Department for Environment Food & Rural Affairs

Environment Agency

Cyfoeth Naturiol Cymru Natural Resources Wales

Llywodraeth Cymru Welsh Government

# Estimating flood peaks and hydrographs for small catchments:

# R3 – Summary of reassessment of FEH methods and recommendations

## FCERM Research & Development Programme

## Research Report

Date: March 2024

Version: SC090031/R3

We are the Environment Agency. We protect and improve the environment.

We help people and wildlife adapt to climate change and reduce its impacts, including flooding, drought, sea level rise and coastal erosion.

We improve the quality of our water, land and air by tackling pollution. We work with businesses to help them comply with environmental regulations. A healthy and diverse environment enhances people's lives and contributes to economic growth.

We can't do this alone. We work as part of the Defra group (Department for Environment, Food & Rural Affairs), with the rest of government, local councils, businesses, civil society groups and local communities to create a better place for people and wildlife.

Published by:

Environment Agency
Horizon House, Deanery Road,
Bristol BS1 5AH

www.gov.uk/environment-agency



Further copies of this report are available from our publications catalogue: Flood and Coastal Erosion Risk Management Research and Development Programme or our National Customer Contact Centre: 03708 506 506

Email: fcerm.evidence@environment-agency.gov.uk.

Author(s):
Elizabeth (Lisa) Stewart

Keywords:
Flood frequency, United Kingdom, rural, urban, plot-scale, QMED, pooling, DDF, ReFH2, local data

Research contractor:
Centre for Ecology & Hydrology, Wallingford, Oxfordshire, OX10 8BB,
01491 838800.

Environment Agency's Project Manager:
Mark Whitling

Project number:
SC090031

# Contents

# Acknowledgements

Particular thanks are due to the Environment Agency's Project Board, members of which were responsible for developing the vision and scope of this research. The board has continued to advise and support the project team, providing valuable feedback, practical suggestions and lively discussions. The project team is also grateful to staff from the Environment Agency, Natural Resources Wales, the Scottish Environment Agency (SEPA) and the Rivers Agency for supplying data and advice on data quality, and to those who have acted as external reviewers.

## Project Board

Anita Asadullah (Project Sponsor, Environment Agency)

Donna Wilson (Project Executive, Environment Agency)

Mark Whitling (Project Manager, Environment Agency)

Andy Eden (Environment Agency)

Tim Hunt (Environment Agency)

Sean Longfield (Environment Agency)

Peter Spencer (Environment Agency)

Rob Stroud (Environment Agency)

Glenda Tudor-Ward (Natural Resources Wales)

## External reviewers

Thomas Kjeldsen (University of Bath)

Claire Samuel (Jacobs)

## Project Team

**Centre for Ecology & Hydrology (CEH)**

Lisa Stewart (Project Manager),

Giuseppe Formetta

Adam Griffin

Ilaria Prosdocimi (now at University of Bath)

Gianni Vesuviano

**Independent consultant**

David MacDonald

**JBA Consulting**

Duncan Faulkner

Harriett Twohig-Howell

Maxine Zaidman

Lara Bentley

Alexander Siddaway

**Wallingford HydroSolutions**

Andy Young

Tracey Haxton

This project follows on from phase 1, which was jointly funded by the Environment Agency, the Centre for Ecology & Hydrology and JBA Consulting.

# Executive summary

This report summarises the results of an analysis of the performance of current flood estimation methods when applied to small catchments using the ‘extended’ data set developed for this project. The background to the project is discussed and the available catchment data are briefly described. The up-to-date versions of the FEH statistical method and ReFH2 have both been found to perform well in small catchments. The results demonstrate that the ReFH1 method and the QMED equation developed by MacDonald and Fraser do not perform adequately in small catchments.

After a pause for the project to consider the implications of these findings, four alternative approaches to flood estimation in small catchments and plots were recommended. Two of these are based on the existing ReFH2 software and require only minor development of the design procedures in urban catchments (summer/winter rainfall profiles and impervious fraction).

Another approach is based on developing a new small catchment flood growth estimation method which could be incorporated into the existing FEH statistical method in an upgraded version of WINFAP-FEH.

The final approach requires more work to develop a simplified plot-scale estimation method based on freely available data, if available.

# Important Note

Work on Project SC090031 ‘Estimating flood peaks and hydrographs in small catchments (Phase 2)’ began in December 2013. Tasks carried out in the early stages of the project have already been documented in several project notes and reports, so it is possible that there may be some inconsistencies, particularly in the various data sets and methods that have been applied at different points in time.

This report provides a summary of the evidence and decisions made at the time those decisions were made. This report is published for scientific completeness, as a record of which decisions were based upon which information. Tasks or activities described as “forthcoming” or “ongoing” within this report were statements made at the time this report was written. They may or may have not been completed depending on how each part of the project progressed.

# 1. Background

This report provides a summary of the analysis carried out in Task 2.1.1 of Project SC090031 'Estimating flood peaks and hydrographs in small catchments' *(*Phase 2*)* and makes recommendations for the remainder of the project to meet project milestone 5 – 'Evaluation of existing FEH methods and recommendations' (see Appendix A).

The aim of Task 2.1.1 was to evaluate the performance of the existing FEH methods of flood peak and hydrograph estimation in small catchments using the 'extended' data set of peak flow data developed during Task 1 and to make recommendations for developing improved methods. Subject to the agreement of the Project Board, developing these improved methods will be the focus of Tasks 2.1.4 and 2.1.5.

Earlier in the project, data for a small number of plots were analysed and the results were reported in two project notes (JBA, 2015; WHS, 2014).

Table 1 provides a summary of the task structure of the project and the agreed deliverables. The tasks that were complete at the time of writing this report are also shown in the table to differentiate them clearly from the next stages of the project. As indicated in the flow chart in Figure 1, a decision is needed on the requirement for improved methods for estimating floods in small catchments. This report sets out evidence-based recommendations for the final stages of the project.

Section 2 outlines the main conclusions of the analyses carried out in Tasks 2.1.1 and 2.1.2 (Re-evaluation of FEH methods and analysis of plot-scale data) and makes general recommendations for improving current methods. Recommendations for the final sub-tasks of this stage of the project are presented in section 3, together with a proposal for producing a range of improved methods for small catchments and plots. For the user, the choice of method will depend on the type of application, the available data and the degree of accuracy required.

**Table 1 - Structure of the project and deliverables**

| Task | Description | Deliverable | Completed at time of writing this report |
|---|---|---|---|
| **1.1** | Create shortlist of additional stations | Shortlist | Yes |
| **1.2A** | Review/QA data and ratings (existing) | Final data set of peak flows (AMAX/POT) and QMED | Yes |
| **1.2B** | Review/QA data and ratings (new) | Final data set of peak flows (AMAX/POT) and QMED | Yes |
| **2.1.1** | Evaluation of existing FEH methods | Report | Yes |
| **2.1.2** | Analysis of plot-scale runoff estimation | Project notes (JBA/WHS & CEH) | Yes |
| **2.1.3** | Recommendations for development of new method(s) | Summary report | Yes |
| **2.1.4** | Development/validation of new methods | Methods | No |
| **2.2** | Guidance on use of local data | Inclusion in final project report | No |
| **2.3** | Investigation of high intensity short duration rainfall | Report | Yes |
| **3.1** | Internal review of Phase 2 | Comments and amendments | No |
| **3.2** | Draft report and recommendations | Draft report | No |
| **3.3** | External peer review (EA-led) | Final report | No |
| **3.4** | Worked examples and dissemination | User guidance/webinar | No |

Table summary: Table 1 shows the task structure of the project and the agreed deliverables. It shows the tasks, lists the main deliverables, and highlights those tasks that had been completed by the time this report was written.

The flowchart in Figure 1 shows the key steps within Task 2.1:

- 2.1.1: Evaluation of FEH methods using extended small catchment data set
- 2.1.2: Analyse new data for small plots
- 2.1.3: Recommendations for the development of improved methods
- 2.1.4: Development/validation of the new methods
- 2.1.5: Report and recommendations

It is assumed that the reader has a detailed understanding of FEH methods, hydrological terminology, and catchment descriptors.

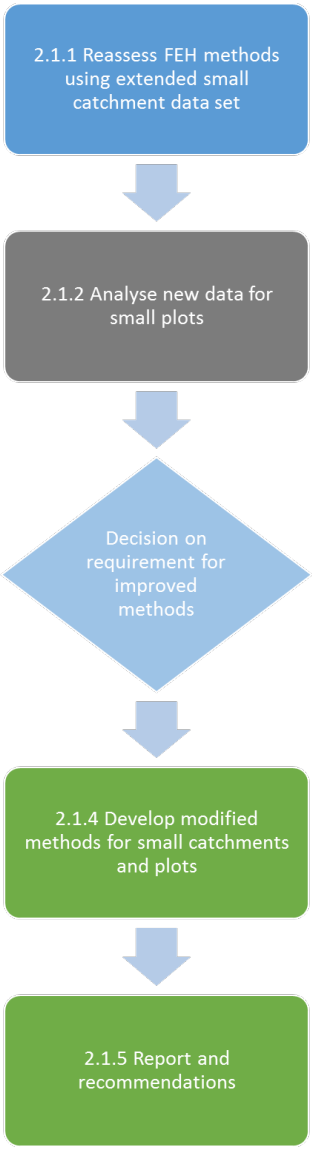


**Figure 1 - Flow chart of structure of Task 2.1**

# 2. Reassessment of FEH methods in small catchments and plots

This section provides a summary of the results of the analyses carried out in Tasks 2.1.1 (Reassessment of FEH methods using 'extended' data set) and 2.1.2 (Analysis of plot-scale data). Full details are provided in the technical report (Stewart and others, 2016) and two project notes (JBA, 2015; WHS, 2014).

## 2.1 Data

Task 1 of this project was concerned with developing an 'extended' set of peak flows and QMED values for small UK catchments, defined as draining an area of up to 40 $km^2$. This definition was used to allow for a 'transition zone' of intermediate catchments to ensure seamless integration between any new methods for the smallest catchments and existing generic methods. Data for a total of 217 small, gauged catchments were collated and the catchments were divided into 'high-quality' and 'extended' subsets considered suitable for estimating QMED and QT. Details of the sources of the data and the total numbers of catchments in each subset are given in Table 2. Gauge locations are illustrated in Figure 2.

**Table 2 - Summary of data available to the analysis**

| Data sources | Used in these data subsets within this project | Number of stations |
|---|---|---|
| **Updated NRFA peak flow data** | Both 'High-quality' QMED & 'Extended' QMED | 119 |
| **Additional stations identified in Task 1.2** | Both 'High-quality' QMED & 'Extended' QMED | 32 |
| **Added to NRFA peak flow data shortly after Task 1.2** | Both 'High-quality' QMED & 'Extended' QMED | 2 |
| **MacDonald and Fraser stations** | 'Extended' QMED only | 64 |
| **Gauged AMAX data suitable for pooling** | Both 'High-quality' QT 'Extended' QT | 58 |
| **Gauged AMAX data** | 'Extended' QT only | 134 |

Table summary: Table 2 shows sources of the data and the total numbers of catchments in each subset:

- 153 'high quality' QMED stations, made up of 119 NFRA peak flow data, 32 additional stations added in task 1.2 & 2 added to NFRA peak flow data after task 1.2
- 217 'extended' QMED stations, made up of the 153 'high quality' QMED stations, and an additional 64 from MacDonald and Fraser
- 58 'high quality' QT stations for which gauged AMAX data is flagged as suitable for pooling
- 192 'extended' QT stations, made up of 134 stations for which gauged AMAX data is not flagged as suitable for pooling and the 58 'high quality' QT stations

The map in Figure 2 shows the locations of the sites identified for Phase 2 study and the flood peak record for each location:

- purple: 4-20 years
- yellow: 21-40 years

- Blue: 41-64 years

QMED value data is available where locations are marked with a coloured dot only, whilst flood peak record data is available for those marked with a dot with a surrounding circle.

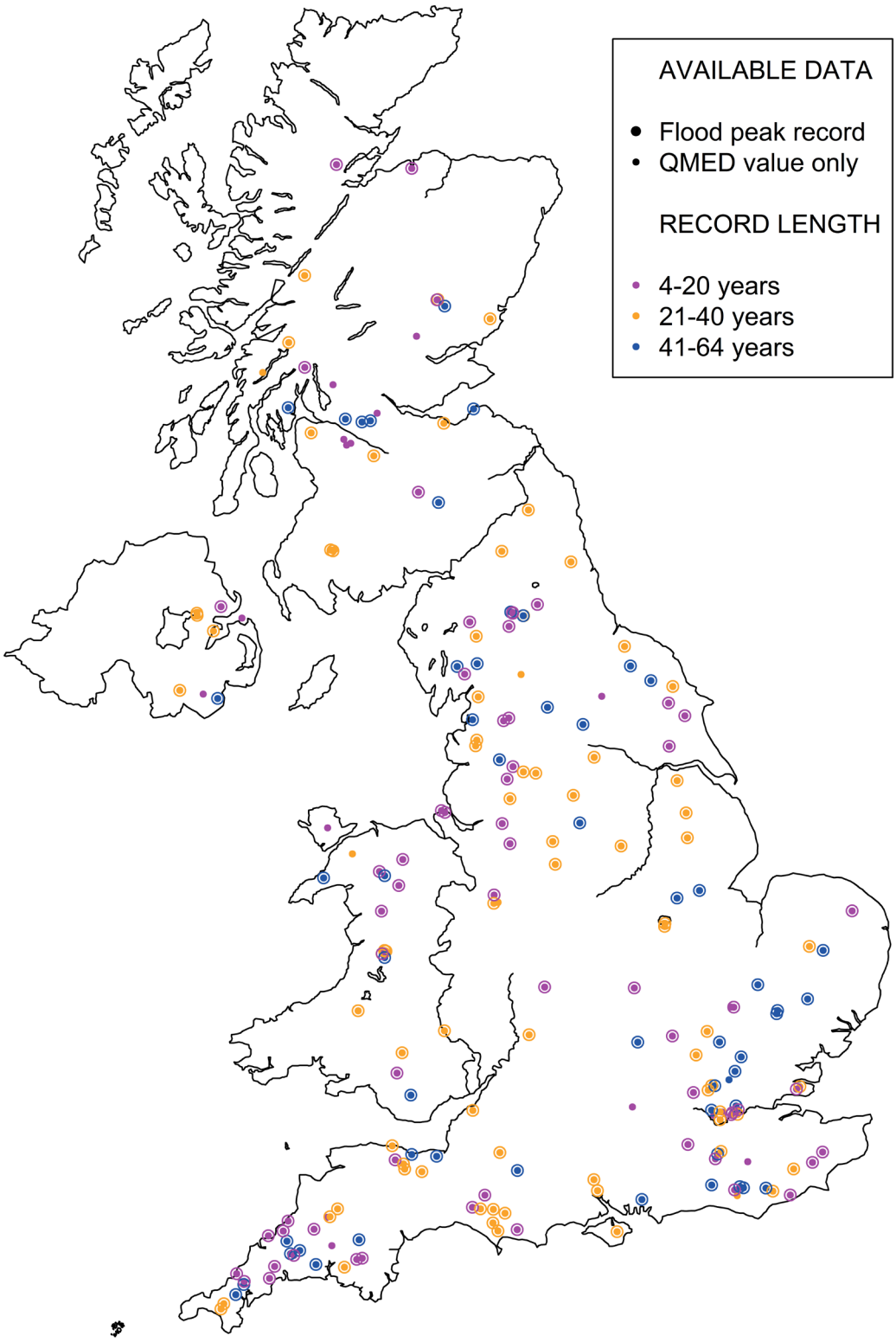


**Figure 2 - Location map of sites identified for phase 2 study**

Tables 3 and 4 indicate how the 'high-quality' and 'extended' data sets can be further broken down by degree of urbanisation. Overall, the study data set is somewhat less urbanised than the NRFA peak flow data set, although this is not highly urbanised in general. It should be noted that the automated approach adopted in this study was not able to apply the ReFH1 and ReFH2 methods on catchments with values of FARL of less than 0.9, and therefore the total number of catchments analysed for each data set is less than the total shown in Table 2.

**Table 3 - Number of catchments per data set for QMED estimation**

| Data set | Essentially rural ($URBEXT_{2000}$ < 0.03) | Moderately urbanised (0.03 ≤ $URBEXT_{2000}$ < 0.15) | Heavily urbanised ($URBEXT_{2000}$ ≥ 0.15) | Total |
|---|---|---|---|---|
| **'High-quality'** | 103 | 19 | 24 | 146 |
| **'Extended'** | 150 | 24 | 33 | 207 |

Table summary: Table 3 shows the number of 'high-quality' and 'extended' data sets for the QMED estimation broken down by degree of urbanisation (essentially rural, moderately urbanised and heavily urbanised).

**Table 4 - Number of catchments per data set for QT estimation**

| Data set | Essentially rural ($URBEXT_{2000}$ < 0.03) | Moderately urbanised (0.03 ≤ $URBEXT_{2000}$ < 0.15) | Heavily urbanised ($URBEXT_{2000}$ ≥ 0.15) | Total |
|---|---|---|---|---|
| **'High-quality'** | 43 | 7 | 5 | 55 |
| **'Extended'** | 133 | 21 | 28 | 182 |

Table summary: Table 4 shows the number of 'high-quality' and 'extended' data sets for the QT estimation broken down by degree of urbanisation (essentially rural, moderately urbanised and heavily urbanised).

Ongoing discussions with staff from the Environment Agency and Natural Resources Wales have identified several other catchments that were rejected during the Task 1 data collation exercise that might still prove useful in the next stage of the project, for example for testing and verification of new methods.

## 2.2 Main results

The analysis of the application of the existing FEH methods and MacDonald and Fraser's QMED equation using the rural/urban/'high-quality'/'extended' subsets produced the following key results:

QMED estimation:

- ReFH2 performs best overall for small rural catchments (< 40 $km^2$), particularly in urban and/or wetter and less permeable catchments

- FEH statistical method came a close second for rural catchments and performed well in permeable catchments
- estimated error in QMED was not found to be related to catchment area

QT estimation:

- little difference in performance of the most up to date FEH methods was found in rural catchments
- FEH statistical method tends to select similar pooling-groups for all small catchments because of the weight given to catchment area in the pooling distance measure

The analysis of plot-scale runoff carried out earlier in the project was limited by the small number of data points but identified the following results:

- ReFH1 and the FEH statistical method appear to underestimate QMED at two out of three sites, although the available records were not long
- ReFH2 is a better estimator of QMED than ReFH1 when applied to small catchments
- ReFH2 estimates are broadly scale-independent over the range of small catchments present in the NRFA peak flow data set

## 2.3 Recommendations

The re-evaluation of the existing methods of flood estimation using the 'extended' data set has resulted in the following recommendations:

- the most up to date FEH methods (FEH statistical and ReFH2) should be used rather than the MacDonald and Fraser QMED equation
- ReFH2 should be used rather than ReFH1 in all catchments
- the form of the QMED estimation equation for small catchments should be reviewed and alternative catchment descriptors should be investigated
- further work should focus on reviewing the pooling procedures for small catchments to overcome the problem of overgeneralisation of growth curves - several possible approaches could be considered, including exploring additional catchment descriptors to define pooling-groups for small catchments.
- further work should consider the choice of design inputs (summer versus winter) for (small) urban catchments in ReFH2, together with the specification of the default estimates of impervious extent

Further details of the proposed research to develop improved methods in small catchments and plots are presented in section 3.

# 3. Proposed project outputs

## 3.1 Introduction

The original specification for this project envisaged that up to three sets of methods would be investigated, with the choice of method in any instance depending on the application. The three sets of methods were broadly defined as follows:

1. Full FEH methods:
    - FEH statistical method as applicable to all catchments of at least 0.5 $km^2$ in area
    - 'Extended' ReFH method (now known as ReFH2 since upgraded software was released in 2015)
2. A rapid analysis method tailored to small fluvial catchments.
3. A simplified method for plot-scale areas (for greenfield/brownfield and post-development assessments) for limited return periods which makes use of free data.

## 3.2 General recommendations

Following on from the results and recommendations presented in section 2, it is proposed that the current versions of the FEH methods (FEH statistical method and ReFH2) should continue to be used to provide flood estimates in small fluvial catchments, especially where catchment-wide studies require estimates at multiple points along the river network. The FEH data and software packages (FEH Web Service, WINFAP-FEH 3 and ReFH2) are subject to ongoing review and development and continue to be appropriate to the full range of catchment areas in the UK, 0.5 $km^2$ being the recommended lower limit to reflect the resolution of the underlying spatial data. Work on the next version of WINFAP-FEH is now under way and is expected to be released in late 2016. These existing 'full' methods correspond to points 1(i) and (ii) above.

The results summarised in section 2 have identified the requirement for a new pooling methodology for small fluvial catchments to overcome the problem of the same catchments appearing in multiple pooling-groups. At the same time, it is also recommended that the QMED equation should be revisited to identify alternative key catchment descriptors to characterise flood response in small catchments. It is envisaged that any new QMED estimation and pooling methods for small catchments would be integrated into the existing FEH statistical procedures as implemented in WINFAP-FEH in due course. This represents the recommended approach to point 2 above. Further details of the proposed research are provided in section 3.3.

Finally, a simple, freely available method suitable for plot-scale flood estimation aimed at point 3 is required. This could be based on a conservative implementation of a simplified FEH statistical method. There is also a requirement to provide a methodology for

estimating flow volumes and therefore a simple way of deriving hydrograph shape should also be developed. The proposed approach is outlined in section 3.3.

Since the project scope was originally identified, the ReFH2 software has been released and is now recommended in the Construction Industry Research and Information Association (CIRIA) SuDS manual (CIRIA, 2015) for estimating greenfield and post-development runoff rates and volumes. It is therefore recommended that ReFH2 using the standard FEH design inputs (derived from the FEH13 rainfall model) should be the preferred approach to flood estimation in small plots (that is, an alternative to 3 above but using FEH catchment descriptors and rainfall inputs). This does not require any further major development at present, although the use of summer and winter design profiles will be explored, together with the sensitivity of the results to the impervious fraction used.

As a result, it is proposed that the final deliverables of this project should be four alternative methods for flood estimation in small catchments and plots as illustrated in the flow chart in Figure 3. These are:

- FEH statistical method, including a new pooling method appropriate to small fluvial catchments
- ReFH2 applied to small fluvial catchments
- ReFH2 plot-scale for small areas without a defined river flow network
- A new simplified method using free data for plot-scale application (replacing the use of IH124)

## 3.3 Outline of proposed research and final project deliverables

The research proposed for the final tasks of the project is as follows:

**Development of a revised QMED equation for small catchments (< 25 km$^2$)** This work will consider the relationship between QMED and permeability as indexed by both BFIHOST and BFI estimated from gauged data and will consider several catchments for which these two values differ markedly. The possibility of using alternative amalgamations of HOST using finer resolution soil mapping will also be explored. Substituting SAAR with alternative climatological indices such as RMED-1H will be considered.

**Development of a revised pooling procedure for small catchments.** This work will consider alternative catchment descriptors as described above. It is envisaged that the final method will be incorporated into WINFAP-FEH in due course.

**Further refinement of ReFH2 method for small urban catchments and plots.** This work will focus on refining the recommendations for selecting appropriate design storm profiles and the sensitivity of the results to the choice of impervious fraction.

**Analysis of hydrograph shape.** This analysis will seek to characterise key metrics of hydrograph shape from observed data. These values will be compared with design hydrographs from the ReFH2 model. Suitable flood event hydrographs will be abstracted from continuous flow data for about 20 catchments using readily available software. The

method developed by Archer and others (2000) will be used to characterise hydrograph shape. The results of the analysis will be reported in the final project report.

**Development of a free precautionary method for plot-scale areas.** It is proposed that this method will take the form of digital grids/maps of runoff rates in l/s/ha for specified key return periods (T=1, 2, 30, 100 years). The use of regional envelope curves based on observed flood event data will also be explored. The proposed delivery mechanism is via the FEH Web Service interface (free of charge) to ensure that the method is supported and integrated with existing methods for all catchments. As this method will need to be based on data sets that are freely available for commercial use, the first step in the development will be to identify the sources of such data.

**Development of a short-cut method to derive hydrograph shape.** This work will revisit the short-cut method outlined in FEH Vol. 4, with the aim of providing a simple updated method. It is hoped that it will be possible to incorporate this method into the free precautionary method described above.

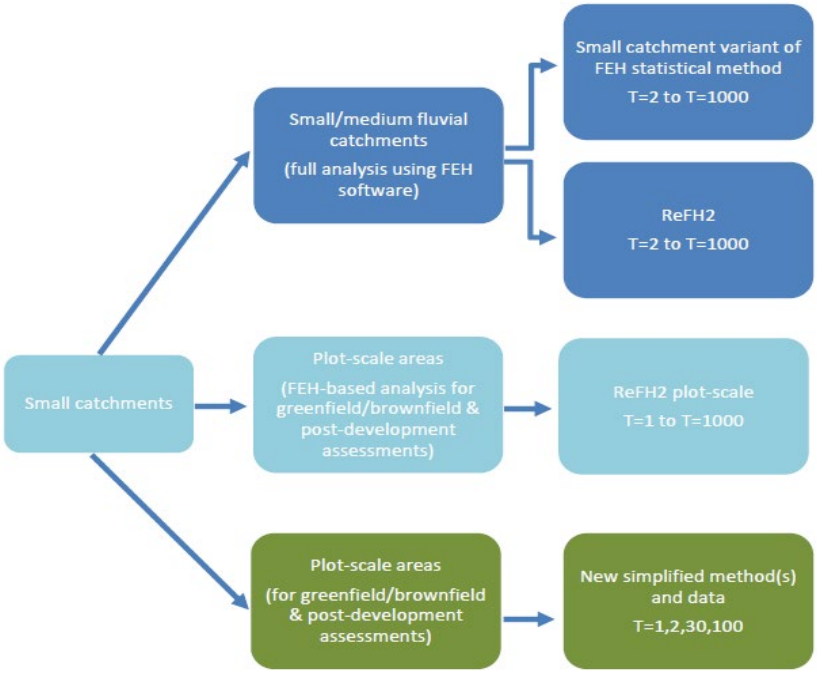


**Figure 3 - Schematic representation of proposed final project outputs**

# References

ARCHER, D., FOSTER, M., FAULKNER, D. and MAWDSLEY, J., 2000. 'The synthesis of design flood hydrographs' Proc. Flooding: risks and reactions. CIWEM/ICE Conference, London, October 5, 2000, 45 to 57.

CONSTRUCTION INDUSTRY RESEARCH AND INFORMATION ASSOCIATION (CIRIA), 2015. 'The SuDS Manual' CIRIA C753, London.

JBA CONSULTING, 2015. 'Investigations of plot-scale runoff data' Project note (SC090031) March 2015.

KJELDSEN, T.R., 2009. 'Modelling the impact of urbanisation on flood run-off volume' Water Management, 162, 329 to 336.

KJELDSEN, T.R., MILLER, J.D. and PACKMAN, J.C., 2013. 'Modelling design flood hydrographs in catchments with mixed urban and rural land cover' Hydrology Research, 44 (6), 1,040 to 1,057.

WALLINGFORD HYDROSOLUTIONS, 2014. 'Evaluation of ReFH2 for plot-scale estimation of QMED' Project note (SC090031) December 2014.

WALLINGFORD HYDROSOLUTIONS, 2015b. 'The Revitalised Flood Hydrograph Model ReFH 2: Technical Guidance'.

# Appendix A: Project milestones

**Table 5 – Main project milestones**

| Milestone | Description | Status (at the time of writing this summary) |
|---|---|---|
| **1** | Draft final shortlists for review by Project Board (spreadsheet and notes) | Complete |
| **2** | Construction of extended data set (report and data set) | Complete |
| **3** | Analysis of high intensity, short-duration rainfall (report) | Complete |
| **4** | Analysis of plot-scale runoff (report) | Complete |
| **5** | Evaluation of existing FEH methods and recommendations (report) | Under review |
| **6** | Guidance on use of local data (report) | Complete – to be included in final project report |
| **7** | Development/validation of new methods (report) | Incomplete |
| **9** | Internal review of Phase 2 (report) | Incomplete |
| **10** | Draft final report | Incomplete |
| **11** | Final project reports | Incomplete |
| **12** | Project dissemination | Incomplete |

Table summary: This table summarises the 12 project milestones and highlights those that were complete when this report was written.

# Would you like to find out more about us or your environment?

Then call us on

03708 506 506 (Monday to Friday, 8am to 6pm)

Email: enquiries@environment-agency.gov.uk

Or visit our website

www.gov.uk/environment-agency

## incident hotline

0800 807060 **(24 hours)**

## floodline

0345 988 1188 **(24 hours)**

Find out about call charges (https://www.gov.uk/call-charges)

## Environment first

Are you viewing this onscreen? Please consider the environment and only print if absolutely necessary. If you are reading a paper copy, please don't forget to reuse and recycle.