09 - BENEFITS OF RAINFALL RUNOFF APPROACHES IN FLOOD RELIEF SCHEME DEVELOPMENT

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Abstract

The Flood Studies Update (FSU) provides the main methods for flood frequency estimation in Ireland but has limitations when calibrating hydraulically complex volume related flood models in small flashy ungauged catchments and their use in development of flood relief schemes (FRS). In particular predictive performance modelling all of the measures within the options appraisal, climate change adaptation studies and identifying opportunities for some types of Green Infrastructure are constrained without a process based runoff model. This paper presents some of the findings from our recent studies for the Mountmellick and Kilkee FRS. Hydrograph shape is critical where flow volume is a factor in the appraisal of scheme options.

The Flood Studies Supplementary Report No. 16 (FSSR 16) Rainfall Runoff approach is the most recent runoff based method that has been tested for Irish conditions. This method was first established in 1985 and has been superseded in the UK by the FEH, ReFH and ReFH2 methods, but not for Ireland. Alternative approaches to estimating the flows at ungauged and gauged locations need to be evaluated for Irish conditions. A uniform standard is not necessary, as different methods may suit different catchment types. The paper recommends further research into validating international methods such as US SCS, ReFH2, and continuous simulation based on water balance models. The paper will conclude with a discussion on the data quality, coverage and availability for these alternative methods. Are new soil or infiltration datasets or models needed? We propose further development of an IreFH model.

1. INTRODUCTION

As with all hydrological analysis, our preference should be to use gauged and observed data. However, as we know, we do not live in an ideal world and we often need to derive flood hydrographs for ungauged catchments. When we look to the future, it raises more questions. Even where we have good quality gauge records, we cannot be sure the future hydrological regime will be the same as the past? Recent papers have considered the effect of non-stationarity and potential future trends and projections on statistical flood estimation (Faulkner *et al.* 2019s and 2019b). Ireland is in the process of developing flood relief schemes for present day levels of flood risk, which are adaptable to future change (OPW, 2018). It is not possible to assess the potential benefit of catchment scale and other natural flood management measures if using observed and purely statistical flood estimation methods. Representation of these measures is possible through explicit schematisation of features or changes in hydraulic models, but would be expensive in terms of computational and human resource.

Going back to the start, the Rational and Modified Rational Method has specific Irish foundations, with the development in 1851 of the rational method by Thomas James Mulvaney. The model estimates peak runoff only with no separate routing or runoff elements to test potential catchment measures. The non-linear C coefficient complicates things further (Bevan, 2012), as the value of C varies over time and space with rainfall intensity, storm duration, antecedent rainfall and soil conditions, season, soil type, infiltration capacity, slope, land use and cover, and more. In reality rainfall today, will not result in the same runoff response from an identical storm tomorrow. This variation is what all rainfall-runoff models are seeking to represent.

Understanding fluvial flow volume and response times is critical for developing flood relief schemes if we wish to maximise opportunities for Green Infrastructure. Typical Green Infrastructure measures may not be the sole element of a flood relief scheme and will more likely complement structural measures as part of an integrated flood risk scheme. Green Infrastructure measures such as catchment wide attenuation, floodplain and river restoration, woodland planting, etc. are intended to attenuate, delay or reduce river flow or runoff to reducing peak discharge and alter hydrograph shapes. The FSU approach which focuses on an index flood and growth curve does not capture these volume effects. The FSU hydrograph methods also have limitations. We need a method that can test the effect of catchment change on both hydrograph shape and peak discharge.

We start with a recap on FSU and FSSR, followed by two case studies where FSSR-16 rainfall runoff methods have been applied, and undertakes a proof of concept review of whether alternative rainfall-runoff models, in this case ReFH and SCS, could be applied.

This paper then discusses the range of possible rainfall runoff models and their suitability for Ireland. The objective is to identify where further research, hydrometric gauge data or testing is needed improve; scheme options appraisal, climate adaptation plans and incorporate, test and justify Green Infrastructure measures in Ireland.

1.1 FSU methods and limitations

The philosophical foundation of the FSU methods is to apply a growth curve to an index flood. For gauged and ungauged flood estimation sites is the index flood is the median AMAX record. The FSU methods are entirely statistical. Statistical descriptors and distribution fittings are used in the implementation of gauged records for QMED, pooling groups and hydrograph shapes. Regression and principal component analysis were used to develop the catchment descriptor QMED model and selection of appropriate pooling group members. The FSU has no rainfall runoff or process based model elements. For a full description of the approach to the FSU technical research reports and volumes (Murphey *et al.,* 2014).

Where peak flow estimates are the main objective of a study FSU methods are appropriate. However, when we want to understand opportunities for, and the performance of, catchment scale and more natural approaches to flood management we are limited to sensitivity tests on the FSU estimates. Such tests may include; reducing peak flow, altering hydrograph shape, delaying the time to peak, etc. The FSU 7 parameter QMED formula includes the FARL, ARTDRAIN2, S1085 and DRAIND catchment descriptors which reflect the attenuation and routing effects of catchment conditions on the index flood. These descriptors are to calibrate the model in an empirical basis, rather than represent any actual physical processes. There is no function in the pooling group approach to deriving growth curves to evaluate variation in the effect of routing and runoff response at different flood probabilities. This would require complex statistical analysis of sampled gauges with different conditions or measures, to derive scenario specific growth curve models.

These tests can inform the potential change in discharge but cannot be linked to the spatial distribution or scale of different measures which may be viable. The effect of different storm spatial and temporal variation across a contributing catchment cannot be modelled using the FSU methods. There is also no ability to represent the temporal change in catchment descriptors as successive Atlantic Storms pass over Ireland, (e.g. November 2009, storms during Winter 2013/14, November and December 2015 [storms Abigail, Barney, Clodagh, Desmond, Eva and Frank, Winter 2020 Storms Ciara and Dennis), and specifically no rule for temporal variation of rainfall or catchment descriptors such as Soil Moisture Deficit (SMD), Catchment Wetness Index (CWI) in the FSU methods.

The Interactive Bridge Invoking for the Design Event Method (IBIDEM) allows for an FSU derived hydrograph to be adjusted by an FSR rainfall runoff hydrograph (O'Connor *et. al,* 2014). The model is empirical and calibrated to the AREA, SAAR and URBAN catchment descriptors. There is no representation of the distribution of features and characteristics within the catchment that influence runoff or flow routing. The IBIDEM method is only concerned with hydrograph shape, to be scaled to a FSU derived peak discharge estimate. Sensitivity tests to vary these descriptors could infer the potential effect but will be highly uncertain. Therefore, the effect on peak discharge of upstream flood storage or catchment measures cannot be represented.

There are further challenges to the application of FSU methods in small and urban catchments. Very few small or urban gauged catchments were used to calibrate the FSU methods. Work Package 4.2 of the FSU (OPW, 2012) includes research on the methods and uncertainties in small and urban catchment flood estimation in Ireland. At the time of the analysis only 41 gauging stations with a catchment area less than 30km^2, out of a total 630 gauging stations (OPW and EPA stations) could be considered to record small or urban catchment flow estimation. Of these 41, only 28 stations had more than 10 years of records. This was too small a sample for statistical significance to be determined and so 35 gauging stations were used (6 stations were considered outliers). The work package reviewed seven methods (FSSR_6, IoH_124, ADAS 345, TRRL, FEH_statistical, FSU_7variable, and FSU_3variable) and found that some methods significantly overestimated peak flow, specifically IH124. The best performing methods for estimating QMED were found to be the UK FEH statistical formula, FSU 3 variable, and a new FSU 3 variable formula.

The resulting uncertainty in small and urban catchment flood estimation is due to the limited data available to calibrate or verify hydrological methods. The methods may be appropriate, it is just there was insufficient data to confirm this. FSSR_16 and ReFH were not evaluated because the indicator of performance was QMED and these methods do not require an index flood.

On top of this, with the statistical FSU methods it is impossible to isolate effects on different sub-catchments unless there is a comprehensive catchment gauge network. This is where rainfall-runoff and process based models are required to test the effect of measures on runoff or river discharge response.

1.2 FSSR 16 Rainfall Runoff method

With the exclusion of IH124 as an appropriate method, the Flood Studies Supplementary Report No. 16 (FSSR 16) approach is the most recent runoff based method commonly applied in Ireland. This method was established in 1985 as an update to the 1975 FSR rainfall runoff (hydrograph) method and has been superseded in the UK by the FEH, ReFH and ReFH2 methods, but not for Ireland.

The FSR unit hydrograph rainfall runoff model was developed using only one Irish gauge. The research for the FSSR16 rainfall runoff method is based upon no (zero) Irish gauges (Boorman, 1985). The calibration of rainfall probability, storm duration and profile, and Catchment Wetness Index (CWI) is therefore not necessarily calibrated to derive Irish river flow probabilities. The need to calibrate parameters for baseline design event hydrograph estimation, means that the values become removed from the catchment characteristics they represent and so adjustment of these parameters to test options is hard to justify.

The statistical FSR flood growth curve development is based on 342 Irish rain gauges and 112 Irish river flow gauges (Cunnane & Lynn, 1975), which derived a relationship between storm and flood probabilities for design event estimation (as presented in Table 1-1. Storm profiles are linked to local conditions through the DDF parameters. This relationship is key to design event modelling when using the FSSR 16 model approach.

Table 1-1: *Relationship between storm and flood return period (from Cunnane & Lynn 1975).*

Flood return period	Storm return period
2.33	2
5	8
10	17
20	35
25	42
50	80
100	140
250	300

In subsequent development of the FSU methods UK gauges were not used, and the UK FEH methods are not based on gauges in the Republic of Ireland. In Ireland we have a deficit of small and urban catchments available for use in QMED estimation, pooling groups and for the validation of alternative methods. The UK has many of these and hydrological conditions are not hugely dissimilar, especially between Northern Ireland and the Republic. Data availability and licensing is not an issue. Exclusion of the UK data in the development of the FSU methods has meant that the FSU methods are not recommended for flood estimation for catchments smaller than 25km^2. This does not mean that the methods are not appropriate, it is just that they have not been tested. Whereas UK research has found the FEH and ReFH methods can be applied to very small catchments which removes the catchment size limitation of Irish methods (Vesuviano *et al,* 2016, Kjeldsen *et al.* 2013, Environment Agency 2020, Environment Agency 2012, Beskeen *et al.* 2011)

2. CASE STUDY 1: MOUNTMELLICK

The Mountmellick Flood Relief Scheme (FRS) examines three key watercourses, the Owenass, Pound and Triogue Rivers and their tributaries which all flow into the River Barrow. Figure 2-1 shows the study area and the dense network of watercourses. The Owenass and Pound watercourses flow through Mountmellick town, the area of key risk receptors to fluvial flooding. There are three active gauges within Mountmellick town, one on the Owenass (14114 Mountmellick Mill) and two on the Pound (14121 Manor Court and 14120 Chapel Road). The Pound gauges were installed in 2019.

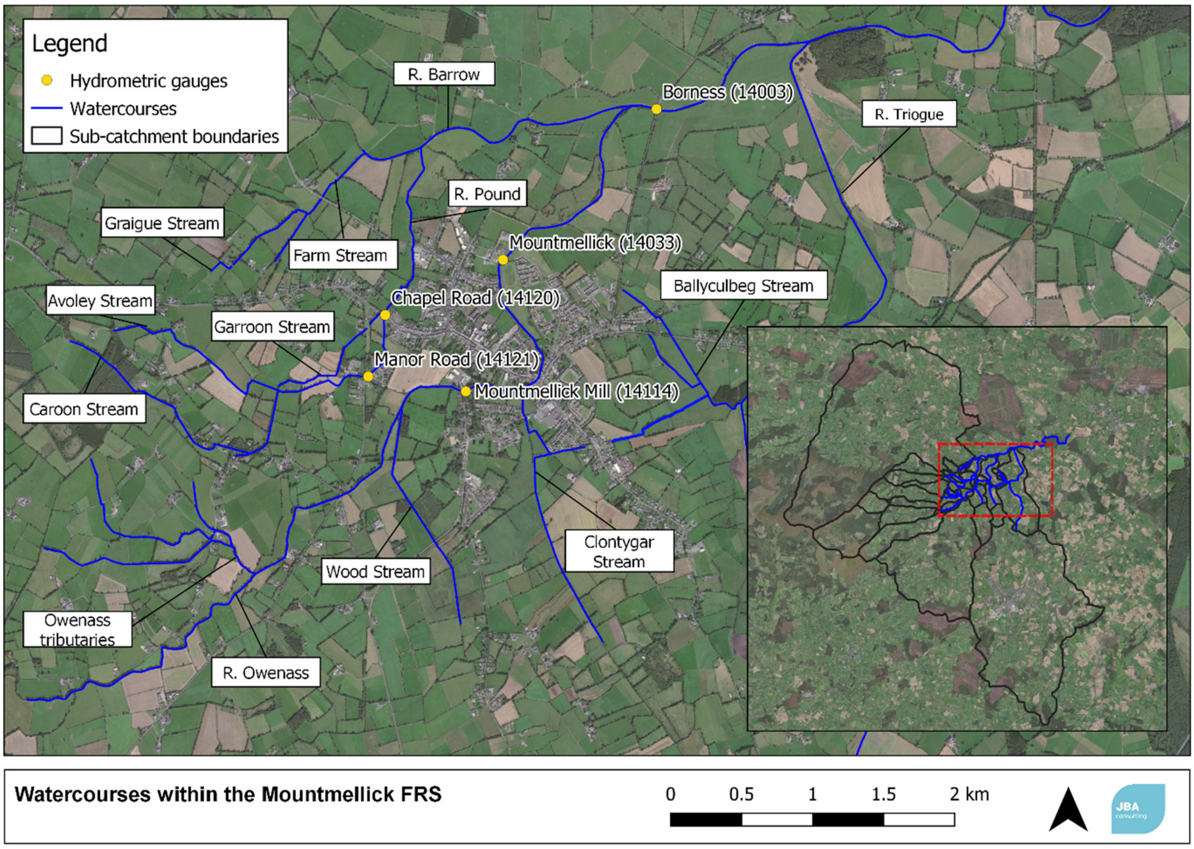

Figure 2-1: *Watercourses within the Mountmellick FRS*

2.1 Use of FSSR 16 Rainfall Runoff

The fluvial response of the system is largely dictated by the variable topography and land use of the area. Figure 2-2 shows the contrast in elevations between the upper catchments and those located in the flat low-lying Barrow flood plain. The steep topography results in a sharp initial response to rainfall events and increased runoff as recorded on the three gauges.

The catchment flood response is complex, flow upstream on the Owenass is heavily attenuated in the floodplain upstream of the gauge location. More critically there are known cross flows between the Owenass and Pound catchments during high flow events which limits the ability of the gauges to accurately record and quantify flows travelling through the watercourses separately in larger events as the two separate watercourse catchments combine.

These key system features are not accounted for or captured using the traditional FSU and Hydrological Estimation Point (HEP) methods. As a result, a rainfall runoff method was selected for flow estimation for the flood relief scheme due to the following:

- Unlike the HEP approach, it can take into account the cross flow between catchments. The catchment descriptors do not allow for loss of flow to another catchment.
- It provides volumetrically consistent method to producing an inflow hydrograph upstream of the floodplains protecting Mountmellick.
- It makes good use of the available rainfall and hydrometric gauges (especially for February 2020), which have been used in the calibration and validation of the models.
- The ability to test the potential effect of upstream catchment change such as changes in land management practises, forest cover and operations, and measures to slow the response to rainfall in the Slieve Bloom mountains on flow response.

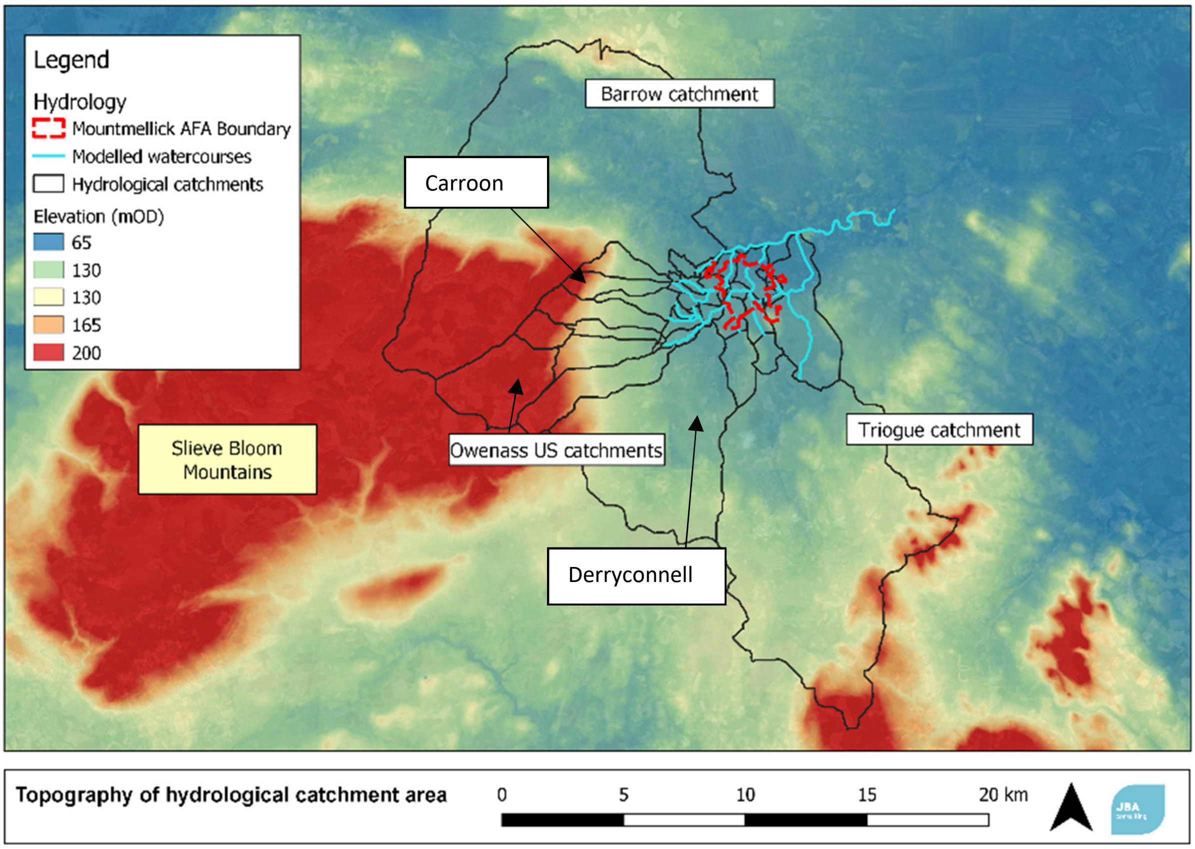

Figure 2-2: *Topography of hydrological catchment area*

2.2 Data Requirements

A rainfall-runoff model for the study area was developed using Flood Modeller (FM). Separate FSSR16 units were created for each main sub-catchment within the system which in turn generate the inflow hydrographs. In addition to this the model includes flow estimations for the upland Slieve Bloom sub-catchments catchments of the Owenass connected via hydrological routing units to the upstream boundary of the hydraulic model. Refer to Table 2-1 for the required data inputs for the FSSR16 FM units. The specific catchment characteristics were input for each individual sub-catchment unit.

Table 2-1: *FSSR16 input parameters*

Input parameter	Design run value
SAAR	Standard Average Annual Rainfall over catchment area in mm. For design runs the latest SAAR data for the period 1980 – 2010 has been used
M52D	Depth of rain estimated to fall for a 20%AEP (5 year) event with a duration of 2 days. This value is sourced from the MET Eireann DDF database for each catchment.
M525D	Depth of rain estimated to fall for a 20%AEP (5 year) event with a duration of 25 days. This value is sourced from the MET Eireann DDF database for each catchment.
SPR	Standard Percentage runoff – proportion of rainfall falling on the catchment that enters the river system instead of being intercepted. For design runs the SPR values for each catchment are derived from WRAP SOIL type.
CWI	Catchment wetness index estimated using the FSSR method.
Flow return period	Altered to match the desired AEP event.
Storm duration	An 11-hour design storm duration was initially used

2.3 Calibration

Due to the availability of gauge data the hydrological model was able to be calibrated using three different storm events of varying severity: Storm Dennis 2020, Storm Ciara 2020 and November 2017. The hydraulic and hydrological models were developed and calibrated simultaneously due to the influence the hydraulic mechanisms of the system has on the hydrologic response at recorded at the gauges. Rainfall data for calibration was sourced from the nearest available raingauges in the wider area as there are no gauges present within the main study area. The sparse network of rainfall data over the area is a major limitation of the method due to the inability to fully understand and represent the variability of the rainfall for the events in relation to the spatial pattern of the storms and the orographic impact of the Slieve Bloom Mountains on rainfall depths. Figure 2-3 shows the variability of rainfall recorded for several gauges in the wider area.

Hydrological calibration was carried out by iteratively applying various rainfall hyetographs and rainfall depth combinations to the FSSR16 units and comparing the modelled hydraulic response to the observed levels recorded at the available gauges. To ensure the rainfall applied was representative of the sub-catchments recorded rainfall depths were scaled relative to catchment SAAR values. Hydrological calibration proved complex due to the cross flow and flood plain interactions in the system particularly for the Storm Ciara, the medium sized storm calibration event. The balancing the flow transfer from the Owenass to the Pound proved critical in the producing a good hydrological calibration for all three gauges. – applying differing rainfall combinations resulted differing responses at the gauges (refer to Figure 2-4). Through testing of different rainfall, testing of runoff coefficients and times to peak in the hydrological model a good calibration was achieved, and any adjustments made to the hydrological model were transferred through to the generation of design storms.

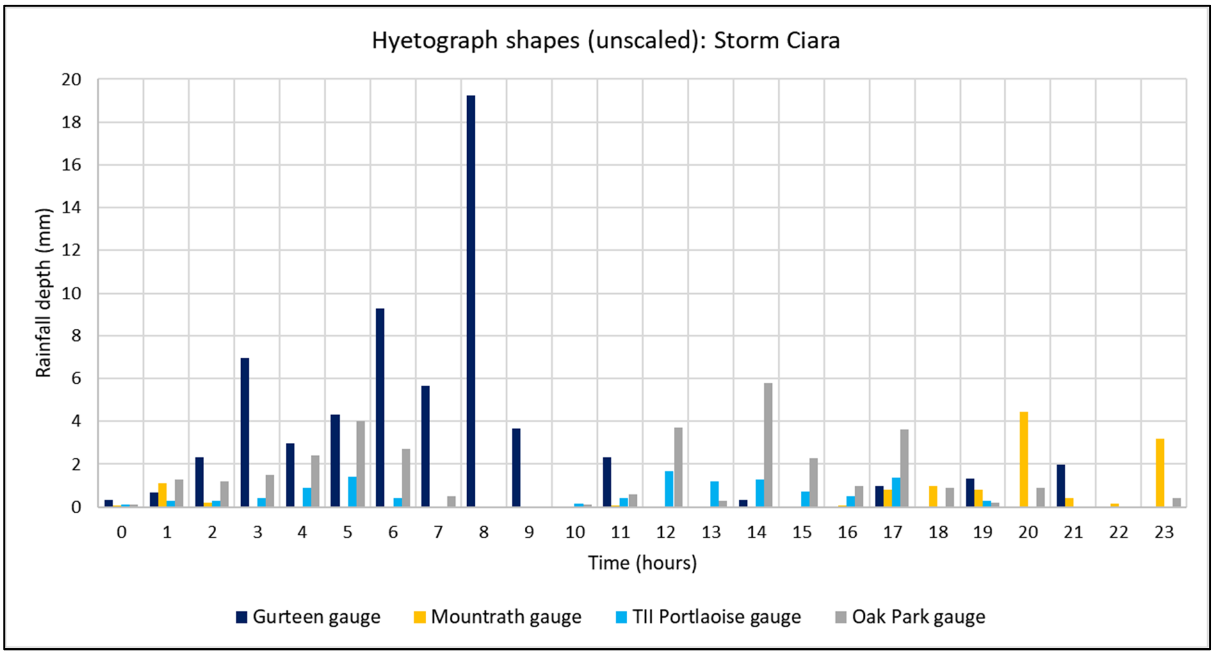

Figure 2-3: *Hyetograph shapes from proximal gauges*

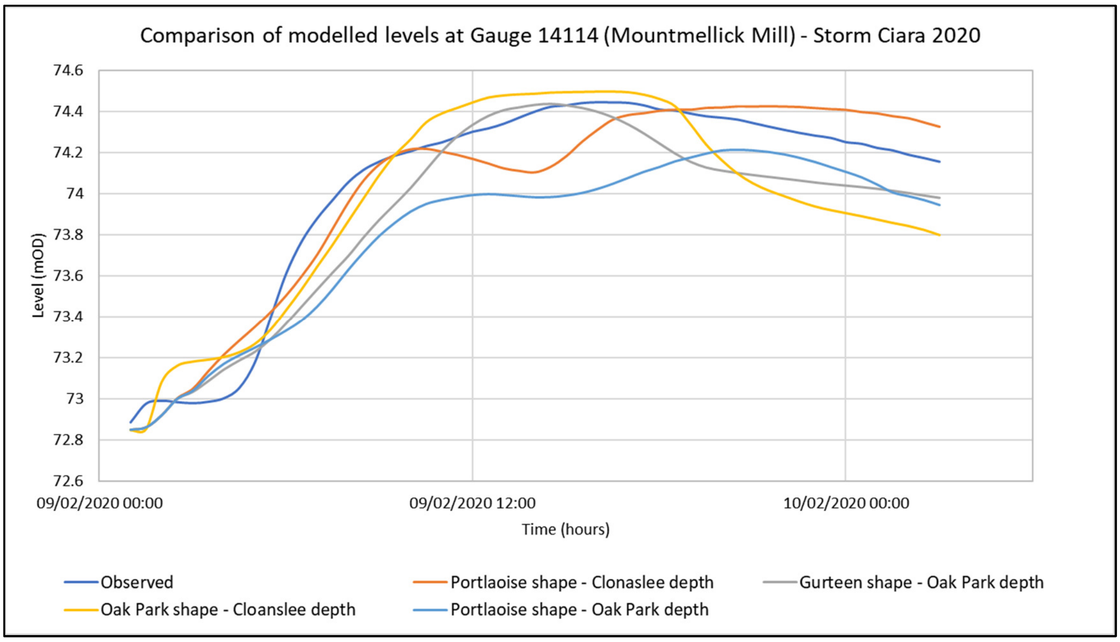

Figure 2-4: *Comparison of modelled hydrograph levels at Gauge 14114 (Mountmellick Mill) – Storm Ciara 2020*

2.4 Why do we need a process-based model?

As highlighted in Section 2.1 the presence of significant flood plain attenuation and cross flow between catchments meant that the traditional HEP approach used in methods such as FSU were not suitable for this system to accurately replicate the observed flows and response. In addition to this, the use of a rainfall model allows for efficient testing via adjustment of input parameters within the FSSR16 FM units. Examples include testing of upland catchment land use changes in relation to forestry by altering time to peak values or re-meandering of watercourses by adjusting the mean stream length and slope values.

2.5 Could ReFH be used?

This section looks at the potential application of ReFH in Ireland as a proof of concept for some of the Mountmellick catchments. The Revitalised Flood Hydrograph (ReFH) model was developed in the UK to improve upon the FEH and FSR methods of flood estimation for ungauged sites. The model framework comprises of loss (runoff), routing (transformation) and baseflow components. The input data to the model are UK catchment descriptors and antecedent soil moisture conditions. Actual and design event rainfall profiles can be input into the model. A key difference between ReFH and FSR rainfall runoff models is that a seasonal variation of soil moisture and design rainfall is accounted for. ReFH is suitable for use on catchment areas from 0.5km^2 to 1,000km^2 (Kjeldsen 2007). There are limitations to the accuracy of the model for urban catchments with $URBEXT_{1990}$ greater than 0.5. The second version of ReFH takes account of newer rainfall DDF model and revised equations for model parameters and initial soil moisture, with additional calibration of the model to a larger sample of hydrometric gauges. The limitations with using ReFH1 on permeable catchments with BFIHOST greater than 0.65, are no longer valid. The latest version ReFH2.3 has been calibrated to the relationship between the rainfall and flow event probabilities and performs well for almost all catchmenhts. (Environment Agency, 2020). A review to compare the input datasets for ReFH with the Irish FSU catchment descriptors is made later in this paper.

UK research on small catchments (less than 25 km^2) found that FEH and ReFH methods are appropriate for a full range of catchment sizes and that older ADAS 345 and IoH 124 should no longer be used (Faulkner, 2012b). The same research also found that smaller catchments are not well represented in the UK hydrometric gauge network and uncertainty in small catchment flood estimation is high. This is similar to Ireland. The research recommends using FEH and ReFH methods for catchments greater than 0.5 km2.

Check 1: ReFH datasets. Licenses.

The latest ReFH version 2.3 is available as standalone software under license from Wallingford Hydro Solutions and can be applied using dedicated model units in Flood Modeller Pro and Infoworks ICM. There are some limitations with the application of the Flood Modeller Pro ReFH2 unit (Environment Agency 2020). An ReFH1 spreadsheet was produced by the Centre for Ecology and Hydrology for the Environment Agency but is no longer available. Separate tools and programmes can be developed to run the models. For this proof of concept, a bespoke R programme code has been used to implement the ReFH1 methods.

Check 2: datasets

It is worth noting that all parameters of the ReFH loss, routing and baseflow model can be derived from hydrometric gauge data or data transfer from similar or neighbouring catchments. The catchment descriptor approach requires a number of datasets, which are noted in Table 2-2, with some of the differences between the UK FEH and Irish FSU descriptors discussed in the table.

Table 2-2. *Catchment descriptors required for ReFH and available in the UK and Ireland.*

ReFH model component	**Descriptor or dataset required**	**FEH or UK data**	**Comparable Irish dataset**
Rainfall model	DDF model parameters (C, D1, D2, D3, E and F)	FEH99 or FEH13	FSU DDF model / Met Eireann DDF model outputs
	D (storm duration)	Tp SAAR	Tp SAAR
	ARF (Areal Reduction Factor)	AREA	AREA
	SCF (Seasonal Correction Factor)	$URBEXT_{2000}$ BFI_{HOST19}	URBEXT BFI_{soil}
	Storm Profile	FSR winter & summer	FSR winter & summer
Loss model	C_{ini} (initial soil moisture)	BFI_{HOST} PROPWET	BFI_{soil} FLATWET
	C_{max} (maximum soil capacity).	BFI_{HOST} PROPWET	BFI_{soil} FLATWET
Routing model	Tp	PROPWET DPLBAR $URBEXT_{1990}$ DPSBAR	FLATWET *Possibly* MSL URBEXT *none*
Baseflow model	BF (initial baseflow)	SAAR AREA	SAAR AREA
	BR (baseflow recharge)	BFI_{HOST} PROPWET	BFI_{soil} FLATWET
	BL (baseflow lag)	BFI_{HOST} DPLBAR PROPWET $URBEXT_{1990}$	BFI_{soil} MSL FLATWET URBEXT

In Ireland the DDF model parameters are different, but fortunately we can simply use the resulting DDF model output for the desired storm duration and probability. Care may need to be taken to review the growth curve relationship between rainfall and flow annual exceedance probabilities. (Fitzgerald, 2007)

PROPWET is the UK FEH index of the proportion of time that soil is wet. FLATWET was developed in the FSU research as an indicator of moderately wet catchment conditions and based on Soil Moisture Deficit (SMD) with no allowance for soil, terrain or landcover. In FLATWET moderately wet is defined as the proportion of time there is an SMD of less than 8.5 mm.

DPLBAR and MSL are different indicators of the length of a catchment. MSL is the Main Stream Length and a measure of river length as opposed to DPLBAR which measures the total slope. DLPLBAR is likely to be shorter than MSL for most catchments.

DPSBAR (mean Drainage Path Slope) provides an index of overall catchment steepness. S1085 is a measure of river slope, excluding the most downstream 10% and upstream 15% of the river.

Most of the FSU catchment descriptors are comparable to those required for ReFH, however DPSBAR and DPLBAR need to be calculated from GIS DTM data, and careful review is needed when using FLATWET as a proxy for PROPWET. For this proof of concept MSL has been used as a proxy for DPLBAR, and S1085 for DPSBAR. Further research to validate the model and the comparison between UK and Irish catchment descriptors would be beneficial.

Check 3: suitability of Irish catchments

When first developed ReFH1 was not deemed suitable for are urban or permeable catchments (with descriptors greater than 0.15 for URBEXT or 0.65 BFIHOST). The more recent ReFH2 model has been tested and is valid for application on catchments beyond these thresholds, however a comparison here to the range of Irish catchments is useful for context. The higher prevalence of lakes and karstic groundwater bodies in Ireland needs consideration.

The FEH $URBEXT_{1990}$ and $URBEXT_{2000}$ descriptors are derived from the proportion of urban and suburban land cover within the catchment. In Ireland the FSU descriptor URBEXT is based on the proportion of the catchment with a land cover from any of six CORINE land cover categories[1]. The UK and Irish urban catchment descriptors are not identical but give an indication of the degree or urban coverage within a catchment. Only 0.75% (1,005) of the 134,000 ungauged FSU catchments have an URBEXT value less than 0.15[2]. The urban limitation of ReFH is not likely to be a significant concern for most catchments in Ireland, with the exception of application to very small catchments with high degree or urban and impermeable land cover.

A Baseflow Index (BFI) can be derived directly if baseflow volume can be separated from the total flow volume. Where data is unavailable, the proportion of soil types within a catchment can be calculated and using the model developed by Boorman et al. (1995) to define a Standard Percentage Runoff (SPR) for each soil type, the baseflow index can be determined. This UK descriptor BFI_{HOST} is an area weighted function of WRAP HOST soil type classifications and SPR value for HOST soil types. As an indicator of baseflow index BFI_{soil} and BFI_{HOST} can be inferred to different means of deriving the same indicator and therefore directly comparable. 6% (8,496) of the ungauged FSU catchments have a BFI_{soil}

[1] 111: Continuous urban fabric, 112: Discontinuous urban fabric, 121: Industrial and commercial units, 122: Road and rail networks, 123: Sea ports, and 124: Airports.

[2] Based upon the FSU ungauged node GIS layer dated 16th December 2013.

value of greater than 0.65. The large proportion of Irish catchments are likely to be within the suitable range of permeability for ReFH model application.

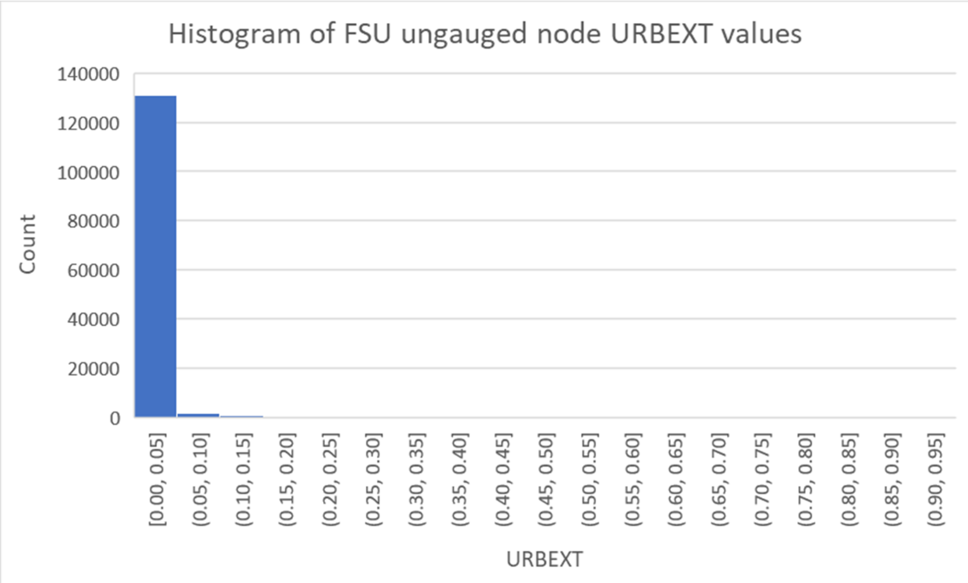

Figure 2-5: *Histogram of FSU ungauged catchment URBEXT values*

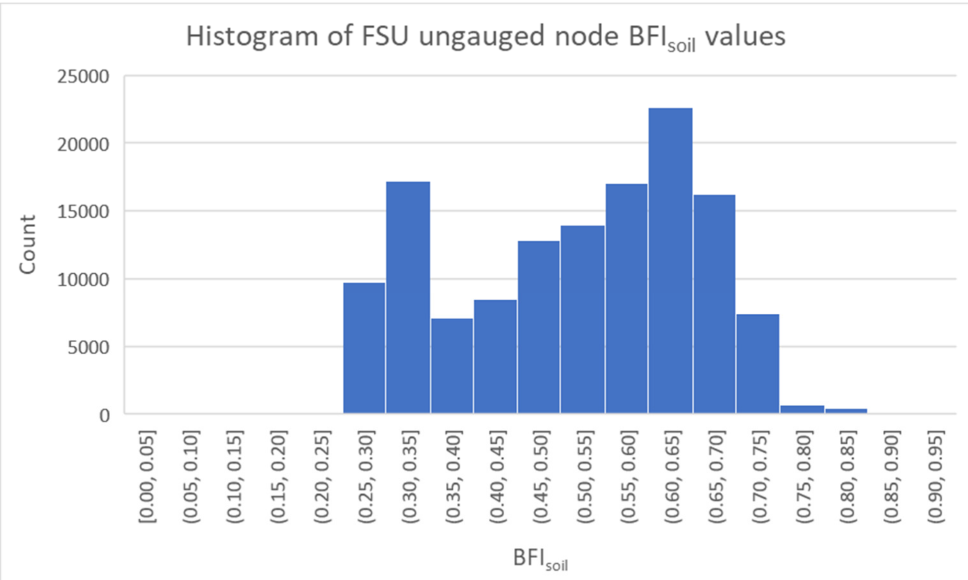

Figure 2-6: *Histogram of FSU ungauged catchment* BFI_{soil} *values*

Check 4: can ReFH be used to test options?

Testing of catchment management changes to reduce runoff can be tested through adjustments to the runoff and baseflow model components and descriptors. Testing of river and floodplain restoration or change can be represented through adjustments to the routing and baseflow components and descriptors.

Check 5: Proof of concept and comparison to FSSR 16 estimates for Mountmellick

A proof of concept for the application of ReFH to selected sub-catchments to Mountmellick has been carried out. Three sub-catchments have been selected as labelled in Figure 2-1.

FSU and FSSR16 Catchment descriptors have been derived in the hydrological analysis for the Mountmellick Flood Relief Scheme by JBA (in progress). The current method proposed for the flood relief scheme is the FSSR 16 rainfall-runoff method. The same rainfall profiles as the FSSR 16 inflow boundaries are used for this proof of concept.

The ReFH catchment descriptor DPSBAR has been derived from the catchment DTM and applying the GRASS GIS r.watershed programme[3], which outputs Slope Steepness (S) factors as defined in the Universal Soil Loss Equation (RUSLE). Raster statistics within each catchment are applied to derive the mean slope values. DPLBAR is a more complex calculation and so for the purpose of this proof of concept the MSL has been used as a proxy value of slope length. Careful conversion of units is required, but the measurement is the same as the FEH DPSBAR and DPLBAR descriptor.

Table 2-3*: Mountmellick Catchment Descriptors*

Catchment	**Upstream Owenass Slieve Bloom**	**Derryconnell**	**Carroon**
Brief description	Upland peatland catchment	Lowland catchment with drainage scheme	Small lowland catchment
Node ref.	503_hep_00026	503_hep_00023	503_hep_00005b
FSU ID	14_300_2	14_253_3	14_1855_1
Area	11.42	39.19	3.04
SAAR	1504	1042	1047
FLATWET / PROPWET	0.6	0.59	0.59
URBEXT	0	0	0
MSL / DPLBAR	5.98	11.54	4.76
DPSBAR	199	67.2	139.8
BFI_{soil}	0.31	0.50	0.53
Tp	1.81	3.70	1.77
C_{ini} / CWI (Nov 2017)	137.17	127.97	127.97
C_{max}	221.71	370.52	350.57
BL	28.1	40.7	34.7
BR	0.88	1.47	1.56

The outputs for the November 2017 rainfall profile and 1% AEP design event winter storm profile are presented in Figure 2-7. These show the different components of the resulting hydrographs.

[3] https://grass.osgeo.org/grass78/manuals/r.watershed.html

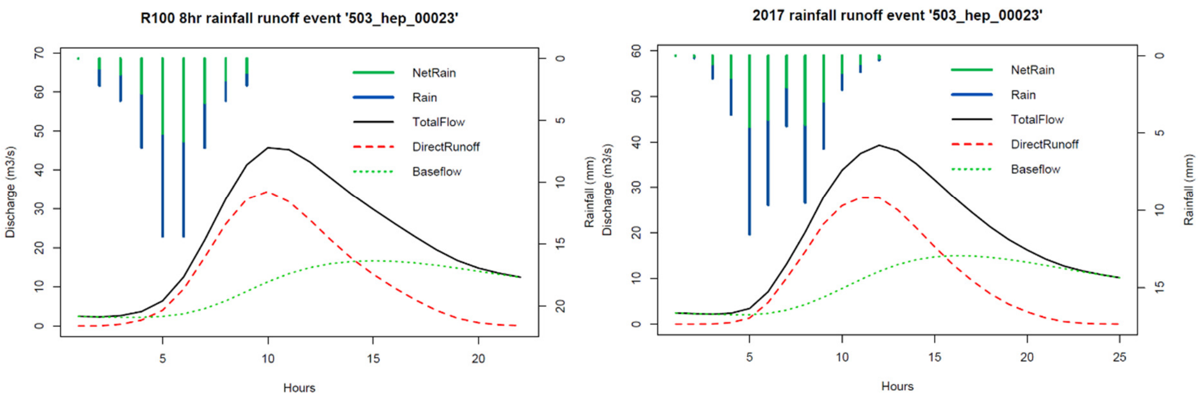

Figure 2-7: *Example ReFH output hydrographs demonstrating the direct runoff, baseflow and total flow (left for November 2017 event, right for 1% AEP design event with winter storm profile)*

A comparison of the November 2017 event hydrographs (Figure 2-8) and a short duration storm 1% AEP flood event (Figure 2-9) for each sub-catchment is presented below. It is clear our ReFH proof of concept model overestimates all events and catchments and for the Derryconnell the 1% AEP hydrograph has a much greater deviation from the FSSR 16 hydrograph. This potentially due to the differences between the MSL and DPLBAR, and S1085 and DPSBAR descriptors. It could also be due to the use of the FSSR 16 CWI value which has been directly input into ReFH. Further refinement and calibration of the ReFH model could be made to achieve a closer match. This would include delineation of specific DPSBAR and DPLBAR descriptors from the widely available DTM data. This proof of concept shows that there is no practical reason for not considering ReFH methods for Irish catchments. Just like any hydrological modelling method, the catchment characteristics and assumptions need to be evaluated before accepting an output. ReFH is no different in this matter. What is most encouraging is the ability of the ReFH hydrograph to show the kink in the rising limb of the upstream Owenass sub-catchment. This suggests that ReFH has the ability to represent catchment shape and characteristics in the output hydrograph, whereas FSSR 16 tends to give a smoother catchment shape. ReFH is being widely used in the UK for testing of Green Infrastructure flood management measures, and future research in Ireland should consider ReFH. Recalibration of the C_{ini} because the parameter is calibrated to UK rainfall and flow records. The design event rainfall – runoff relationship is likely to be different for Ireland, and should be the focus of further research.

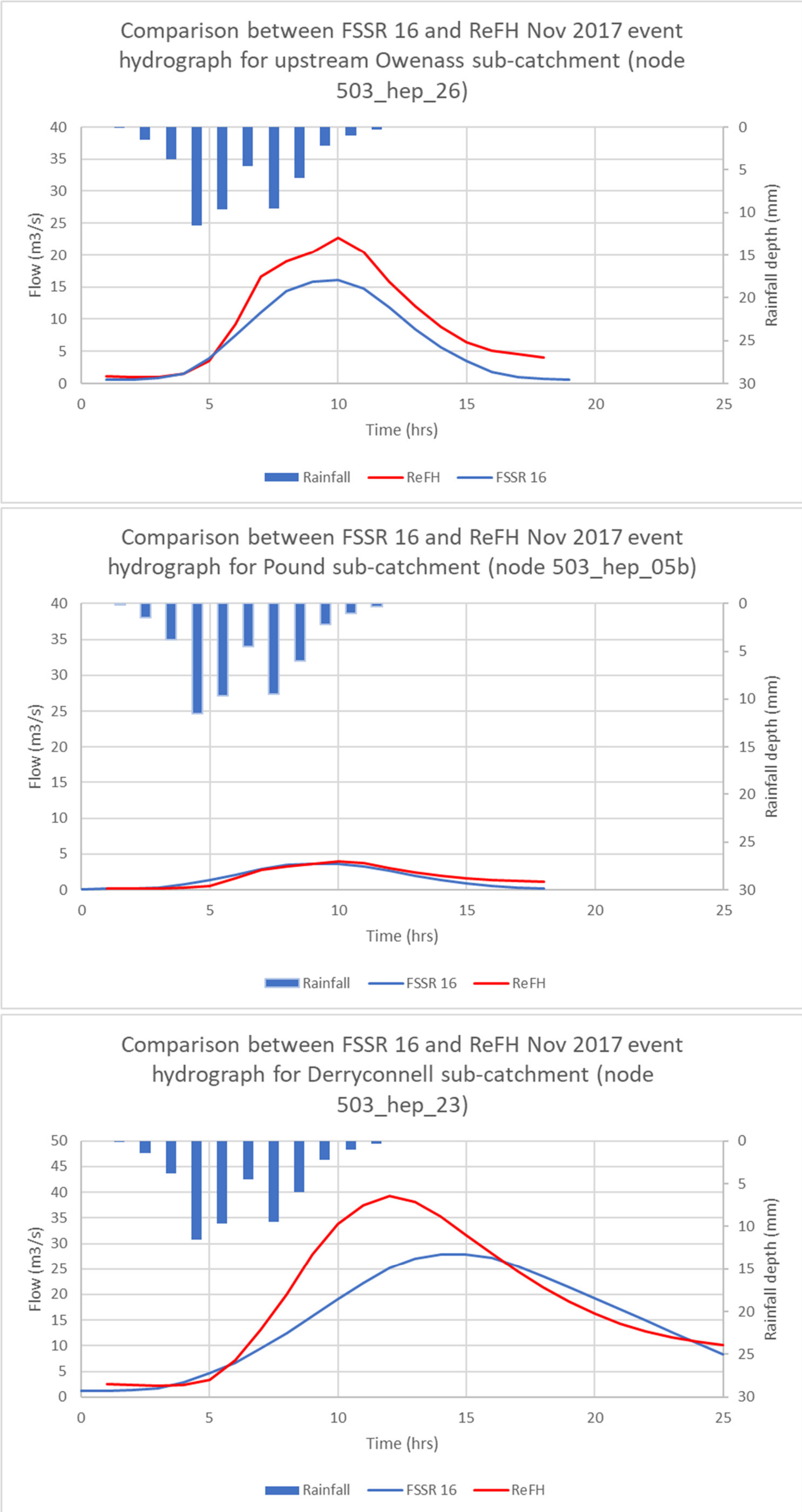

***Figure 2-8:** Mountmellick ReFH and FSSR 16 hydrographs for November 2017 event*

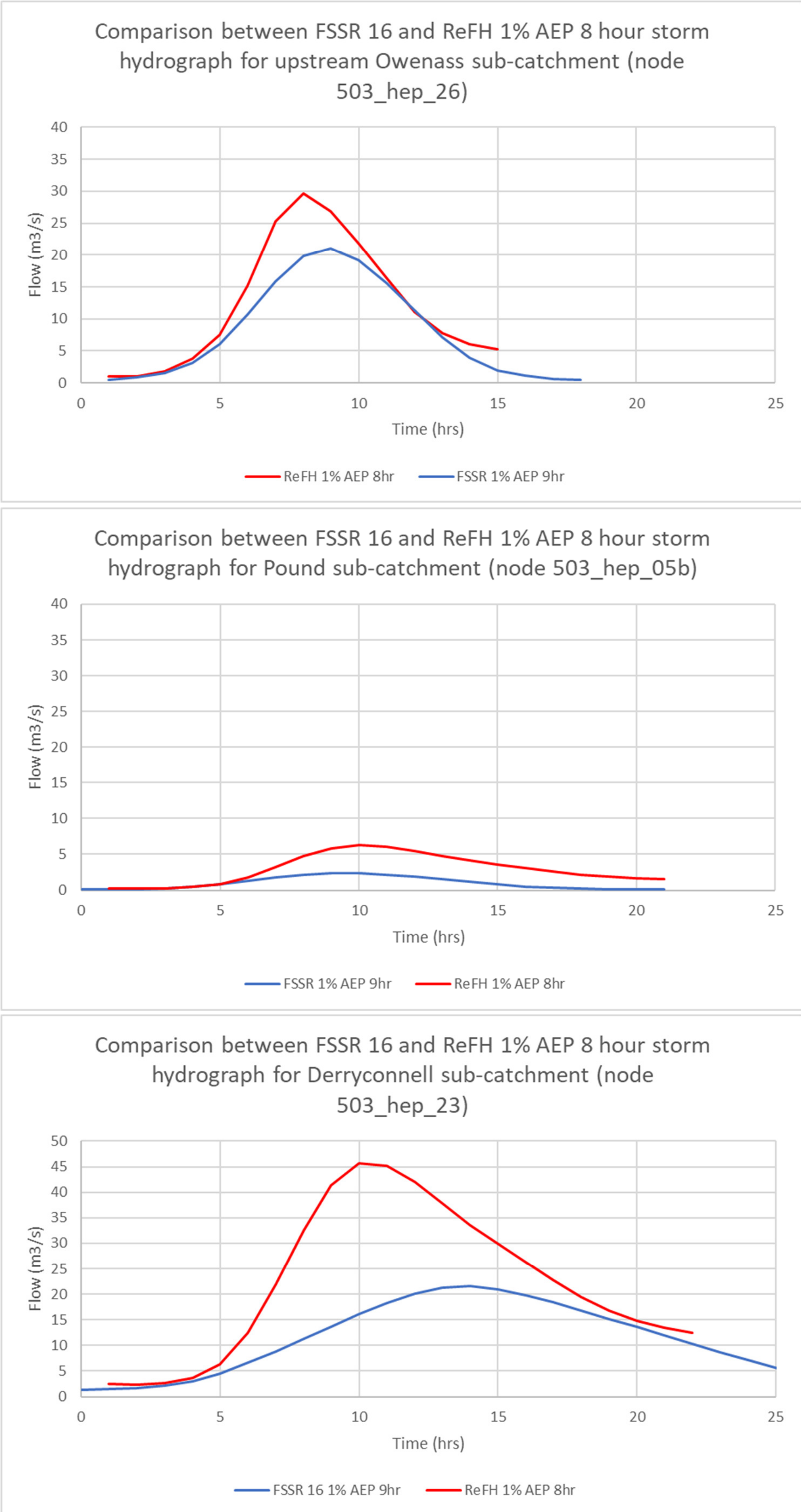

Figure 2-9: *Mountmellick ReFH and FSSR 16 hydrographs for the 1% AEP design event*

3. CASE STUDY 2: KILKEE

3.1 Use of FSSR Rainfall Runoff

The Kilkee Flood Relief Scheme considers the two main watercourses that flow through the town, The Atlantic Stream and the Victoria Stream, their tributaries and additional drainage channels. Figure 3 shows the watercourses in the study area.

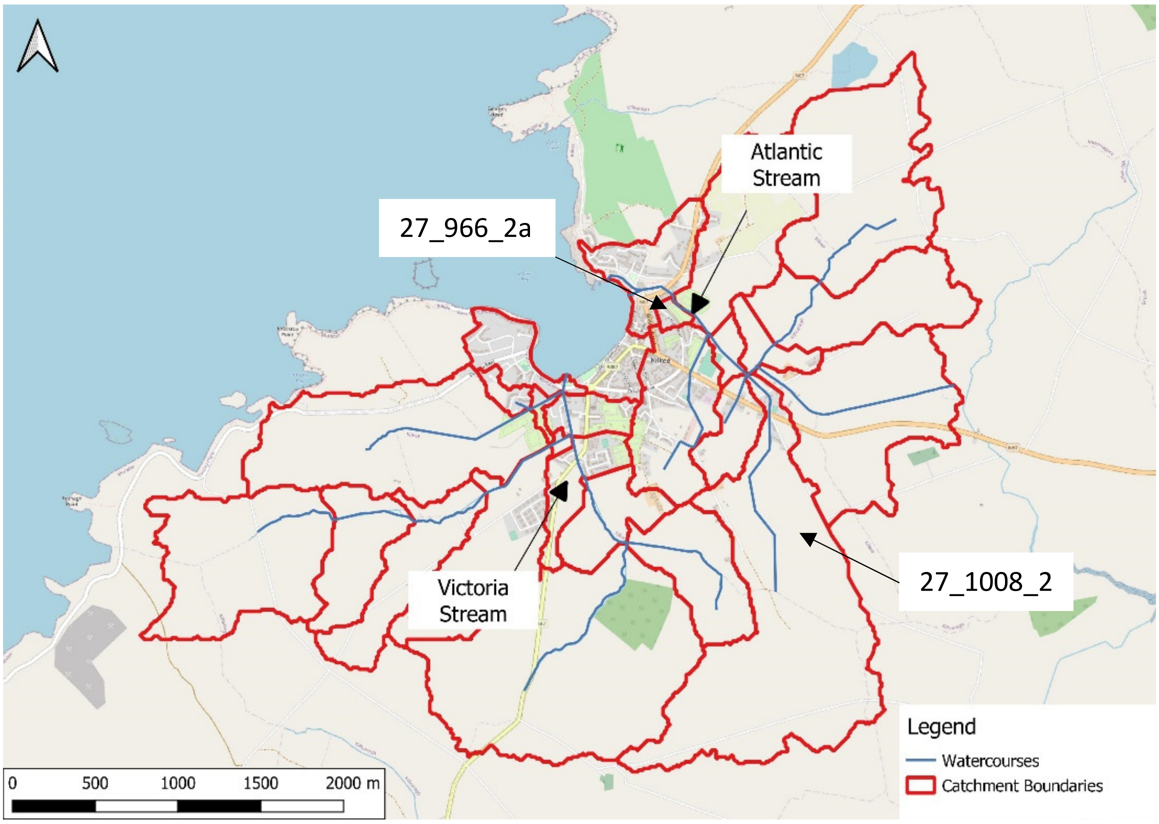

Figure 3: *Kilkee Flood Relief Scene Watercourses and sub catchments*

Upstream measures to reduce the flooding problems of the area will be considered as part of the scheme. Adjustments will be made to the catchment descriptors, model parameters or hydrograph shape to represent a reduction in volume from these upstream measures to assess the potential benefit of the implementation of upstream measures. If these adjustments show that upstream measures reduce the risk and are viable then the upstream measures will be modelled hydraulically.

3.2 Data Requirements

A rainfall-runoff model of the Kilkee catchment area was developed within Flood Modeller and separate FSSR16 units for each sub catchment have been constructed.

Table 2-1 details the specialist inputs required in each FM FSSR16 unit to allow estimation of flows. These specialist inputs are in addition to the basic catchment descriptors (e.g. area), which were detailed earlier in this report. The table also details how they have been derived for the design run inflows.

As flooding in Kilkee has occurred in both winter and summer months the 75% winter storm hydrograph profiles and the 50% summer storm hydrograph profiles were both compared. The summer profile has a higher peak flow; however, the winter profile has a larger volume of flow. In each case, a 75% winter storm hydrograph profile has been used to generate the inflow. Volume is considered a key factor to flood risk in the area so the selection is not likely to be critical but a sensitivity test using summer storm profiles will be carried out in the hydraulic modelling.

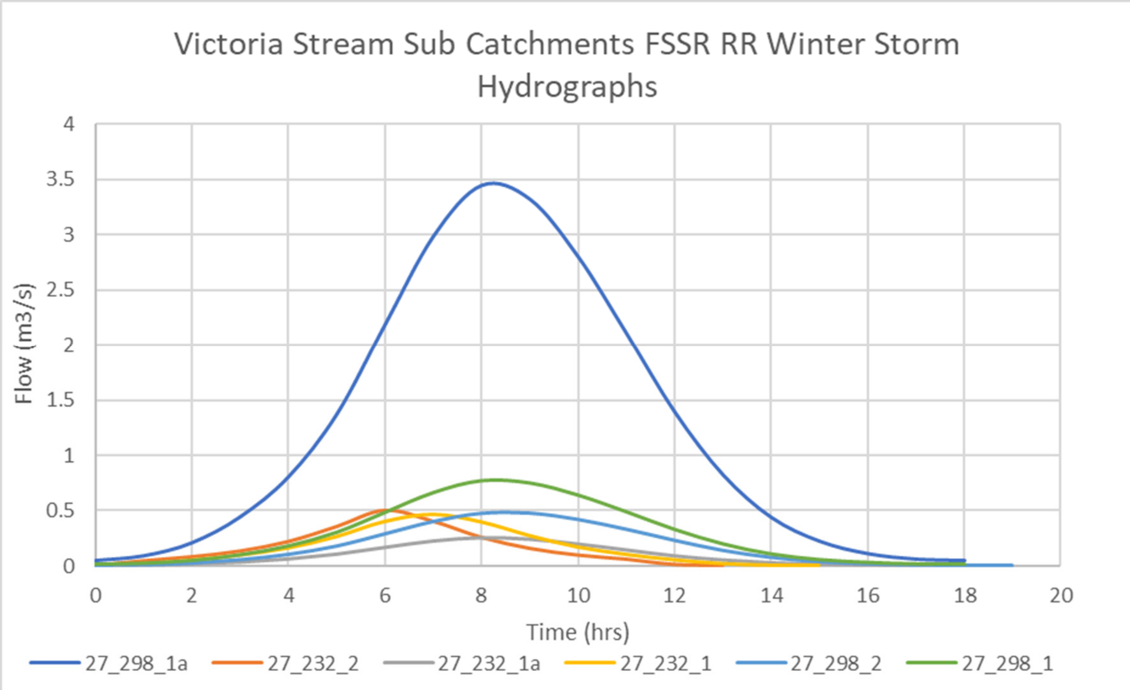

Figure 3-1: *Winter Storm Hydrographs for sub catchments of the Victoria Stream*

3.3 Validation

There is no river gauge data to calibrate the hydrological model. Instead the validation will focus on the comparing the hydraulic model outputs for recent observed flood events. The coupled hydrological and hydraulic validation is necessary because the operation of sluices, gates and maintenance of trash-screens is expected to have a strong influence on flood mechanisms. For this reason the volume of flow and runoff stored and diverted is critical.

3.4 Could a US SCS type approach be used?

The US National Resources Conservation Service (SCS or TR-55) method (USDA, 1986) is a rainfall runoff model which uses a Curve Number (CN) as a runoff coefficient or calibration factor. Widely researched tables are published for different soil types and land cover. Allowances for different proportions of impervious areas are also given in the method. The SCS model and coupled routing models can be based upon a spatially varying grid within Hec-HMS. This ability to disaggregate individual sub-catchments with different runoff, transformation (or routing) and baseflow components based on readily available data gives flexibility to the analysis and identification of different flood management strategies.

The method is widely used globally in all Regions, with the exception of the UK and Ireland, and scaled up to large catchment wide applications without apparent concern. Perhaps the principal difference is the prevalence of peat based soils in Ireland, however Soil Type D in the CN lookup tables is for poorly drained soils. Importantly, the FSU Work Package 4.2 did not explore whether the US SCS Curve Numbers can be translated to Irish soil conditions. The CN number is based on empirical relationship and embedded in this value is an allowance for antecedent conditions and time varying infiltration. There is also no calibration of the relationship between rainfall and river flow probabilities.

Breaking down the hydrological model into constituent components such as the SCS CN approach could allow the analyst to match the catchment and data to a method. For example, where river cross section or pipe network survey data is available the actual geometry of these networks can be applied to the routing model. Where data is not available, more general routing models can be adopted. Despite the limitations and lack of calibration the flexibility and simplicity is appealing, hence this proof of concept.

Check 1: SCS licenses and software

SCS methods are free to use and available in both free (e.g. Hec-HMS) and licensed model software platforms (e.g. MIKE NAM, Flood Modeller Pro) which can be coupled with rainfall, transformation, baseflow and snow melt models (e.g. Hec-HMS, Flood Modeller). Licensing presents no constraint to use. The approach taken below uses Hec-HMS modelling platform to couple the SCS CN loss model to transformation and baseflow models.

Check 2: datasets

At the simplest level a SCS model can be developed from a DTM and information on soils and land cover only. The model detail can be scaled to account for channel and pipe networks, finer resolution land cover, soil, subsoil and vegetation data and more. A rainfall DDF model is required for deriving a storm input, with appropriate selection of storm duration. The model approach is not reliant on any pre-determined catchment descriptors.

Check 3: suitability of Irish catchments

No formal research papers are readily available on the application of SCS approaches to Irish catchments. Some of the CFRAM studies used MIKE NAM rainfall runoff and routing models, which may have applied SCS methods. The critical test is how to convert the US SCS Curve Numbers (CN) and soil types to relevant Irish catchments.

Given that the CN is simply a runoff coefficient, a different version of Percentage Runoff (PR) or Standard Percentage Runoff (SPR) some form of lookup chart could be developed for testing. The lack of specific national research has not constrained the use of SCS globally. In Ireland, peatland soils for raised bog and blanket bog need to be considered. The CN lookup tables have multiple combinations of soil type, land cover and land use. This may give an unrealistic presumption of precision in the application of the model, for what is in effect a calibration factor.

The transformation (routing) and baseflow model elements can be selected from a whole range of international best practise approaches, with substantial academic literature (e.g. Kinematic Wave, Muskingham, Muskingham-Cunge, etc.). Specific Irish characteristics, such as the effect of Arterial Drainage schemes can be represented in these routing models.

Check 4: can a SCS model framework be used to test options?

The gridded SCS CN model allows for fully spatially variable loss model, which can be applied to any practical spatial resolution. The effect of spatially variable natural flood management measures, such as soil management and afforestation can tested in the model.

The Hec-HMS suite includes a range of runoff models. SCS Unit Hydrograph model includes surface, channel and pipe runoff elements. Other models are available such as the ModClark Model, which uses a spatially varying grid based travel time parameter. Kinematic Wave Models can be used where hydraulic calculations enhance the representation of runoff.

For open channel flow routing to flood estimation points, Hec-HMS includes Lag, Muskingham, Modified Plus, Kinematic-wave and Muskingham Cunge methods. The SCS CN runoff model could also be coupled with a detailed hydraulic model if data is available to extend to the catchment outlet.

The flexible nature of the Hec-HMS platform allows for catchment specific testing of upstream and inline natural flood management measures, and can be scaled to the level of detail required or quality of input data available. With the FSSR16 approach, it is only possible to represent the total change in catchment descriptors from a natural flood management measure. With the flexible SCS CN approach and coupled routing models, the actual location of a measure can be represented.

Check 5: Proof of concept and comparison to FSR Kilkee

As a simple proof of concept a basic hydrological model of the Atlantic Stream, Kilkee has been developed in Hec-HMS. The model uses the catchment boundaries developed for the Kilkee Flood Relief Scheme. No canopy (vegetation) interception or evaporation loss or snow melt parameters are required. Two sub-catchments have been tested, one very small heavily urban (27_966_2a), the other including some of the upland catchment and low proportion of urban land cover (27_1008_2).

For the upland catchment (27_1008_2) of 1.61km^2, a SCS CN of 86 with 0.9% impervious has been selected. The 86 CN relates to moderate to poorly drained soils (soil type C for BFI_{soil} of 0.333) and poor grade pasture (Table 2-2c Runoff curve numbers for other agricultural lands, SCS TR-55). For the smaller urban catchment (27_966_2a) of 0.028km^2, a SCS CN of 92 and 62.9% impervious has been used. The 92 CN is for poorly drained soils (soil type D) and high density residential with average lot sizes of 1/8 acre (Table 2-2a Runoff curve numbers for urban areas, SCS TR-55). The FSSR 16 model uses an SPR of 75 for 27_1008_2 and SPR of 70 for 27_966_2a, and both use the FSSR formula for Time to Peak (Tp), Unit Hydrograph parameters and Catchment Wetness Index (CWI). A uniform 11 hour storm duration has been applied for the proof of concept tests. This is greater than the critical storm duration of the smaller catchments, but representative of storms that have caused flooding previously.

Channel routing parameters for sub-catchment 27_1008_2 are based on the typical cross section, slope and length of channel as recorded in the CFRAM river channel survey. Collectors have been included to represent the lateral drainage ditches with inferred geometry from the LiDAR DTM. The surface or sheet flow parameters are also based on the LiDAR DTM. Typical roughness values have been applied. For sub-catchment 27_966_2a assumed surface water drainage network details and geometry have been applied, with the assumption that they drain all of the sub-catchment. Both sub-catchments have an initial baseflow of 0.1 m^3/s, a recession constant of 0.5.

The results of the comparison are presented in Figure 3-2. The upstream catchment has a reasonable match to the peak flow but with a distinctly sharper hydrograph shape. The much smaller urban catchment FSSR 16 peak flow estimate is much less than the SCS CN model. It is clear that more refinement is needed for the smaller catchment, but this is only necessary if the timing of this sub-catchment inflow is critical to either flooding within the sub-catchment or contributing to downstream flooding. The SCS CN loss and kinematic-wave routing methods allow for refinement based on changes to model elements such as pipe network geometry. The SCS CN model may appear more refined and precise, but even with significant experience it will not be clear as to whether refinements are reducing design event and scenario uncertainty or making things just look better.

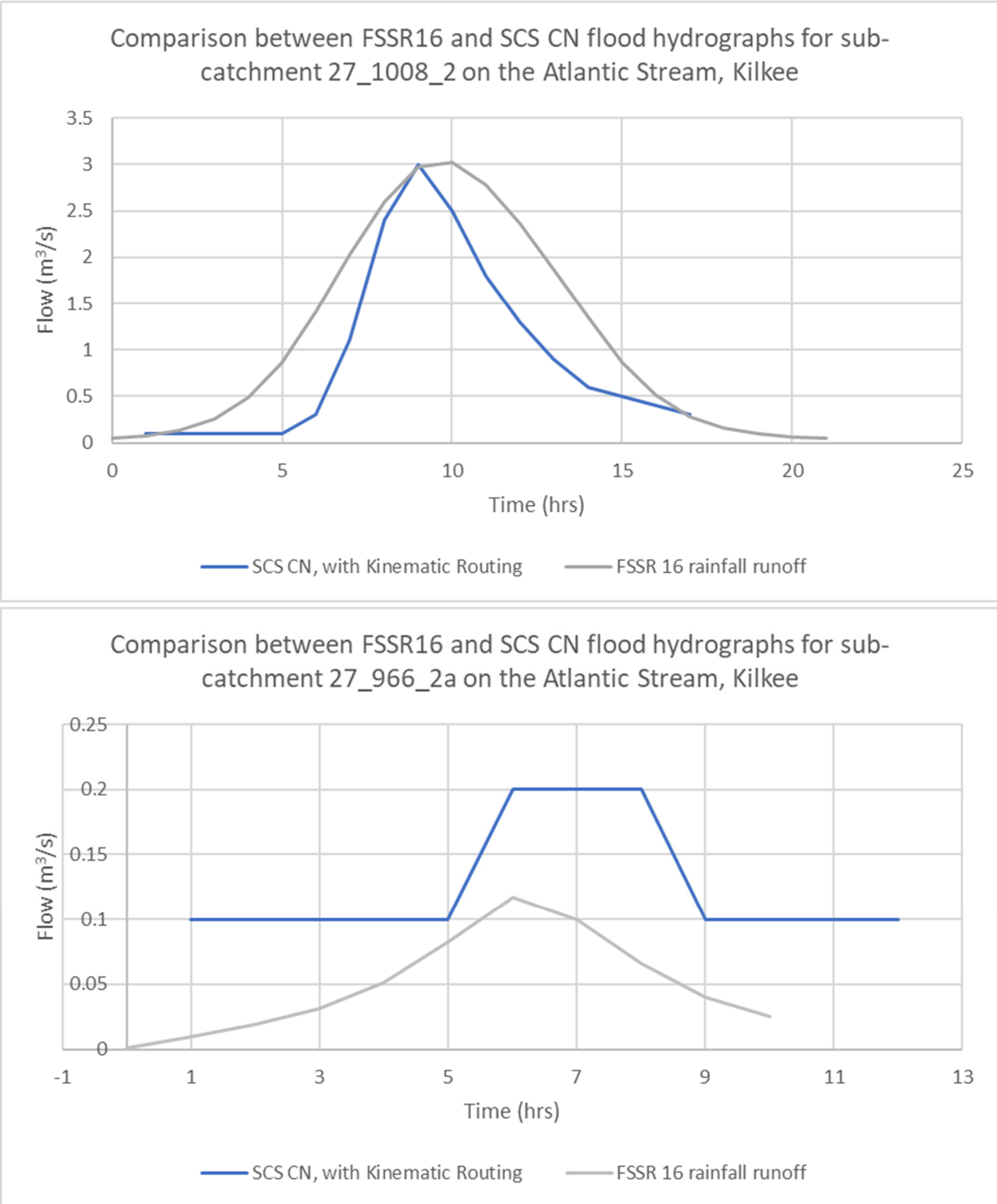

Figure 3-2: *Comparison between FSSR16 rainfall runoff and SCS CN derived flood hydrographs for two sub-catchments on the Atlantic Stream, Kilkee*

4. DISCUSSION ON COMPARING THE ABILITY OF DIFFERENT MODELS TO TEST CATCHMENT SCALE FLOOD RISK MANAGEMENT MEASURES

The case studies presented above, have demonstrated that it is possible to apply alternative rainfall runoff models to Irish catchment data. Both the ReFH and SCS CN approaches require calibration to ensure design event flood hydrographs are valid. Given the FSSR16 model was not developed using, or calibrated to, any Irish hydrometric gauges the status of all three models could be considered equally appropriate. The ability to calibrate models is limited to gauged data records, and further the ability to identify signals from catchment change in gauge data is highly uncertain. Stochastic modelling approaches would be able to evaluate the degree of uncertainty when applying models to ungauged or sparsely gauged catchments.

For identifying opportunities and optimising catchment scale flood risk management measures, process based models need to be able to represent the cumulative and distributed nature of different scales of measure, and the change in conditions over time (during an individual storm, successive storms and a season). This suggests some form of distributed model with temporal variation in parameters would be beneficial.

To revisit FSU, given it is focused on the peak discharge we are limited in our ability to test upstream measures because we cannot adjust QMED, pooling group or single site growth curves or data transfers, to reflect a specific upstream change unless we have specific knowledge of the reduction on peak flow.

The FSSR 16 model is commonly understood and links catchment processes to an estimated hydrograph. The CWI, Tp and PR parameters can be calibrated to fit observed gauge hydrographs. For design events, the relationship between rainfall and river flow probabilities, and Irish national growth curve is used. This simplifies the actual variation in flood growth curves across Ireland and assumes the rainfall – flow probability relationship derived in in the 1975 FSR research is still valid.

To test catchment scale options with an FSSR model we can:

- adjust Slope and Stream Length (S1085 and MSL) to test floodplain and river restoration, but we have no ability to change roughness or additional attenuation effect, and
- adjust SPR and CWI can reflect changes to soil conditions or overall catchment storage, but is the adjustment cannot reflect the actual distribution of measures.

The problem is that it will never be viable to implement Green Infrastructure and catchment measure uniformly across an upstream catchment. To test the effect of possible measures we need spatial variation.

Our criteria for model selection needs to be as follows:

- Loss models that can account for spatially varying changes to soil conditions or vegetation cover.
- Routing or transformation models that can account for spatial variation in drainage ditch, river and floodplain restoration, afforestation and woodland.
- Need to understand the temporal variation and coincidence of a storm track moving across the catchment, successive storms, or localised convective storm on one part of the catchment.
- On top of this, understand climate change?

For RefH to be applied in Ireland, further research to calibrate design flood estimation of the model to a range of Irish catchments is required. This research should also focus on the ability to adjust parameters to represent catchment scale flood measures. The time varying nature of soil conditions and baseflow model offer some potential for testing options and simulation of longer durations, such as successive storms.

The US SCS CN model does not have any time varying element, nor any subsurface processes, so it is not possible to evaluate the change in runoff processes during a storm. The simplicity and widespread global application of the model should not be confused with model accuracy. Further research may find that curve numbers can be adapted for Irish conditions.

4.1 Other rainfall runoff methods

Continuous simulation, and subsequent statistical analysis of modelled peak flows, allows for direct modelling of antecedent conditions. On the basis the model is run over a sufficiently long period, this removes a number of assumptions from design event and options appraisal modelling:

- the need to pre-determine antecedent conditions,
- the need to calibrate a relationship between rainfall and discharge probabilities,
- joint probability of tributary response is inherently included in the output,
- embedded uncertainty if stochastic models are run with input parameter variations.

Furthermore, as soil moisture accounting is dealt with automatically, assigning an antecedent wetness condition is no longer a problem. The CS model parameters can be modified to reflect changes in land management in sub-catchments, especially regarding soil characteristics.

The continuous simulation methodology also provides further examining in uncertainty in flood frequency estimation and the question of consistency of model parameterisations for both continuous flow series and flood frequency simulation.

In the study of Beven (1987), a stochastic rainfall generator was used in conjunction with TOPMODEL to generate 100-year simulations with an hourly time step. This was one of the few studies that have attempted to evaluate the simulations in terms of the reproduction of both observed hydrographs and flood frequency characteristics. It was found that different optimal parameter sets appeared to be necessary to obtain good simulations of both hydrographs and frequency characteristics. (Cameron et al 1999). One of the benefits of the method is that a generated model for one catchment can be also applied on another catchment (TOPMODEL).

Fully distributed models such as the Explicit Soil Moisture Accounting (ESMA) approach require specific and high-resolution data and calibration to the specific soil conditions in the study area. For application in flood studies we would be dependent upon the ability to represent runoff and routing effects at the correct scale. ESMA models are ideal at deriving soil moisture deficits. In Ireland this is reported daily at selected weather stations for a poorly, medium and well drained soils. This parameter may be sufficient level of precision for input into less complex data heavy flood estimation models.

Semi-distributed models are more practical and can be scaled to the level of detail and resolution required. Hydrological response units (HRU) can offer simplification to a fully distributed catchment schematisation. HRUs are parcels of land with similar hydrological characteristics (e.g. soil, slope, etc). A hydrological similarity or topographic index can be derived in GIS software and used as an input to semi-distributed rainfall runoff models. These HRUs become lumped elements that form a broader distributed catchment model. PDM models are based on connected stores and can be run as continuous simulations to cover long time periods. When one store is full, runoff or another store is activated. ReFH is a lumped PDM type of model. These models do not have any upstream spatial variation and so only the cumulative effect of catchment scale measures can be appraised. PDM models have been given spatial elements such as in the Grid to Grid (G2G) models applied in the UK where weather forecast models have been linked to derive flood forecasts. Depending on the spatial resolution of the grid, upstream catchment measures could be appraised.

TOPMODEL is another PDM model, initially developed for small catchments in the UK, which uses the topographic index and includes sub-surface (vertical and horizontal, soil and root zone) and surface flow processes. The routing component is based on a delay function applied to each DTM grid cell in terms of slope and flow path length to the catchment outlet.

The initial conditions for soil saturation are important, however continuous simulation allows for long lead in time to stabilise a model prior to a storm rainfall event and also the possibility of modelling the effect of different antecedent conditions on resulting river flows. The application of TOPMODEL requires the setting of different soil parameters (e.g. transmissivity, porosity), which unlike the FSU catchment descriptors are not readily available. TOPMODEL can present the cumulative change in runoff from catchment measures, but needs to be coupled with a separate routing model for appraisal and optimisation of catchment scale measures. In practice, the model is an attempt to combine the computational and parametric efficiency of an approach using a distribution function with links to physical theory and the ability to more rigorously evaluate the spatial prediction patterns offered by the fully distributed model. (Q) Although it should be noted that this model can only produce a good information on limited range of catchments, which are frequently wetted and have relatively thin soils and moderate topography. It might produce a good fit when calibrated to observed discharges for a wider range of catchments, but it does not then produce good results for good reasons. It is serving only to provide fast runoff generation that is a nonlinear function of storage deficit. A number of different attempts have been made to improve the theory of TOPMODEL which lead to simplified fully distributed models such as HRU.

Another approach to review is stochastic generalization of dynamic models. Such generalization can be performed for all the considered dynamic models, but this would require the involvement of a rather complex mathematical applications of the characteristics, which is hardly justified at this stage. Therefore, stochastic generalization of the simplest dynamic model of a catchment area with lumped parameters is considered, which leads to the Fokker-Planck-Kolmogorov equation for the evolution of the probability density of water discharge in the downstreamt section. The FPK equation can be considered as a genetic model of a runoff formation, which gives a solution in the form of probability density curves evolving over time. For general hydrological conditions a family of Pearson III curves is given, this is usually confirmed by observed data. T. Rossman etal in his study on a Canadian river tested the FPK model for the regime of extreme events in hydrometeorological time series and possible mechanisms of alteration. As a result this model can be used for river bassins with natural rainfall-runoff cycle.

Other models are available, such as URBS common used for flood forecasting, the SMHI HYPE and e-HYPE models, and SWAT. The US Environmental Protection Agency SWAT model uses the SCS CN approach in a grid based distributed hydrological model. Most applications of SWAT tend to be based on a daily interval for water resource modelling as opposed to shorter term sub-daily flood generating rainfall events.

4.2 Remember routing of flow

We must remember that Green Infrastructure and Natural Flood Management measures also seek to reduce the speed of flood waves and attenuate flows through river and floodplain restoration. These effects can be modelled in a range of routing model approaches. Such measures cannot be represented in the runoff model alone.

The most accurate means of representing the routing of flow and runoff is through detailed hydraulic models. It is not always practical to extend model coverage to the full catchment. Fast and efficient 2D hydraulic models such as LISFLOOD and JFLOW can now solve shallow water equations and where a DTM is available can be used to represent routing and attenuation of flow. The testing of measures is possible though adjustments to the DTM or surface roughness values. Older routing models such as Kinematic wave models, Muskingham and Muskingham-Cunge are still valid and can represent measures such as river and floodplain restoration.

4.3 A word of caution with direct rainfall models

Direct rainfall models, where rainfall is input directly onto a 2D hydrodynamic model grid can identify potential overland flow pathways and surface water ponding. Models built with widely available hydraulic modelling software packages (e.g. Flood Modeller, TUFLOW, Hec-RAS 2D, Infoworks, and others) can include time and spatially varying loss and surface roughness parameters for modelling of overland flow. It is important to recognise that many of these models do not have any sub-surface component and without such should not be used as hydrological models for river discharge estimation or fluvial hazard modelling. The loss model may also not fully consider infiltration of ponding into soils which then subsequently discharge through soils into rivers.

5. CONCLUSIONS

This paper has confirmed that the conclusions of Bevan (2012) in that a new generation of rainfall runoff models are required, also apply to Ireland. This is especially true if we want to appraise and optimise catchment scale, natural flood management and green infrastructure approaches to managing flood risk. The hydrological concepts of runoff generation, sub-surface and surface flow and channel routing still apply. We need research for calibrating the transfer of model parameters to catchments with no gauges or measurements.

Continuous simulation using PDM type models such as Grid to Grid, TOPMODEL, SWAT, URBS and E-HYPE present opportunities that should be explored. The ability of these models to represent the effects of distributed catchment change is appealing, but sub-daily timesteps are critical for capturing small catchment flood hazard.

In the meantime, we need realistic and practical tools for hydrograph estimation and to appraise flood management measures. The existing FSU methods for peak flow estimation and hydrograph shape generation do not allow for testing of options through hydrological models. Hydraulic models are needed to optimise and evaluate the performance of distributed catchment storage and land use measures as well as river and floodplain restoration measures. This is not always practical. The alternative is to make an informed judgement on how a measure will alter the peak and hydrograph shape. This is not a robust means of justifying Government investment.

The SCS CN runoff model is easy to implement and has been widely adopted across the world. However, there are conceptual issues in that the model is empirical, and assumes antecedent soil moisture conditions are entirely a function of land cover and use. Further research may confirm that these empirical values are appropriate, but without this the model should be used with caution.

We have found that if we follow the reasons for previously dismissing the potential application of ReFH model to Ireland (**IreFH**), we should also have reason to dismiss the widely used IH124 and FSSR 16 methods. Neither are based on any gauges on the island of Ireland. Perhaps the rational method developed by the Irish Mulvaney in 1851 is the only method prior to the FSU that has been validated to Irish conditions. Sadly, this does not derive a hydrograph and subsequent research has found the C coefficient masks non-linear variation in runoff generation and so is of little use to us. ReFH is the most recent method and can be applied to small and urban catchments and has comparable FSU or easily derived Irish catchment descriptors. We therefore recommend that IreRH research is commissioned to calibrate an IreFH model to Irish gauge data, in terms of both peak discharge and hydrograph shape. This will require review of the C_{ini} (antecedent soil conditions), adjustment of the design event rainfall input data and perhaps reinstatement of the ReFH1 α factor to reflect the relationship between rainfall and flow flood probability. The research should also standardise the catchment descriptors to be applied and consider the unique geography of Ireland.

6. ACKNOWLEDGEMENTS

The authors wish to acknowledge peer review of this paper by Duncan Faulkner and the project and steering groups for the Kilkee and Mountmellick Flood Relief Schemes.

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