continuous series rainfall, causing unrealistic over-prediction of the model and leading to incorrectly calibrate the contributing areas. Modellers should therefore be aware that the ReFH2 model within ICM is not suitable for continuous events. This is a significant limitation of the software, as watercourses respond to rainfall much more slowly than urban catchments so that, generally, discrete events should not be considered. However, as currently there is no direct solution to this issue, discrete events were used for verification of the Inverness model. It should be noted that for this project greater importance was given to design model predictions against known flooding, as a result of the described uncertainties in the ReFH2 model and of the availability of depth data only.

Within InfoWorks ICM it is possible to graph the soil moisture content *C* over time throughout a simulation. It was found that when the ReFH2 contributing area is assigned to any runoff area apart from runoff area 1, the soil moisture variation will not be plotted correctly. It will instead be plotted as a constant flat-line graph set to the assigned value of C_{ini} (this was observed in InfoWorks ICM v9.5 as well). The variation of soil moisture content is graphed correctly when the contributing area is set to runoff area 1. Although this does not affect in any way the model calculations and predictions, modellers should be aware of this issue when visual observation of the variation of *C* is required.

Regarding the application of C_{ini}, modellers should also be aware that the initial soil moisture is not applied correctly if the 'ReFH ACF/alpha' parameter within the rainfall profile properties is set to zero. This parameter was set to 1 for this study.

For design simulations, when a long duration was set in conjunction with a timestep control to end the simulation after the rainfall ended, the simulation failed at the end of the initialisation. Innovyze confirmed that this is due to a stack overflow in the ReFH base flow calculation, which is caused by the fact that, after hydraulic initialisation, the software performs a runoff only run for the ReFH routing model subcatchments, before continuing with the hydraulic simulation. This issue was observed in v8.5 of the software, however it appears rectified in later versions of the software (ICM v9.5 tested).

5 Conclusions

Within the Inverness ICS model, the watercourses were represented as 1D river reaches, with the rural hydrology represented via subcatchments employing the ReFH2 runoff model. The ReFH2 model was calibrated with a host of parameters, with the initial conditions (C_{ini} and B_{F0}) estimated from Wallingford HydroSolution packages based on available data. The application of the ReFH2 runoff model was deemed a suitable means for the representation of rural flows within the catchment, however a significant limitation of the runoff model was observed. The lack of degradation of the soil moisture content can lead to wrong model calibrations and subsequently to wrong model predictions. The results showed the unsuitability of the ReFH2 runoff model when used in conjunction with continuous events within ICM.

References

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