



Flood Modelling Guidance for Responsible Authorities

Version 1.1

1 Executive Summary

Developing our knowledge of flooding and how we can effectively assess potential impacts on our communities is essential in implementing effective and sustainable flood risk management plans. Flooding is a complex natural process arising from a range of sources (e.g. rivers, sea, surface water/pluvial) and from a range of mechanisms. Using information on the characteristics of floods we are able to assess the potential impact of floods using computer simulations. Computer flood models are key tools in assessing, testing and informing the delivery of flood risk management actions; while there will remain inherent uncertainty in representing natural systems, quality models enable the production of flood maps and data that support communication with the public and enable key policy and investment decisions.

Utilising a **consistent** framework to guide model development will support a common understanding and effective **communication** of flood study needs within and between organisations. Ensuring a clear description of model needs enables models to be developed appropriately to deliver study objectives. Thus, with an improved knowledge base, common language and improved communication, **model quality** can be raised to improve confidence in information that empowers decision-makers to act in support of flood risk management.

This modelling guidance document is therefore intended to provide a common technical basis to support Responsible Authorities in the planning, development and use of flood models to inform flood risk management decisions. As flood modelling science is constantly evolving, this guidance will be revised as our understanding improves. SEPA's strategic flood risk team (strategic.floodrisk@sepa.org.uk) welcome any questions, comments or suggestions for improvement regarding this guidance.

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2 Introduction

2.1 Purpose of the Flood Modelling Guidance

This technical flood modelling guidance document is intended to support those in Responsible Authorities who are responsible for developing and commissioning flood studies in respect of flood risk management planning. This guidance provides technical guidance for the modelling aspect of flood studies and should be used in conjunction with the Local Authority Flood Study Checklist¹, which provides additional information on non modelling aspects of a flood study. The Flood Risk Management (Scotland) Act 2009 (FRM Act) has established a collaborative approach to the development of new information in support of flood risk management. As part of this approach the adoption of consistent principles at each step of the process will ensure that we develop nationally comparable risk-based information. This will allow Responsible Authorities to develop, share and understand flood risk on a common basis. Establishing a common understanding through guidance will enable strategic and local needs to be linked by common values, approaches and definitions of quality for appropriate use.

The flood hazard and flood risk information which underpins flood risk management decisions is often derived from computer flood models. Flood models use simplifications and assumptions to represent complex natural systems and this leads to inherent uncertainty, which must be acknowledged when making decisions based on model results. This document therefore seeks to provide guidance for Responsible Authorities on where uncertainty may arise in flood modelling and how it may be managed through the modelling process so that it can inform appropriate decisions. An important component of this is that contractors work to a common set of best practice guidelines in building models and in documenting the modelling process; Responsible Authorities are encouraged to refer their contractors to this guidance document to promote compliance with best practice. For site-specific Flood Risk Assessments (FRAs) to inform land use planning, guidance is provided in [SEPA's Technical Flood Risk Guidance for Stakeholders](#) (SEPA, 2015). Table 2-1 shows where this guidance and the Technical Flood Risk Guidance for Stakeholders should be followed.

Who?	Developer	Responsible Authority		
What?	FRA	Flood Study	NFM Study	Integrated catchment study
Which Document?	Technical Guidance for Stakeholders (SEPA, 2015)	This Guidance		Scottish Water and UDG guidance for modelling sewer systems in addition to this Guidance.

Table 2-1: Which document do I need?

This guidance document is intended to provide a technical overview of the development of flood models to a standard that allows them to inform flood risk management decisions. Project-specific requirements will need to still be considered as each model is unique to the location and scale of study as well as to budget, time and resource. This document, however, seeks to identify the main elements to consider when establishing a flood modelling project and offers guidance on planning, input data, model set-up, model calibration, model quality checks and reporting requirements.

¹ Local Authorities who do not have a copy of the Flood Study Checklist can obtain this from frmplanning@sepa.org.uk or from the SCOTS – Flood Risk Management group web portal (Knowledge Hub) <https://khub.net>.

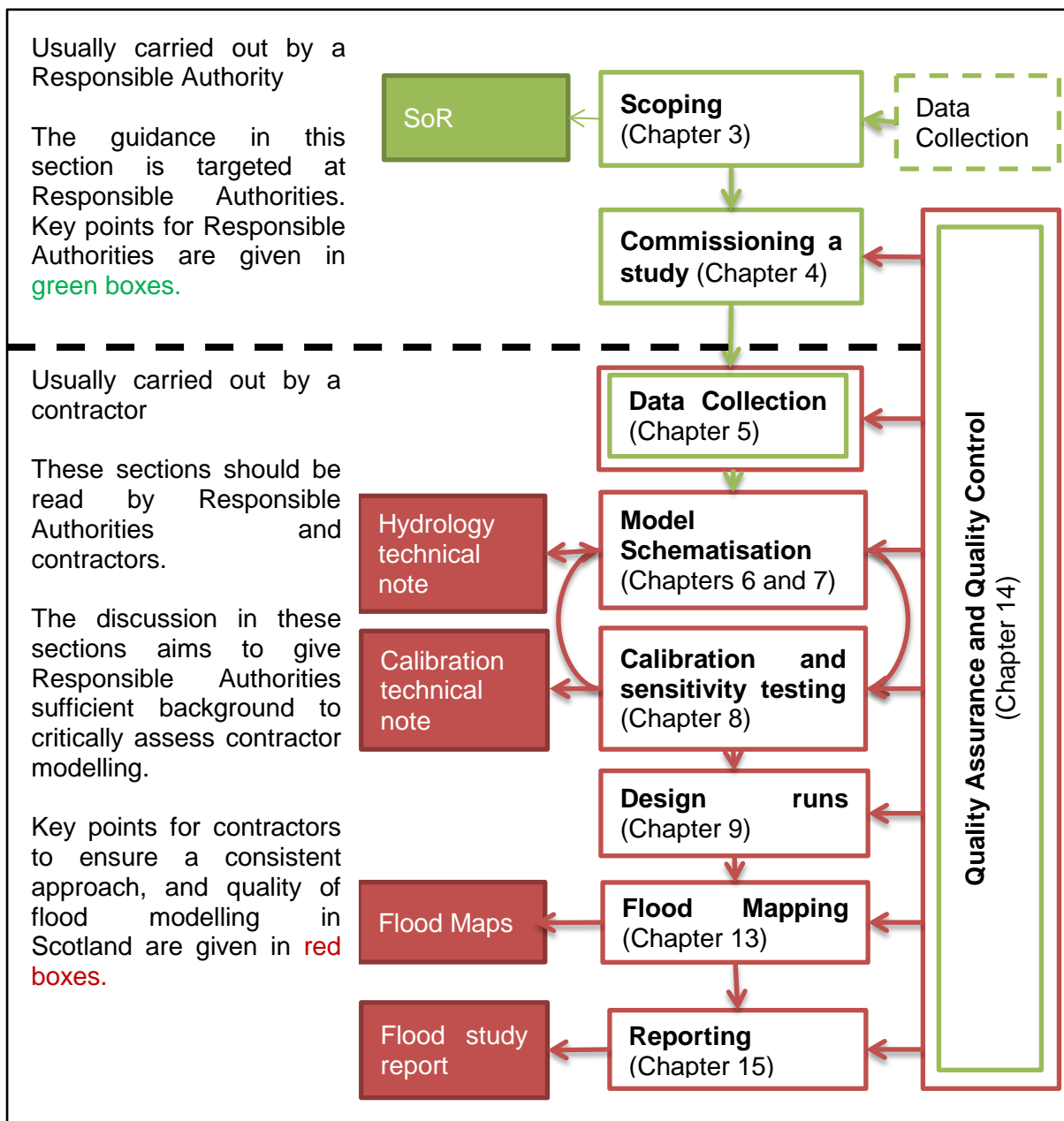


Figure 2-1: Layout of this document.

The guidance covers fluvial, pluvial and coastal flood studies. Fluvial and coastal studies are covered in detail; however, for pluvial studies where a detailed representation of the surface water drainage network is required, Scottish Water and CIWEM Urban Drainage Group² (UDG) guidance for modelling sewer systems should be followed. For studies covering combined pluvial and fluvial flooding or combined pluvial and coastal flooding this guidance should be used for the fluvial and coastal components of the studies.

2.2 How to use this guidance

Figure 2-1 shows the structure of this guidance document, and how the different chapters relate to different phases of a flood modelling project. For studies to be carried out later in a Flood Risk Management Planning cycle, Responsible Authorities may wish to carry out the

² Formerly WaPUG

scoping stage earlier in the cycle, in order to identify the need for any additional data collection.

Responsible Authorities often appoint specialist modelling contractors to carry out some or all aspects of a flood study. Where they consider it appropriate Responsible Authorities may pass this guidance onto their contractors and ask them to consider the relevant aspects in their work. To assist with this, key points for contractors are highlighted in red boxes while key points for Responsible Authorities are highlighted in green boxes.

2.3 SEPA input into modelling studies

SEPA is able to support flood studies via the provision of data, technical advice and a review of outputs. Early notification of a study by a Responsible Authority will enable SEPA to plan its resources and consider how best it can provide support as well as helping to ensure that study outputs can be incorporated into future hazard map updates and inform future flood risk management strategies. In the first instance ensure that the Regional Planning Manager is up to date with plans to progress a study via the local partnership and that contact is made with SEPA's Strategic Flood Risk team (strategic.floodrisk@sepa.org.uk). Where appropriate a named contact within Strategic Flood Risk will be identified who will assist in developing links with other SEPA teams.

SEPA is able to provide support for modelling studies at the following stages:

Scoping stage – SEPA can advise on any known linkages with other studies and the suggested study area.

Developing a Statement of Requirements (SoR) – a template SoR can be provided on request and SEPA may also be able to review SoRs if required. SEPA can provide details of the available hydrometric data, and other data where appropriate for inclusion in the SoR.

Data Collection – Details of the data held by SEPA which can be supplied for use in a flood study are given in Chapter 5. Data held by other organisations which may be required for a flood study is also given in Chapter 5.

Review of draft outputs – SEPA may be able to assist with the review of the following draft outputs where included in the project scope; technical notes on hydrology tidal/coastal boundary conditions, calibration results, draft design maps and flood levels, draft models and the draft model report. SEPA may consider an independent review or audit of hydraulic models to support consistent quality in Responsible Authority studies.

Due to the number of studies identified, in the first Flood Risk Management cycle, SEPA's resource requirements for supporting modelling studies are likely to be significant. To enable SEPA to plan and prioritise input to studies it would appreciate being informed of planned delivery dates for key project outputs and notification of any significant changes to these timescales

3 Scoping

3.1 Introduction

The first task is to define the scope of the study. This will establish the purpose of the assessment, the level of assessment and the data requirements to inform decisions.

Notifying SEPA that a study is planned for a particular area will allow SEPA to provide advice to feed into the scoping phases. In particular SEPA can advise on known linkages with other studies and can provide details of hydrometric and other data (held by SEPA) for the study area. It is recommended that SEPA's Strategic Flood Risk team (strategic.floodrisk@sepa.org.uk) and the appropriate Regional Flood Risk Planning Manager are contacted to advise that the study is taking place.

This chapter provides guidance for Responsible Authorities in:

- Developing a conceptual model of a catchment;
- Identifying opportunities for joint studies;
- Identifying the appropriate level of complexity for a flood study;
- Selecting suitable modelling software to meet the study objectives.

Further information on scoping Natural Flood Management (NFM) Studies or studies with an NFM component is given in Chapter 12.

3.2 Define Modelling Objective

It is important to develop a clear statement of the purpose of the proposed modelling study as this will determine the level of assessment carried out. The purpose may be for flood mapping to support development planning and management, options assessment for a flood prevention scheme, detailed design etc. Consideration should be given to the required accuracy and level of quality control given the purpose of the model. This should be stated in the Statement of Requirements (SoR). The required study outputs should be listed as part of the modelling objective and further guidance is given in Chapter 15.

Potential future uses of the model and outputs should also be considered, as this may enable the model to be built in such a way as to maximise reuse, and will ensure that necessary outputs are supplied.

3.3 Developing a Conceptual Model

Key points for Responsible Authorities

- Develop a conceptual model of flood risk using the source-pathway-receptor-impacts approach.
- Carry out a catchment walk-over.
- Review available data to determine the need for any additional data collection.
- Set out knowledge of the catchment in the SoR.

Key points for Contractors

- Develop and revise the conceptual model of the catchment throughout the study.
- Describe the conceptual model in the modelling report.

Before commissioning a study, it is important to understand flooding mechanisms at the study location. A good understanding of the links between the sources and impacts of flooding can help identify the most appropriate modelling approach or whether modelling is the correct approach. A summary of the flooding mechanisms should be provided in the SoR to enable contractors to propose an appropriate methodology for the study.

To help understand the interaction of different actions across catchments and coastlines, the Responsible Authority should use the source–pathway–receptor–impact approach to build a conceptual model of the key processes which need to be considered in the study (Figure 3-1). This approach is a well-established framework in flood risk management. It provides a basis for understanding the causal links between the source of flooding, the route by which it is transmitted and the receptor, which suffers some impact:

- **Sources** are the weather events or conditions that result in flooding (e.g. heavy rainfall, rising sea level, waves etc.);
- **Pathways** are routes between the source of flood waters and the receptor. These include surface and subsurface flow across the landscape, urban drainage systems, wave overtopping;
- **Receptors** are the people, industries and built and natural environments that can be impacted upon by flooding;
- **Impacts** are the effects on exposed receptors. The severity of any impact will vary depending on the vulnerability of the receptor.

For any area there may be multiple sources, pathways and receptors which interact with each other.

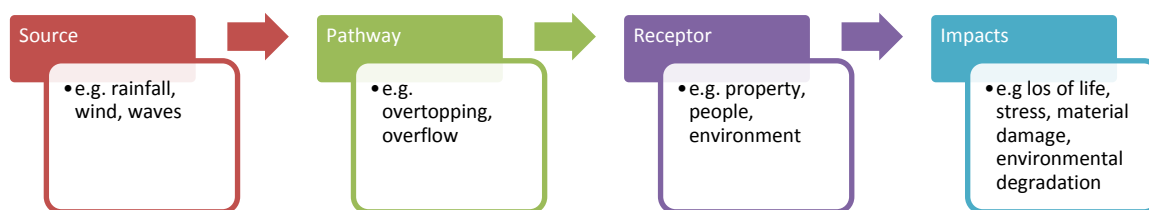


Figure 3-1: The Source-pathway-receptor-impacts model, based on the DEFRA/Environment Agency R&D Technical Report FD2302/TR1 (Sayers, Gouldby, Simm, Meadowcroft, & Hall, 2003).

In developing the conceptual model historic flood information for the area, including any anecdotal evidence, should be examined. A **catchment walk-over** in conjunction with a desk top review of Ordnance Survey maps and aerial photography should be used to identify physical features which may affect flood pathways and possible receptors. Previous studies and SEPA’s national flood hazard maps <http://map.sepa.org.uk/floodmap/map.htm> can also be used to identify possible flooding mechanisms and whether they are adequately captured by the previous modelling approach. For coastal areas the National Coastal Change Assessment <http://www.dynamiccoast.com/> should be used to identify areas where coastal change may be a factor influencing flooding. The historic flood datasets which may be available to help with developing a conceptual model are discussed in Section 5.4.

Available data should be assessed during development of the conceptual model in order to determine the need for any additional data collection. Responsible Authorities may consider assessing available data for studies later in a Flood Risk Management cycle so that data gaps can be identified and filled prior to commencement of the study. Information on relevant data is given in Chapter 5. A list of available data, with a brief description, should

be set out in the SoR, together with any survey requirements etc. SEPA can assist in determining the availability of hydrometric and other data for inclusion in the SoR.

Knowledge of the catchment should be set out briefly in the SoR, including any key areas and known flooding mechanisms which need to be considered. These key features should also be marked on a location plan to be included with the statement of requirements.

A catchment walkover with an appointed contractor can help develop a shared understanding of the study area. Contractors should develop the conceptual model of the catchment, as understanding of the study area increases throughout the study, and describe the conceptual model in the modelling report.

3.4 Spatial Extent

Key points for Responsible Authorities

- Use the conceptual model in setting the study extent.
- A single study covering a larger area is likely to be significantly cheaper than several smaller studies and may also be more accurate and robust
- Studies for inclusion in SEPA's hazard maps should have a study area consistent with the strategic nature of the maps.

The conceptual model described in section 3.2 should be used in setting the study extent. Consideration should also be given to the area of interest, availability of calibration data, future use of the model and cost and time for a study

The study extent should be sufficient to represent the assumed flooding mechanism (i.e. it should cover the flood source, flood pathway and any receptors). Boundaries of the study area should be sufficiently far away from the area of interest, considering flow controls, to have no impact on the results. Good places to set study boundaries are areas where the flood extents are relatively constrained for large events or where there is a hydraulic control such as a weir or tidal boundary. SEPA's flood hazard maps <http://map.sepa.org.uk/floodmap/map.htm> can be used with large scale mapping to identify constrained sections, which should be reviewed at a site visit.

Data available for calibration should be considered in setting the study extent, as extending the study area to cover calibration data may significantly improve confidence in the study output. For fluvial studies covering gauged rivers it is strongly recommended that the study extent covers at least one and preferably two or more gauges to assist in calibration. This is discussed further in section 5.8 and Chapter 8.

The availability of topographic data should not be used to constrain the study area where other considerations suggest that a larger area would be more appropriate. The preference should be for additional data collection rather than a reduced study extent.

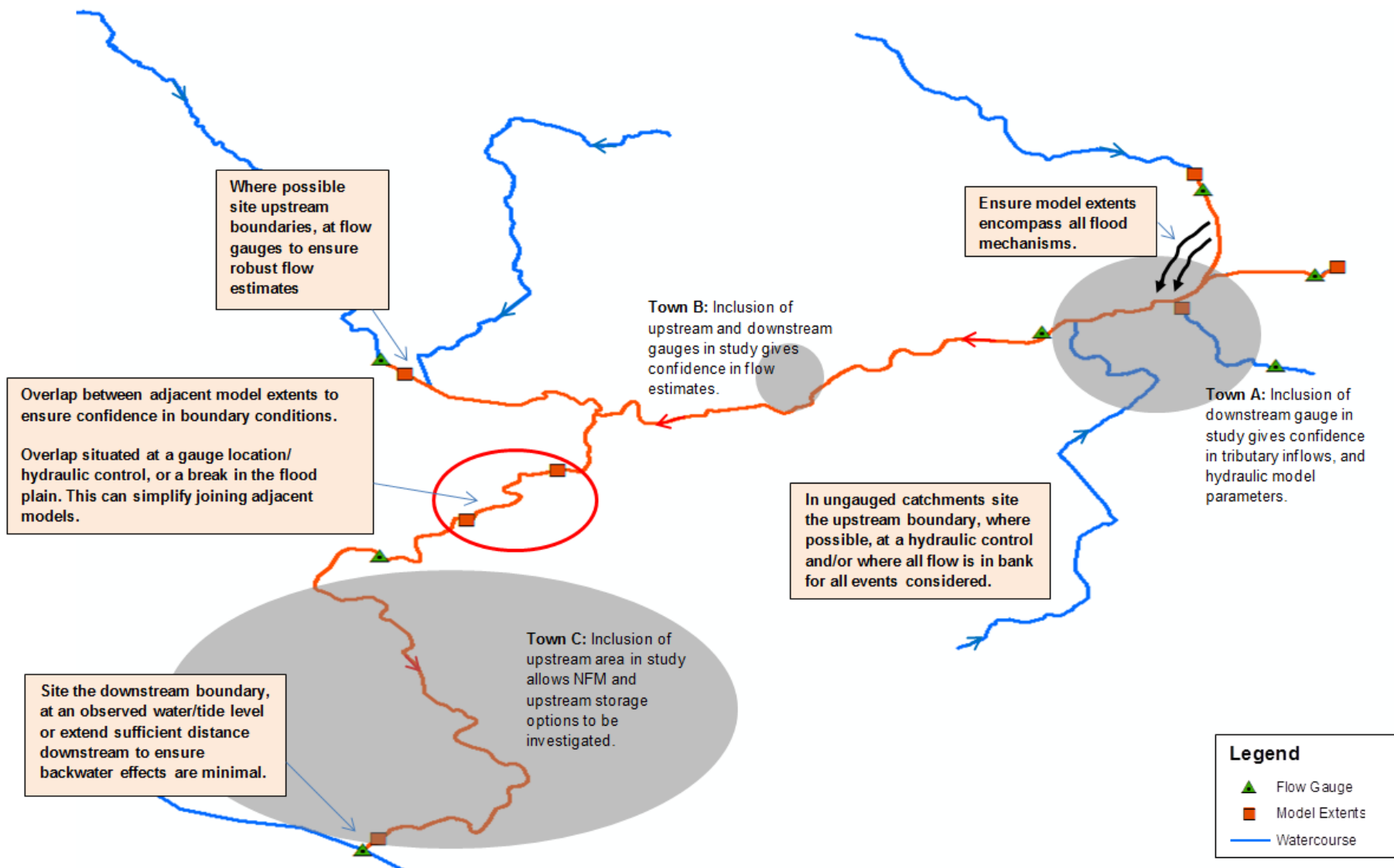


Figure 3-2: Considerations in setting study extents for a hypothetical catchment level study.

The cost and time required for a modelling study will increase with the study extent. However, potential future uses of the model should be weighed against any increase in cost as a single study covering a larger area is likely to be significantly cheaper than several smaller studies and may also be more accurate and robust.

SEPA will consider the study area in deciding whether Responsible Authority studies can be used to update the national hazard maps. For inclusion in SEPA's hazard maps, studies should cover reaches so that they can be tied in smoothly with the national mapping. As inconsistencies between different modelling approaches may be particularly evident in urban areas, studies should not normally have boundaries within continuous urban areas as shown by the Scottish Government Urban Rural Classification³. **SEPA's hazard maps are strategic level and small study areas inconsistent with this level of mapping will not be considered for inclusion in SEPA's national flood hazard maps**, although they may be suitable for site specific FRAs submitted in support of planning applications. In this case the guidance in SEPA's Technical Guidance for Stakeholders on Flood Risk Assessment should be followed (SEPA, 2015). Figure 3-2 shows considerations in setting study extents for a hypothetical catchment.

The study extent should be set out in a location plan included with the SoR.

3.5 Joint Studies

Key Point for Responsible Authorities

Overall knowledge and understanding of flooding might be improved by combining your study with those of other organisations. This may also provide efficiencies in cost, time and quality.

There may be cost efficiencies and quality improvements resulting from a joint study either with partner organisations covering nearby areas or with organisations with different objectives in the same study area.

Benefits may include:

- Sharing costs in model development across multiple organisations.
- Reduction in mobilisation costs for survey.
- Reduction in project management time.
- Reduction in modelling costs and time as modellers will become familiar with the study area and model set up.
- Improved calibration if a study area covers several gauges or extends to an area for which historical data is available.
- Ability to investigate the impact of flood risk management measures and catchment changes upstream of the area of immediate interest.
- Ability to investigate the impact of flood risk management measures on the downstream area.

In order to identify these opportunities, effort should be made to speak to the following organisations during the scoping phase:

- Local authorities upstream or downstream of a study area along the same watercourse, or along the same stretch of coastline.

³ <http://www.gov.scot/Topics/Statistics/About/Methodology/UrbanRuralClassification>

- Scottish Water where surface water flooding or combined flooding is considered to be an issue.
- Commercial organisations or government agencies such as Transport Scotland and the Forestry Commission where it is known that large planning applications or developments are proposed within an area.
- Major land owners.
- SEPA which may be aware of other studies or work within the area, including studies being carried out by SEPA's Flood Forecasting and Warning and River Basin Management Planning teams. The Strategic Flood Risk team will act as a single point for this type of enquiry at scoping stage.

Case Study – River Kelvin Flood Mapping Study

Glasgow City Council, East Dunbartonshire Council and SEPA worked together to commission the River Kelvin study. This enabled the model to be calibrated against two gauges in the river Kelvin catchment, increasing confidence in the results and ensuring flood maps were consistent across the local authority boundary.

Case Study – Metropolitan Glasgow Strategic Drainage Programme

The Metropolitan Glasgow Strategic Drainage Partnership (MGSDP) was created in response to the significant flooding that occurred in Glasgow in July 2002. The extreme rainfall event led to flooding from multiple sources requiring an integrated, catchment based, partnership approach to reduce the risks and impacts of uncontrolled flooding, improve water quality and also as a result enable sustainable urban regeneration and growth. The key partners involved are Glasgow City Council, South Lanarkshire Council, North Lanarkshire Council, Renfrewshire Council, East Dunbartonshire Council, SEPA, Scottish Water, Scottish Canals, Network Rail, the Scottish Government and Clyde Gateway as organisations responsible for, or with an interest in, flood risk management in the area. Further information about the MGSDP Vision, Objectives and Guiding Principles is available on the website – www.mgsdp.org

A dedicated Programme Management Office was established to provide overall co-ordination of the partnership and facilitate collaborative working to review and improve knowledge and understanding of flooding issues and integrated solution delivery. A phased approach was undertaken with an initial information gathering phase identifying historical flooding issues, data shortfalls and existing studies leading onto pluvial modelling. Given the complex nature of flooding the need for integrated catchment modelling was identified and now been progressed based on catchment areas served by the several waste water treatment works within the Metropolitan Glasgow area. The modelling is currently being used to help develop and deliver a range of appropriate flood management and water quality interventions.

Based on these studies the benefits of integrated working include:

- Service delivery improvements
- Economies of scale
- Efficiency savings through improved systems and practices
- Sharing of knowledge and good practice
- Streamlining of communication
- Development of a strategic and co-ordinated approach to project delivery
- Creating cost and time savings
- Development of collaborative and integrated flood risk strategies and projects in line with Flood Risk Management (Scotland) Act 2009 duties
- Enhancement of public confidence.

Further information and contact details are available here:
<http://www.mgsdp.org/index.aspx?articleid=2017>.

3.6 Level of Assessment

The level of assessment should be considered at the scoping stage as this has implications for the amount and quality of data required, the modelling effort and ultimately the cost of the study. The level of assessment should be appropriate to meet the modelling objective, for example, a high level scoping study to understand areas for further work is only likely to require a simplified modelling approach or desktop study. Generally, as a study tends towards the detailed assessment and design of flood risk management options, the model complexity will increase.

Point to Note:

It should be noted that, in some cases, limitations in scientific understanding may mean that a more detailed and complex approach may not provide additional confidence in the conclusions which can be drawn from the modelling. This particularly applies to some aspects of Natural Flood Management (NFM); see **chapter 12**.

SEPA's modelling framework sets out a hierarchical approach with 3 levels of assessment national or strategic, catchment or feasibility and local or design, Figure 3-3 and Table 3-1.

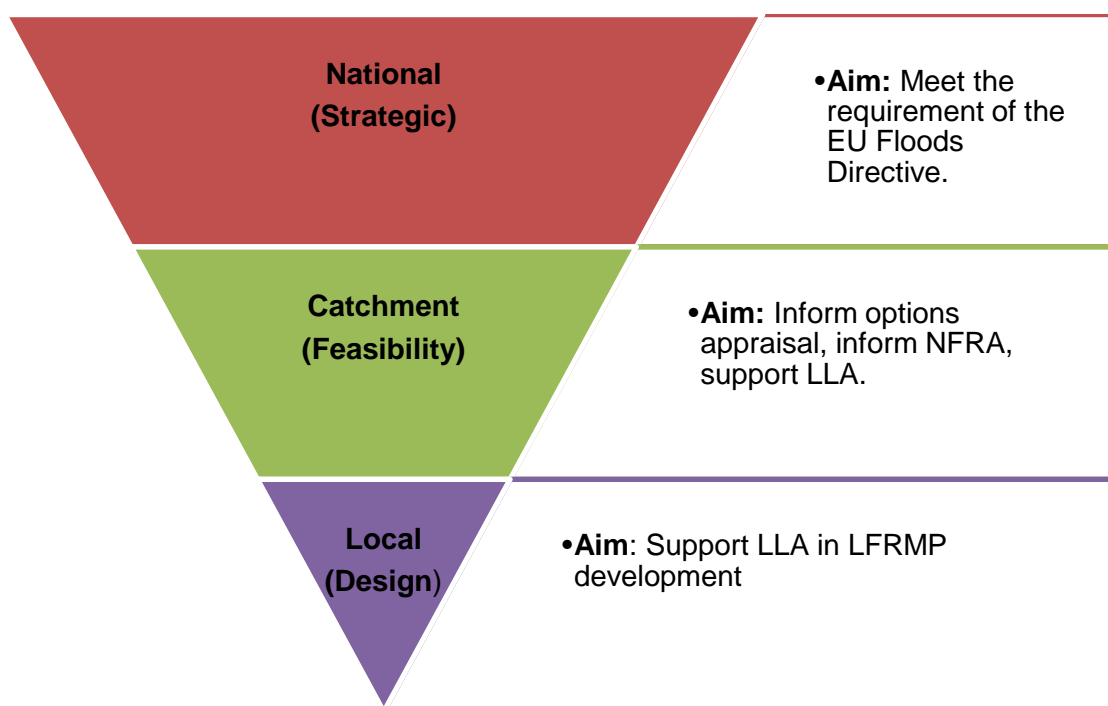


Figure 3-3: SEPA's modelling hierarchy.

3.7 Modelling Approach

There are a range of possible modelling approaches that can be adopted. Responsible Authorities should understand which approaches will be suitable to meet the modelling objectives at scoping stage as this will affect time and cost of a study. The appropriate approach depends on the required study outputs, the flooding mechanisms, and the level of assessment required. Models can be categorised by whether they are steady or unsteady and by the dimension of the modelling. Table 3-2 provides an overview of model dimensions which might be considered and the circumstances where they may be applied. Table 3-3 provides an overview of steady and unsteady analyses and where they may be appropriately applied.

		National (Strategic)	Catchment (Feasibility)	Local (Design)
Example Objectives		Producing national hazard maps to meet requirements of EU Floods Directive.	Options appraisal. NFM studies. Screening maps for LUP in more complex areas.	Detailed design of flood defences or NFM measures. Site specific FRAs for developments.
General description		Broad scale assessment; national overview; based on national datasets; strategic direction setting; e.g. FRM planning -> national comparison; awareness raising; improved understanding	Catchment scale assessment; improved understanding of the catchment; inform flood risk management option feasibility; flood warning area development; emergency planning	local focus; consider interactions of sources; detailed representation of local features
Scale		National, large or multi- catchment, or long reaches of coastline.	Catchment scale, major firths or long reaches of coastline with similar orientation.	Small catchment or section of larger catchment, short lengths of coastline e.g. town frontage.
Approaches	Fluvial	Use of historic flood extents, 1D or 2D hydraulic modelling. Flows from national datasets e.g. CEH flow grid.	1D, 2D or 1D-2D hydraulic modelling. Hydrology using FEH methods and distributed inflows. Range of scenarios.	Detailed hydraulic modelling (1D or 1D-2D); range of modelling scenarios; consideration of climate change. Local-scale assessment of design flows; explicit use of local information.
	Pluvial	Use of historic flood extents, rapid flood spreading, 2D hydraulic modelling. FEH DDF model. Limited number of durations	2D hydraulic modelling. FEH DDF model. Range of scenarios.	
	Coastal	Use of historic flood extents, Level projection, rapid flood spreading, 2D hydrodynamic modelling.	Hydrodynamic and wave transformation modelling. 2D hydrodynamic model for flood inundation. Range of scenarios. Consideration of climate change	
Structures	Fluvial	Typically blockages caused by structures removed from DTM.	Definition of key structures using basic information to represent height, length, etc. Structures such as foot bridges may be omitted.	Explicit and refined definition of key structures and channel features.
	Pluvial	Buildings likely to be removed from the DTM.		
	Coastal		Raised defences added to DTM. Overtopping analysis for defences.	Overtopping analysis for defences.
Calibration/ Sensitivity Testing		Check of selected locations against historic records. Reality checks	Check against historic records; sensitivity testing. Calibration at gauges.	Calibration at gauges for multiple events. Installation of additional gauging. Comparison with historic records. Sensitivity testing.
Limitations		Not suitable for site specific information. Large spatial range -> relatively lower spatial accuracy	Assumptions on Hydrology and limited assessment of local influences	Can be time consuming and expensive.
Data Requirements	Fluvial	DTM	DTM Channel cross section survey	DTM Channel cross section survey
	Pluvial		DTM	DTM Drainage network information
	Coastal		DTM Bathymetry	DTM Bathymetry Defence and beach profiles
Quality Control		Review of input data. Review of method. Consistency checks. Screening for physically unrealistic results.	Review of input data. Review of models and hydrology by independent internal reviewer.	Review of input data. Detailed review of models and hydrology by independent internal reviewer or external reviewer.

Table 3-1: Overview of different levels of assessment.

Model Type	Description	Uses
0-D / Rapid Flood Spreading	0D models use simple rules to spread water over the floodplain between adjacent depressions. Advantages: Short run times. Limited data requirements. Limitations: Only produce final state of inundation, do not capture flow pathways. Flow velocity not available. Input data requirements: Digital Elevation Model (DEM) or Digital Terrain Model (DTM)	To provide a general overview of pluvial flooding when the detailed data required by most 1-D or 2-D models are unavailable. This may be appropriate for strategic levels studies covering large areas; however for local flood studies the 1D and 2D approaches below are more likely to be appropriate.
1D - Hydrological Routing	1D routing models use a storage equation to model changes in the shape of the flood hydrograph along a river reach. Parameters in the equation are either calculated from the channel geometry or estimated from observed data. Advantages: Short run times. Limited data requirements (sparse cross sections). Limitations: Loss of accuracy. Levels are not calculated. Input data requirements: Cross sections or a DTM from which cross sections can be extracted	To provide boundary conditions for more detailed river models. Frequently used in flood warning where short run times are required.
1D	In 1D models flow is averaged over depth and across defined cross sections. Models can be steady or unsteady. Advantages: Accurate representation of flow and level within channel. Good representation of hydraulic structures. Usually short run times allowing multiple scenarios to be run. Limitations: Complex floodplain flows cannot be represented. Floodplain velocity not available. Input data requirements: Channel sections and structures.	Fluvial: Used for modelling in bank flows, in channel hydraulic structures and narrow well defined floodplains. Pluvial: Used for modelling surface water drainage networks.
2D	In 2D models flow is averaged over the flow depth and horizontally over a model grid cell or element. 2D models may be divided into those which solve the full shallow water equations and those which solve a simplified version of the equations to reduce computational effort. Either a regular grid or irregular mesh may be used. Advantages: Accurate representation of floodplain flow. Simple model build. Limitations: Cannot accurately represent structures or in channel flow particularly for narrow watercourses. Higher resolution models may have long run times. Input data requirements: Digital Elevation Model (DEM) or Digital Terrain Model (DTM).	Fluvial: Used for modelling floodplain flows where the channel capacity and transition between in bank and out of bank flow is not important (e.g. larger flood events). Pluvial: Used for modelling overland flow where interaction with the surface water drainage network is not important. Coastal: Used coastal inundation modelling.
1D-2D	The channel is modelled in 1D and linked to a 2D model of the floodplain so that they can exchange flow. Advantages: Accurate representation of flow and level within channel and floodplain flow routes. Limitations: Large time inputs required to set up complex models. Long run times. Potentially costly. Input data requirements: channel cross sections and DEM.	Fluvial: Used where there is a need to understand both the channel and floodplain processes. Pluvial: Used where there is need to understand how the surface water drainage network interacts with overland flows e.g. an Integrated Catchment Model (ICM). Coastal: May be used where there is a well-defined drainage network along which flood waters can propagate.
3-D or Physical Models	3d and physical models allow vertical flow to be modelled. Input data requirements: 3d structure information, DEM, bathymetric survey. Advantages: Can represent vertical variations in flow. Limitations: Costly and complex.	Not commonly used in flood studies. They may be necessary for design in some complex cases for example, understanding of flow over, through and around structures.
Nearshore wave models	Simulate the processes such as energy dissipation due to bottom friction, white capping, or depth induced breaking, growth due to wind, refraction and shoaling. Advantages: Allow nearshore wave conditions to be assessed in the absence of long series of observations. Limitations: Large time inputs required to set up complex models. Long run times. Potentially costly. Input data requirements: Bathymetric survey and a DTM of the intertidal area. Water levels. Offshore wave conditions.	Used in coastal flood studies to transform wave conditions from offshore wave models inshore to produce boundaries for overtopping models.
Overtopping Models	Empirical and physically based models are available. Advantages: Allow overtopping rates to be assessed. Limitations: Depend on the type of model. Expert judgement may be required to determine the appropriate model in each case. Input data requirements: Nearshore wave conditions and water levels. Crest and toe levels, and defence profile, including information on roughness.	Used in coastal flood studies to predict the rate of water overtopping flood defences, and provide boundaries for 2D inundation models.

Table 3-2: Modelling approaches

Model Type	Description and Uses
Steady Flow	In steady state modelling it is assumed that flow does not vary with time at given location. This assumption can be made for many applications where floodplain flow is limited, for instance in narrow valleys.
Unsteady Flow	<p>Unsteady models allow flow to change with time. Unsteady models are required for problems where flood wave propagation or flood storage or attenuation within the system is of interest.</p> <p>The areas where unsteady flow should be considered include where:</p> <ul style="list-style-type: none"> • there is a tidal boundary; • there is flood storage within the system; • hydrograph timing is of interest; • floodplain flow needs to be taken into account; • there are pumps or gates to which control rules are applied.

Table 3-3: Overview of basic model types

3.7.1 Selection of Modelling Software

A variety of hydraulic modelling software is available for use in flood model development although there is no universal package which can be recommended for all applications. The Environment Agency has carried out benchmarking tests of 1D and 2D hydraulic modelling packages commonly used in Flood Risk Management in the UK (Crowder, et al., 2004) (Neelz & Pender, 2013). These provide a summary of the key features of the modelling packages and the time taken to set up models using different packages. It is not advised that software should be used unless it has been thoroughly peer reviewed or extensively tested through an extended period of use by several different organisations. Advice should be sought from SEPA if the suggested software is not covered by the Environment Agency benchmarking, including where the use or development of novel tools is proposed in developing areas of flood risk science such as Natural Flood Management or Climate change.

In any tender the contractor should set out which modelling software will be used and why it is appropriate to meet the project objectives.

In addition to the ability of the selected software to meet the project objective the Responsible Authority should consider:

- If there is a sufficient pool of people in the industry experienced in using the selected software to enable the model to be reviewed and audited
- If use of the proposed software will restrict future use and development of the model to specific contractors, either because the software is in-house to a particular contractor or because there are limited skills.
- If there is support and training available for use of the software to allow any bugs or issues to be addressed and for expert advice to be sought for difficult or unusual schematisations.
- Licensing options and cost if the Responsible Authority either wish to rerun or update the model themselves or to view the model schematisation and results. However it should be noted that higher license costs may add functionality necessary for meeting the project objectives or be offset by improved workflows, customer support,

improved model stability or reduced run times which may reduce time costs for the modelling study.

SEPA has licenses and skills in a number of modelling packages, Table 3-4, and may be able to review models or assist local authorities in viewing models and results and rerunning models if necessary. Some modelling packages either have free versions with limited functionality, or viewers available at a reduced cost when compared to the full license. Information on this is available from the relevant software suppliers.

Modelling Software	Software Supplier	1D River	1D Sewer	2D Land	Coastal	
					Surge	Waves
FloodModeller ⁴	https://www.floodmodeller.com/en-gb/	✓	x	✓	x	x
Delft 3d / SWAN	https://www.deltares.nl/en/software/delft3d-4-suite/	x	x	✓	✓	✓
HECRAS	http://www.hec.usace.army.mil/software/hec-ras/	✓	x	x	x	x
Infoworks ICM	http://www.innovyze.com/	✓	✓	✓	x	x
Infoworks RS 2D		✓	x	✓	x	x
JFLOW	http://www.jbaconsulting.com	x	x	✓	x	x
MIKE FLOOD ⁵	http://www.dhigroup.com/	✓	✓	✓	x	x
TUFLOW/ ESTRY	http://www.tuflow.com/	✓	x	✓	✓	x

Table 3-4: Flood modelling software currently used by SEPA.

⁴ Formerly ISIS.

⁵ The MIKE suite is capable of modelling waves and hydrodynamic flows with estuaries, but SEPA's flood risk teams do not currently have a license for this functionality.

4 Commissioning a study

4.1 Introduction

Responsible Authorities have commissioned and managed flood studies successfully over a number of years. The guidance in this chapter does not aim to replace Responsible Authority expertise or procurement and project management procedures, however it highlights some factors which Responsible Authorities should consider in commissioning a study to ensure:

- Flood modelling is at a consistently high standard across Scotland
- Data from flood studies can be shared with other Responsible Authorities
- SEPA has sight of timescales and project milestones, so it can provide timely input if required.

Key points for Responsible Authorities

- SEPA may be able to assist with reviewing SoRs.
- Ask contractors to provide evidence of quality control.
- The Intellectual Property Rights (IPR) for any data collected explicitly for the project or generated by the project should be held by the Responsible Authority.

4.2 Statement of Requirements (SoR)

A SoR for the study area should be developed following the scoping exercise set out in Chapter 3. A template SoR suitable for a range of flood studies at different scales and levels of detail is available and further details are given in Appendix A. Responsible Authorities may use this template where they consider it appropriate for their study; use of template should produce modelling and mapping outputs which meet the requirements for inclusion in the national hazard maps. Developing an appropriate SoR is one of the most important parts of any modelling study and, where required, SEPA may be able to assist with their review.

4.3 Quality Control

The contractor should provide evidence of how they will carry out quality control and quality assurance through the project, including setting out internal review procedures for modelling and hydrology. Evidence of quality control should be included as one of the deliverables within the SoR. Further detail on this is given in Chapter 14.

4.4 Resources

The project must be adequately resourced from both the contractor and Responsible Authority sides.

The contractor should demonstrate that sufficient staff are available with the correct level of experience to deliver the project in their tender. This should include identification of an internal reviewer with sufficient experience who is not directly involved in the project. Contractors should also be able to demonstrate that they have sufficient computational resources and software available to deliver the project.

The Responsible Authority should ensure that appropriate staff will be available at key points in the project to enable timeous supply of data and information, and so that outputs can be reviewed within the stated timescale.

In exceptional cases there may be additional computational resource requirements for large projects, including purchase of data storage, computer processing power or additional software licenses, and contractors may include costs for purchasing these in their tender.

4.5 Timescale/Milestones

A proposed programme should be included with all tenders. The programme should show times when input from client and other external stakeholders will be required. A minimum of 10 working days should be allowed for the commissioning body and other stakeholders to review draft outputs.

Where requested by the Responsible Authority, SEPA will seek to support Responsible Authority studies within its resources. Due to the number of studies identified, SEPA's resource requirements for supporting modelling studies are likely to be significant over the first flood risk management planning cycle. To enable SEPA to plan and prioritise input, SEPA should be informed of planned delivery dates for key project outputs and notified of any significant changes to these timescales.

4.6 Risk Register

A risk register should be included in any tender identifying the risk, the likelihood of the risk occurring, the consequence of the risk if it did occur, any mitigation to be taken, and whether the risk is owned by the Responsible Authority of contractor. This register should be reviewed and updated as the project progresses.

4.7 Meetings and Progress Reports

Regular meetings between the contractor and Responsible Authority are advised to ensure good communication links are established.

An inception meeting can be combined with a walk-over survey or site meeting with an appointed contractor. This is advised to ensure that there is a shared understanding of the study area at the outset of the project.

The use of progress reports alongside an agreed programme of works is key to effective project management. These should be at a suitable frequency commensurate to the scale and complexity of the project, however fortnightly to monthly reporting in any agreed format are typical frequencies.

4.8 Intellectual Property Rights

It is important that the Intellectual Property Rights (IPR) for any data collected explicitly for the project or generated by the project are held by the body commissioning the study are not retrained by the consultant. This includes survey data, any models and associated model outputs produced as part of the study and photographs collected on site visits. This requirement should be included within any contract.

Where data is provided by 3rd parties for use in the study, appropriate licensing agreements should be in place to ensure that use of the data does not affect future use of the model. If this is not possible the benefits of collecting new data rather than using the 3rd party data should be assessed.

5 Data

5.1 Introduction

A wide range of data is used in flood modelling studies. Data requirements depend on the project objective including any requirements for quality, the level of detail and adopted modelling approach. At the scoping stage the Responsible Authority should seek to understand the data available and whether any new data is likely to be required as this can significantly affect the cost, quality and timescales for a modelling project. General data requirements for different modelling approaches are set out in Table 3-2

Point to Note:

Data underpins a modelling study. Data requirements will be informed by study objective, time and budget. However, good quality data provides a significant step towards a good quality model.

This chapter aims to:

- Describe the different types of data required for a flood modelling study and their usage and limitations.
- Describe how to obtain datasets held by SEPA and other organisations.
- Provide technical guidance for Responsible Authorities specifying new data collection for flood modelling.

5.2 General Considerations

5.3 Data collection

Key points for Responsible Authorities

- Start data collection early to avoid project delays. SEPA may be able to prepare data requests prior to a contract being awarded.
- Data registers should be kept by the Responsible Authority and the contractor.
- Data licencing agreements should be in place for all data used within the modelling study.

For most modelling activities some data will already exist, while other data will need to be generated.

It is necessary to remember that the data collection process can take some time and may be seasonally dependent; this needs to be incorporated into the project plan. Delays in data collection or in providing data to contractors can cause significant project delays.

Where SEPA holds the data being requested, it may be able to respond to data requests prior to the contract being awarded.

5.3.1 Data registers

A clear record of the data used for a project is important for understanding if there are any licensing restrictions which may impact future use and subsequent implications on the project output if quality issues are identified with input datasets.

It is recommended that a data register is used to record when information is issued or received, where it is located, the date the data was collected, and any relevant licence terms. Where a contractor is used both the Responsible Authority and contractor should keep data registers, and the contractor's data register should be included in the project deliverables.

5.3.2 Licensing

Data licensing agreements should be in place for all datasets used within the modelling study. This for example should stretch to include site surveys, the digital terrain model, the hydrology and all model outputs. Where possible, licences should not restrict the future use of any models or any derived data by SEPA or Responsible Authorities. SEPA should be consulted for advice about how to proceed if a comprehensive licence cannot be achieved.

5.4 Historic Flooding Information

Key points for Responsible Authorities

- A flood study should include an assessment of the local flood history.

5.4.1 Use of data

Historic flooding information should be used at the scoping stage when developing a conceptual model of the flooding mechanisms (as discussed in Section 3.3), in setting the study extent (as discussed in section 3.4) and in identifying possible calibration events for inclusion in a SoR (as discussed in Section 3). Historic flooding information should be used at the calibration and verification stage to increase confidence in model results, as discussed in Chapter 8. Historic flood information may also be used in development of flood frequency curves, and further guidance on this is given in Bayliss & Reed (2001). Observed depths and extents may also be used for strategic level studies instead of a modelled outlines.

Point to Note:

Information on 'real' flood events provides a clear benchmark for establishing good quality flood models. A range of information is available and should be considered in developing and finalising models.

5.4.2 Available Datasets

To ensure that the local flood history and mechanisms are fully understood the local flood history evidence should be compiled and assessed as part of a flood study. All available information should be compiled including photographs, flood outlines, anecdotal descriptions of onset of flooding and receptors affected and summarised in the report. The outline SoR in Appendix A includes compiling and assessing the local flood history.

SEPA maintains an extensive flood event database. The database is subject to development and ongoing quality control of older records but it is a useful source of information in many areas. A large amount of this data was supplied by local authorities, so may duplicate Local Authority records. Depending on the data source, flood records in the SEPA database are available for a range of spatial scales. At present the database does not contain any level information, however SEPA may hold post flood event survey with levels or photographs from which levels can be derived. Other potential sources of flood information are given in Table 5-1.

Source	Sub-source	Type	Comments
Responsible Authority	Flood Prevention Authority Planning Authority	1) Biennial Flood Reports / flood photos. 2) Flood Prevention Scheme studies 3) Strategic Flood Risk Assessments 4) Flood Risk Assessments for e-planning	1) Often available on Council website. 2) Feasibility studies are often undertaken for areas where no formal flood prevention measures currently exist. Many councils have an e-planning website.
Scottish Water		Flood incident reports.	
SEPA	Flood Risk Hydrology	Flood photos, post-flood survey data.	SEPA's flood risk team hold information on past flood events in Scotland in various formats mailto:strategic.floodrisk@sepa.org.uk
	National Flood Risk Assessment	Digitised records of past flooding from multiple sources. Note this is less detailed than the information held in local teams.	Available via SEPA website http://map.sepa.org.uk/nfra/map.htm
British Hydrological Society	University of Dundee	Chronology of British Hydrological Events	Available on-line at http://www.dundee.ac.uk/geography/cbhe/
Media	Television and Newspaper	Flood reports/ photographs.	Material may be found on-line.
SNIFFER	Coastal Flooding in Scotland: A Scoping Study 2008	Final report and GIS data can be found at http://www.sniffer.org.uk/files/7013/4183/7993/FRM10_final_030908_with_security.pdf	Information on past coastal flood events in Scotland as well as the dominant coastal processes.
Local Flood Groups	Local residents	Anecdotal accounts of flooding and/or flood photos.	
Library/ Archives	Books, journals, magazines, newspapers, church records.	Historical flood information & photos.	
Internet	Web search	Accounts of flooding and photos.	Numerous data sources exist on-line.
Buildings/ bridges	Can be on a plaque or chiselled mark	Epigraphic flood data	Often levels of past extreme floods are marked on buildings and bridges.

Table 5-1: Potential sources of historic flood information.

5.5 Topographic and Bathymetric Data

Key points for Responsible Authorities

- Existing topographic data should be assessed to ensure that it is appropriate to use in a new study.
- Use the Environment Agency's Standard Technical Specifications, Version 3.2 for any new survey.

Topographic and bathymetric data is used in the construction of hydraulic models and in the production of flood maps from the subsequent model results.

5.5.1 Reuse of existing data

Existing topographic data should be carefully assessed to ensure that it is appropriate to use in a new study. In particular it should be clear that:

- There have been no major changes to the study area since the data was collected including significant erosion or deposition, vegetation growth, construction of new structures or alteration or removal of existing structures.
- The datum used for the existing survey is the same as for any new survey and any DTM used in the study.
- That the IPR for the existing data allows reuse in this study
- The original survey is of an appropriate quality for the modelling study.

If in doubt a **check survey** should be used to ensure that the existing survey is suitable for further use. The appropriateness of data for reuse depends on the purpose of the modelling for instance, older channel survey data may be appropriate for strategic level mapping, but is unlikely to be appropriate for detailed design. Where older topographic data is in paper format only it may add considerably to the time and cost associated with model building as well as increasing the possibility of human error. It should be noted however that there may still be significant value in original engineering drawings from flood defence schemes, culverts etc. and, where possible, these should be provided for use even if other survey is considered necessary.

Survey data may be contained within existing models however, where possible, original survey plans, drawings, photographs, and any other datasets should be supplied together with the existing hydraulic model as:

- there may be schematisation errors in the existing model;
- different software may require different or additional information for the same structures;
- the location of cross sections may not be clear, particularly for older hydraulic models which are not georeferenced;
- the model may contain a combination of detailed survey information, interpolated sections, and other information such as levels interpolated from Ordnance Survey contours, and it may not be clear which information is from the detailed survey.

5.5.2 Commissioning a New Survey

The Environment Agency's Standard Technical Specifications, Version 3.2 (Environment Agency, 2013) provide a comprehensive technical survey specification. It is recommended that the relevant sections of this specification are used when specifying survey for hydraulic modelling. This should provide efficiencies as survey and hydraulic modelling contractors operating within other parts of the UK are already familiar with producing and using data produced to this specification. A template SoR for use of these specifications is provided in Appendix B.

Point to Note:

Use of the Environment Agency's Standard Technical Specifications v3.2 should ensure that data is supplied in an appropriate format.

The EA Specifications are referenced in this guidance document as the 'EA Specification'.

5.5.3 Data Format

It is important that any new survey is delivered in a suitable format to enable efficient entry of survey into the model as this may significantly reduce model build time and costs as well as reducing the potential for data entry errors. In particular **cross section survey should be supplied in an electronic data format which can be imported directly into the hydraulic modelling software used for the project.** In most cases this will require specifying survey to be delivered in the specific proprietary format for the modelling software to be used for the project; however the recently developed non-proprietary Environment Agency Channel Survey Data (EACSD) format can now be imported directly into some river modelling software. Surveying software packages⁶ are available which are able to export data in the formats required by commonly used modelling software and the EACSD format. **Supply of data in Excel spreadsheet format does not generally enable efficient import of data into hydraulic models.**

In addition to requesting data in the correct format for import into modelling software, it is recommended that data is also requested in the following formats:

- Drawings and plans of the survey in CAD software. This allows key points to be clearly marked and for measurements to be scaled of drawings,
- GIS layers showing section locations and survey points, this allows cross sections to be mapped quickly using GIS software.
- Photographs of cross sections and survey locations.

5.5.4 Channel Survey

Channel survey is required where a detailed assessment of the in-channel hydraulics is required, usually for 1D and 1D-2D fluvial models (discussed further in section 7.2). Survey is required for open channel sections and for structures.

5.5.4.1 Commissioning a New Channel Survey

If a new channel survey is required, section IV of the Environment Agency's Standard Technical Specifications, Version 3.2 (Environment Agency, 2013) (hereafter referred to as the EA Specifications) provides an appropriate specification. Note that the EACSD format referred to in section Data Format 5.5.3 has not yet been adopted by all software vendors. It is therefore recommended that the survey is requested in a suitable format for import into the hydraulic modelling software to be used for the project, as well as the EACSD format. Structures and natural features which have a similar impact on flow to manmade structures should be surveyed as in Section IV of the EA Specifications. Culverts should be surveyed

⁶ Storm Georiver <http://storm-georiver.com/> and MBS Survey Software RXS Tools <http://survey.mbs.com/our-software/mbs-rxs-tools>

as in section XI of the EA Specifications. If detailed economic appraisal is also being carried out, inclusion of topographical survey associated with this (threshold levels, etc.) should be considered within the same commission to minimise costs.

A survey specification for channel survey should contain

- start and end points for the survey
- a specified cross-section spacing
- cross-section width
- instructions for any specific locations to be surveyed
- an instruction to survey structures
- a plan showing the area to be surveyed
- the location of any known flood defences
- whether the bed levels to be surveyed are hard or soft or both
- the hydraulic modelling software format to be used for the deliverables

Access to the river should also be considered when commissioning a new survey. While SEPA and Local Authorities have powers of entry under the FRM Act (section 79(1))⁷ it is recommended that access is pursued by mutual agreement with landowners, taking cognisance of any constraints. Introductory letters may be provided to surveyors to facilitate access

5.5.4.2 Cross-Sections

The appropriate cross-section spacing depends on the physical characteristics of the channel and the scale and purpose of the study; for instance, cross-sections may be further apart for a channel with a uniform cross section and slope, and more frequent cross sections may be required for design of flood defences. It is therefore difficult to provide general guidance on cross section spacing, however generally:

- For large rural rivers on low slopes the maximum cross-section spacing should be around 200 m;
- For smaller streams, steeper slopes, or within urban areas the maximum cross section spacing should be around 50 m;

Cross-section data is also generally required at the following points:

- All major obstructions to flow, such as bridges and culverts as well as road and rail embankments across the floodplain;
- Points of significant changes of shape in the channel and/or change in the floodplain width;
- Significant changes in stream slope, or near control sections (e.g. rapid drops at weirs and dams);
- Areas where there is a significant change in channel or bank roughness;
- At existing flood protection structures;
- Upstream and downstream of confluences with significant tributaries.
- At gauging stations or other locations where information is available for calibration (SEPA can provide information on gauging station locations, and recommended survey requirements).
- Other key areas of interest, e.g. adjacent to proposed development sites.

⁷ The FRM Act gives powers of entry to persons authorised by SEPA (79.1) and local authorities (79.2) for carrying out certain functions including the production of flood hazard maps and the preparation of flood risk management plans.

As an illustration, Figure 5-1 shows the factors considered by SEPA in specifying cross sections for a model of the River Garry.

The floodplain width and the availability and appropriateness of other data for representing out of bank flow paths should be considered in establishing the required cross-section width. Digital Terrain Models (DTMs) used to represent out of bank flow paths are discussed in Section 5.5.5; if a sufficient quality DTM, typically LIDAR, is available over the entire width of the floodplain, and considered to be a good

representation of the actual ground surface, cross sections should be extended as in Section IV of the EA Specifications (e.g. **5 m beyond the top of bank or for vegetated banks 5 m beyond the vegetation line but no more than 50 m**).

Point to Note:

A high quality (LIDAR) DTM means cross-sections need not cover the entire floodplain width.

A low quality DTM (e.g. NEXTMAP data or 'poor' quality LIDAR) means cross-sections should cover the entire floodplain width, or a new DTM should be collected for the floodplain.

Where the DTM is not of sufficient quality, typically areas where only NEXTMap data is available (see section 5.5.5.1), there are quality issues with the LIDAR or significant ground changes have occurred since the LIDAR was flown, **extending cross sections across the entire floodplain width may be desirable**. An initial estimation of floodplain width can be made from SEPA's flood maps and checked during a site visit.

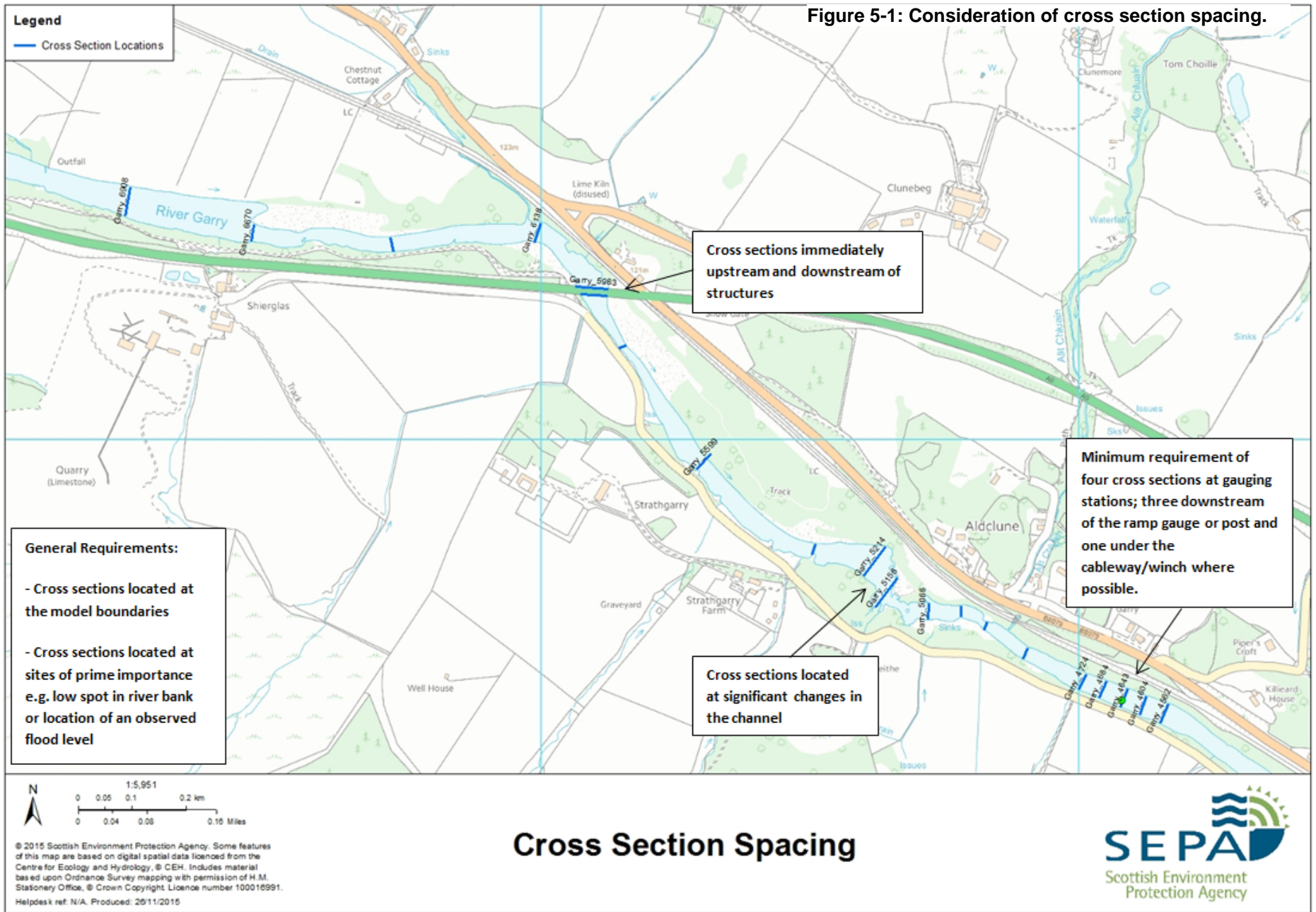
5.5.4.3 Hydraulic Structures

Information is required for all hydraulic structures which may have an impact on flow at the scale of the study. This includes natural drops which may have the same effect as man-made weirs. The information which is required and the structures which are important depend on the level of detail of the modelling. Table 5-2 provides a guide on whether structures may need to be considered at the different levels of assessment described in section 3.6 although it should also be considered where structures are likely to be blocked. In general data is not required for temporary structures. Details on the information ideally required for modelling different types of hydraulic structures for different levels of study is given in Table 5-3. It should be noted that it may be more cost effective to survey all structures at the level required for a detailed study rather than remobilise surveyors to collection additional data for a more detailed study at a later date.

5.5.4.4 Flood Defence Survey

Fluvial flood defences **should be included within a channel survey. In general, embankment and wall crest levels (ideally as a georeferenced string across the top of the embankment), the size and location of any gates, outfalls, weirs etc. should be supplied. If undefended modelling is required, information on embankment and wall toe levels will be necessary to remove flood defences from the base model.**

The Scottish Flood Defence Asset Database (SFDAD), available at http://www.scottishflooddefences.gov.uk/Site/SE_Splash.asp, contains some survey data for some flood defence schemes constructed under the Flood Prevention (Scotland) Act 1961. However, due to the age of some of the survey data, checks should be carried out as in Section 5.5.1.



Level of study	Bridges and short culverts	Weirs and Gates	Long Culverts	Compound Structures and Mills	Dams/Reservoirs and Lochs
Simplified	Not necessary, to include explicitly, but there must be a continuous flow path through the structure.	Not necessary, to include explicitly. If gates are usually open there must be a continuous flow path through the gate.	Simplified representation likely to be necessary. Information on the path of the culvert, survey of inlet and outlet structures and walk through or CCTV survey identifying constrictions may be sufficient.	Not necessary, to include explicitly but there must be a continuous flow path through the mill. Short lades may generally be omitted.	Embankments and spillways need not be represented explicitly. Flow attenuation should be accounted for in the hydrology.
Intermediate	Should generally be included. Footbridges and pipe bridges may be omitted if they are considered to have a negligible impact on flow e.g. wooden plank footbridges and some pipe bridges.	Should generally be included, unless drowned at low flows.	Should generally be included from cross section survey. Manholes and sewer connections may be omitted.	The main flow path and opening should be included based on survey data. It may be appropriate to omit minor flow paths.	Embankments and the main controls should be represented explicitly. Flow attenuation should be accounted for in the hydrology.
Detailed	Should generally be included unless clear span.	Should generally be included.	Should be included from cross section survey. Manholes and sewer connections should generally be included.	All flow paths through the Mill should generally be included.	Embankments and spillways should be represented explicitly. Flow attenuation should be modelled.

Table 5-2: Guide for including different types of hydraulic structures at the different levels of assessment, described in Section 3.6 This is a guide only and the appropriate level of detail will depend on the local circumstances.

Bridges	Weirs and natural drops or constraining features	Culverts	Mills	Dams and reservoirs	Gates
<p>Size and shape of opening including soffit and springing levels;</p> <p>Length of bridge tunnel</p> <p>Upstream (and downstream channel sections if different to upstream section);</p> <p>Size and shape of opening,</p> <p>Number and width of piers</p> <p>Bridge parapet elevation and type.</p> <p>Skew angle.</p> <p>Similar information is required for any relief arches or culverts.</p>	<p>Section along weir crest (crest elevation may suffice for strategic study)</p> <p>Weir length</p> <p>Weir long profile</p> <p>Skew angle or length perpendicular to river for labyrinth weirs</p> <p>Sections immediately upstream and downstream of weir</p> <p>Sections upstream and downstream where channel returns to normal cross section.</p> <p>Similar information is also required for any side weirs.</p>	<p>Size and shape of the opening</p> <p>Entrance type, shape of wingwalls etc.</p> <p>Bar size and spacing for any trash screens</p> <p>Any bends, cross section changes, obstructions, or changes in bed slope along culvert.</p> <p>Soffit and bed elevation at entrance and exit and along culvert.</p> <p>Upstream and downstream channel sections</p> <p>Barrel roughness and condition</p> <p>Any manhole locations</p>	<p>As for bridges culverts and gates.</p>	<p>Top of dam elevation;</p> <p>Normal depth elevation;</p> <p>Spillway type</p> <p>Inlet and outlet elevations and dimensions</p> <p>Depth area/volume relationship.</p>	<p>As for weirs</p> <p>Number and type of gates</p> <p>Sill levels</p> <p>Gate heights</p> <p>Maximum opening</p>

Table 5-3: Information required for modelling different types of hydraulic structures.

5.5.5 Digital Elevation Models (DEMs)

A DEM is a 3D representation of a ground surface created from elevation data. A model of the ground surface within the floodplain is required for almost all flood modelling studies. For 2D or 1D-2D modelling approaches the ground model is used to route flows over the floodplain. For 1D modelling approaches a ground model is required for developing the out of bank schematisation, and for mapping the results.

Ground models may be bare earth where features such as buildings have been removed, usually referred to as a **Digital Terrain Model (DTM)**, or may contain the elevations of surface features (e.g. buildings, vegetation), commonly referred to as a **Digital Surface Models (DSM)**. DTMs are more commonly used in flood modelling.

DTMs may be constructed from ground-based topographic survey, from remote sensing data (e.g. LIDAR) or from a combination of these. The required resolution and accuracy for a DTM depends on the modelling objective and approach, and the study area. The DTM resolution determines the finest possible 2D model resolution, as the resolution cannot practically be increased beyond that in the available DTM. Further discussion on the required resolution for 2D models is given in Section 7.3.1.

DTM information may also be required at a higher resolution than the 2D model resolution in order to allow the modeller to identify the elevations of flow paths and obstructions in the floodplain. Local, detailed flood studies require a more accurate and higher resolution DTM than strategic or catchment level studies. For **rural** floodplains a general recommendation is that the DTM has a vertical accuracy of 0.5m and a spatial resolution of at least 10 m, while for **urban** areas a vertical accuracy of 0.05 m with a spatial resolution of 0.5 m may be required to resolve gaps between buildings (Mason, Schumann, & Bates, 2001).

Point to Note:

Recommended DTM accuracy:

RURAL floodplains

Vertical: 0.5m

Horizontal; spatial resolution of at least 10m

URBAN floodplains

Vertical: 0.05m

Horizontal; spatial resolution of up to 0.5m in some cases.

5.5.5.1 Existing Data Sets

There are several existing DTMs, based on remote sensing data, available for Scotland. In assessing whether these are sufficient for use or if additional data may need to be collected it is important that the resolution, accuracy and collection date are considered.

The accuracy depends on the method of data capture, and how well surface features have been removed from the DSM to create the DTM. In areas with dense vegetation or buildings the accuracy of the DTM may be reduced due to the need to remove features from the DTM.

Table 5-4 provides a summary of the different datasets available for Scotland together with comments on their use and limitations. Generally LIDAR collected from aeroplanes is the best DTM for flood modelling. Figure 5-2 shows current LIDAR coverage for Scotland.

There is no programme to collect a DTM for Scotland at regular intervals so in almost all cases the best available data represents a single snapshot in time. There may therefore be issues if there have been significant changes since the DTM was collected, such as infilling of docks, river realignment, developments involving land raising or erosion or deposition. For coastal studies the state of the tide when the DTM was collected should also be considered.

Whether linear features such as flood defences, agricultural embankments, railway and road embankments and cuttings and small watercourses are picked up in a DTM depends on the resolution as well as the size of the structure. For this reason a DTM should always be supplied to modellers at the highest resolution available. It is however unlikely that any of the available DTMs for Scotland are of sufficient accuracy to determine elevations of flood defences or resolve local drainage networks.

5.5.5.2 New Data Collection

It may be necessary to collect new data where the existing DTM is insufficient to meet the modelling objectives. There are 2 principal survey methods which may be used for this – ground-based topographic survey or LIDAR surveys.

5.5.5.2.1 LIDAR

High mobilisation costs for airborne LIDAR may be prohibitive for surveys of small areas. It is generally more cost-effective (in terms of the cost per km² of data collected) to survey larger areas; working in partnership with other organisations can increase the size of survey areas and reduce costs.

Ground control points should be compared with the elevations in the LIDAR data and if possible a data validation exercise should be carried out following data collection.

LIDAR should be flown when there is no dense vegetation cover as this may obstruct the laser from reaching the ground surface. Generally, data collection should be carried out in the period following significant autumn leaf fall and before the main spring growing season. Where data collection is to be carried out during the winter months issues with snow cover should be considered. Snow cover prevents the laser from reaching the ground surface. Data collection should also not take place when the ground is flooded, as this will also prevent the laser from reaching the ground surface. Surveys should be planned with some contingency time to allow for local conditions. For coastal studies LIDAR should be flown as close to low tide as possible to allow for a detailed representation of the coastline to be collected.

Ground-based LIDAR can be used to collect more detailed data, such as kerb heights, which may be of use for detailed surface water studies. The data collected in these surveys can also be used to develop 3D visualisations of flooding.



Figure 5-2: LIDAR coverage for Scotland (June 2015).

Data Source	Description	Coverage	Horizontal Resolution	Vertical Accuracy	Availability and licensing	Year	Comments/ Limitations
LIDAR	Various LIDAR datasets available	See Figure 5-2	1 m – 2 m	± 0.15 m	Dependant on data source and proposed use. For Local Authority studies LIDAR should be supplied by the Local Authority. Other public bodies should contact The Scottish Government	Varies	Best available. Generally ties in well with ground based survey. Other Public Bodies may hold LIDAR which SEPA is unaware of.
NEXTMap	Synthetic Aperture Radar (SAR)	National	5 m	Depends on area ± 1 m or ± 0.7 m	Contact Scottish Government	2002-2003	Known issues in forested and urban areas. Accuracy means that there may be a considerable offset with other data in some locations.
Getmapping	Stereo Aerial Photography	National	5 m	±0.6 m	Contact Getmapping		Not widely tested by SEPA. Found to be better than NEXTMap in some areas but not all.
OS Terrain 5	Stereo Aerial Photography and ground based survey	National	5 m	± 2 m	Ordnance Survey	Quarterly updates, but may not cover all areas.	New dataset not tested by SEPA.
OS Terrain 50		National	50 m		Ordnance Survey – open data	Annual updates, but may not cover all areas.	Resolution probably too low for most mapping studies.

Table 5-4: Summary of known DTM data sources for Scotland.

5.5.5.2.2 Ground-Based Topographic Survey

Ground-based survey to develop a DTM can either be on a grid pattern across the study area at the required resolution or targeted at particular features such as embankments, ditches or curb or threshold levels.

Where the data is targeted at particular features, modellers may be able to combine the ground based survey with existing remotely sensed DTM to create a new DTM. However, there may be issues resolving inconsistencies between the 2 datasets especially in areas where LIDAR is unavailable.

New topographic survey should be according to Section III of the EA Specifications.

5.5.6 Bathymetric Data

Existing bathymetric data is available from a number of sources.

The European Marine Observation and Data Network EMODnet has produced a 1/8th arc minute⁸ resolution bathymetric dataset of European waters (approximately 130 m east-west resolution and 230 m north-south resolution at 56° north). The bathymetry uses data from hydrographic offices, authorities responsible for management and maintenance of harbours, coastal defences, shipping channels and waterways, and research institutes and industry, and General Bathymetric Chart of the Oceans (GEBCO) bathymetry where no other data is available. The bathymetry is freely available from the EMODnet bathymetry portal. This data is unlikely to be at a sufficient resolution for detailed coastal studies but may be suitable for regional models. There are some discontinuities in the data at the boundaries between datasets.

Some gridded and point data from the United Kingdom Hydrographic Office (UKHO) is available under the Open Government License and can be downloaded from the UKHO inspire portal <http://aws2.caris.com/ukho/mapViewer/map.action>. However, note that the data has not been processed to remove conflicts between datasets at boundaries.

Published Admiralty charts provide bathymetric data at a range of resolutions. Electronic datasets can either be generated by digitising these charts, subject to license from the UKHO, or by purchasing existing electronic versions of the datasets from commercial suppliers (i.e. C-Map, SeaZone). Sea Zone also produce a gridded dataset combining chart data and bathymetric survey. However, license conditions for the electronic versions from these suppliers may restrict usage.

Harbour authorities may also have datasets which they are willing to share for flood studies and should be contacted directly.

5.5.6.1 Commissioning New Bathymetric Surveys

If new bathymetric survey is required, section 7 of the EA Specifications provides an appropriate specification.

5.5.6.2 Coastal Defence Survey

In addition to toe and crest levels for wave overtopping models a profile through the flood defence is required, including information on the roughness.

5.6 Operating Information

⁸ An arc minute is 1/60th of degree.

Information on the operation and maintenance of flood defences, river channels and reservoirs should be provided where possible. There are no set formats for the supply of this information.

Where there are flood defences, or other structures which may be operated during flood events, control rules and procedures will be required for any detailed study. Where structures are manually operated, information on when they were operated during any events to be used for calibration will be required.

Information on known/frequent blockage locations and dredging and weed cutting regimes can be used to inform model sensitivity tests.

5.7 Existing Studies

Key points for Responsible Authorities

- Any existing models should be reviewed by an experienced modeller to determine if they are suitable for use in the new study.

SEPA and the Responsible Authority may be able to identify if any existing models cover the study area. Where existing models are available it should be considered whether they can satisfy the new study. However, it should be noted that sometimes the modification of an existing model to meet the objectives of a new project is as much work as starting from scratch. Questions which may need to be considered are:

- What was the purpose of the existing modelling? Are there assumptions and limitations which make it unsuitable for the new purpose?
- Is the study area appropriate or would it need to be extended?
- Is it at a sufficient level of detail at the study location, or is it too detailed? Are there any areas of the model with lower confidence?
- Have there been any significant catchment changes since the model was constructed?
- What data was used for the original model? Is better data now available e.g. LIDAR instead of NEXTMap for the out of bank DTM, or are there known issues with some of the original data sets?
- Are there any reasons to suspect that the existing model does not provide a good representation of the system? Is the model calibrated?
- Is the model numerically stable, or are run times excessive?
- What software and version was used for the original study. Will it run in more recent versions? Are there any significant changes to results between old and new software versions?
- If the model was built for a flood prevention scheme is it a design model or an as built model?
- Is the model georeferenced to enable flood mapping?
- Does the model contain sufficient out of bank representation to model the range of scenarios required for the project?
- Do intellectual property rights allow the model to be used for the new study?
- Can the model be obtained by the Responsible Authority?

- Is the model sufficiently well documented?

An experienced modeller will be required to answer some of these questions and a contractor should allow time in a tender for auditing any existing model and reviewing modelling reports.

Irrespective of whether an existing model is to be reused for the new study, reports from existing studies should be referenced by the new study. These reports may provide information on historic flood events, highlight issues with adopting particular approaches for the study area, and identify flooding mechanisms which require further analysis in the new study or help in identifying the reasons for any discrepancies between the existing and new studies.

5.8 Hydrometric Data

Hydrometric data can be used to develop flood frequency curves and generate boundary conditions for design events and to calibrate a model. These uses are covered in Chapter 6 and in Chapter 8.

In general two types of data series are of interest for flood studies: **time series data** and **series of extremes**. Two types of extreme datasets are available: Annual Maxima (AMAX) the largest event in any given year and Peak Over Threshold (POT) all events over a given threshold. For AMAX series years should be defined so that series are not cut at a flood prone time of year, to ensure that maxima in consecutive years are independent. In general extreme series will be required for the full length of record, whereas time series data is only required for particular events. However, it may still be necessary to supply entire time series to enable suitable events to be identified.

Point to Note:

Time series data – a more or less continuous record normally considered in relation to specific events.

Extreme series data – dataset of extreme records; two types:

AMAX – the annual maxima

POT – all events over a given threshold

Responsible Authorities should consider the need for any additional hydrometric data as early as possible in a Flood Risk Management Planning cycle, as the greatest benefits are likely to be obtained from a longer period of monitoring.

Key points for Contractors

- River flow data held in the NRFA for Scottish sites is not up-to-date. Data for any Scottish gauges used in the study should be requested from SEPA.
- Complete time series should be requested for any sites used in model calibration.
- Rain gauge data should be requested for gauges within, and surrounding the catchment.
- Any Met Office data (if required) should be requested directly from the Met Office enquiries@metoffice.gov.uk. Government bodies should include the phrase Government Enquiry in the subject line to avoid being charged commercial rather than government rates.

5.8.1 River Levels and Flows

SEPA maintains a network of river flow and level gauges. Information on the location of these gauges is available from datarequests@sepa.org.uk. SEPA is planning to add a web link to a database in the near future. A proportion of SEPA gauges, including those contributing to the Peak Flow Database (formally known as HiFlows-UK), appear on the Centre for Ecology and Hydrology (CEH) website (<http://www.ceh.ac.uk/data/nrfa/data/search.html>), which has a number of search options including an interactive map option. The data available from these gauges includes 15 minute time series data, daily max, monthly max and annual maximum (AMAX) series, although not all of this information is required for the majority of flood studies.

AMAX or POT series of flows are required for design flow estimation for fluvial flood studies. AMAX series are sufficient, unless it is necessary to generate flow estimates for events with a recurrence interval < 2 years, or the record length is < 14 years in which case POT series are desirable. Data is required for any gauges within the study area, gauges upstream or downstream of the study area along the same watercourse, for any sites used in a pooling group and for any donor sites. AMAX series should be generated based on UK water years (1st October – 30th September) rather than calendar years.

Peak flow estimates are derived from a stage-flow relationship (rating) that is calibrated from sample flow measurements (gaugings) through as much of the flow range as possible. However, the derived flow from the rating can only be guaranteed up to the highest gauging, which is often well below the highest recorded stage. Derived flows above the highest gauging are based on a simple extrapolation of the rating and are only credible up to bank full level or as a rule of thumb, 10% above the highest gauged flow. The exception to this is where any floodplain flow has been modelled. The upper limit of sensible derived flow from a rating needs to be understood and factored into how the data is used. The local hydrometric team can advise on rating limits for each station.

AMAX and POT series for some SEPA gauges is available from the National River Flow Archive (NRFA) managed by held CEH. This includes the Peak Flows dataset for use with the Flood Estimation Handbook (FEH) discussed in Section 6.3. **The Peak Flow Database has not been updated with SEPA data since October 2006,**

however, SEPA has recently transferred revised and up-to date data to the CEH for 30 stations and these should appear on the website by the end of 2016. SEPA will work to update all the SEPA gauging stations in the Peak flows station pool, currently numbering 140 stations, over the new few years. In the meantime, up to date AMAX for the study area for any Scottish sites used in a pooling group analysis, and for any donor sites, should be requested directly from SEPA. It is critical to liaise with the local SEPA hydrometric team to ensure that flows are derived using the most appropriate rating for flood estimation. SEPA is currently working to ensure that all AMAX are derived from the most appropriate ratings and until this exercise is complete, a check with the local team is necessary. On occasion it may be simpler for SEPA to supply level data and a rating rather than derived flow data. The exercise also aims to produce POT datasets for those sites contributing to the Peak Flow. It should be noted that SEPA may have revised its rating curves since the last update to HiFlows-UK. These discrepancies will be resolved in future updates as per the exercise described above. Updates on this project can be obtained from SEPA.

Point to Note:

Early engagement with the local **SEPA Hydrometry team** is essential to confirm the availability and quality of gauged data.

Time series of both flow and level are required for model calibration. Calibration events may be identified based on a number of factors including data availability at several gauges and in, most cases, it is easier to request complete datasets rather than submit multiple requests for chunks of the same dataset. Time series of flow are required for any gauges within the study area and gauges upstream or downstream of the study area along the same

watercourse. Time series of level are required for any gauges along the modelled reach. Time series of flow may also be used in deriving design hydrograph shapes. If **spot gaugings** are available these can also be used to assist with model calibration, however this should be discussed with the local hydrometric team who can advise on rogue or problematic gaugings excluded during rating development.

SEPA's Hydrometry team is able to provide information about the reliability of particular gauges and suitability for measuring high flows, including a history of the site. Rating curves are also useful for investigating any discrepancies between the flow record and model output.

Other organisations such as Local Authorities or water companies may also operate flow or level gauges.

On large costly projects consideration should be given to installing additional flow monitoring equipment to collect data. This would be of particular advantage on ungauged watercourses and could prevent over-design with resulting cost savings.

5.8.2 Rainfall Data

SEPA maintains a network of rain gauges. Information on the location of these gauges is available from datarequests@sepa.org.uk. SEPA is planning to add a web link to a database in the near future. Other organisations such as water companies may also install temporary rain gauging. Data from Environment Agency gauges should be requested from the Environment Agency.

Radar data is available from the Met Office and may also be useful in model calibration. To avoid being charged commercial rather than government rates, government bodies (including local authorities) should request radar data directly from the Met Office enquiries@metoffice.gov.uk and include the phrase Government Enquiry in the subject line. Contractors should not request data directly from the Met Office.

Time series of rainfall may be used for calibrating fluvial and pluvial models. For calibrating models data will be required for gauges within and surrounding the study catchment as the most representative gauge may not be within the catchment and rainfall applied to a model may be from area weighting rainfall from a number of different gauges. If it is necessary to generate antecedent conditions for the calibration events rainfall data may be required for a long period prior to the calibration event. Calibration events may be identified based on a number of factors, including data availability at several gauges, and in most cases it is easier to request complete datasets rather than submit multiple requests for chunks of the same dataset.

The FEH Depth Duration Frequency (DDF) model is generally used for generating design rainfall so annual maximum and POT series are not usually required. The FEH DDF model gives rainfall depth as a function of return period and storm duration for all catchments > 0.5 km² and on a 1 km grid across the UK. Example output from the FEH DDF model is shown in Figure 5-3. A new version of the DDF model (FEH 2013) was released in 2015, and replaced the existing DDF model (FEH 1999) for a complete range of return periods and durations. Both the FEH 1999 and FEH 2013 DDF models are available through the FEH web service at <https://fehweb.ceh.ac.uk/>. The FEH 1999 DDF model is also available through the FEH CD-ROM.

FEH 2013 incorporates a significant amount of additional data to FEH 1999 and uses an improved statistical model. In Scotland FEH 2013 includes 176 hourly rain gauges compared to 58 in FEH 1999 which is a significant improvement in data coverage for the

rainfall durations likely to be of most interest to flood risk management. As a result of the improved data coverage and statistical methods, FEH 2013 has higher depths than FEH 1999 for short duration rainfall (< 6 hours) for most locations in Scotland up to the 0.1% AEP event. Further information on the development of the FEH 2013 model is found in the Defra technical report Reservoir Safety – Long Return Period Rainfall (Stewart, et al., 2010).

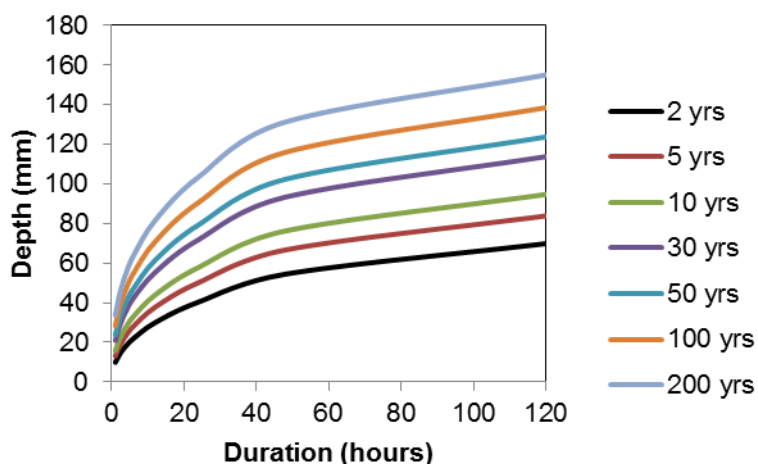


Figure 5-3: Example output from the FEH Depth Duration Frequency Model (DDF).

5.8.3 Soil Moisture and Evaporation Data

Soil moisture and evaporation data are used to assess catchment antecedent conditions for flood event analysis, and to calibrate rainfall runoff models. The Met Office Rainfall and Evaporation Calculation System (MORECS) provides an assessment of soil moisture on a 40 km square grid for the UK. To avoid being charged commercial rather than government rates, government bodies (including local authorities) should request MORECS data directly from the Met Office enquiries@metoffice.gov.uk and include the phrase “Government Enquiry” in the subject line. Contractors should not request data directly from the Met Office.

5.8.4 Reservoir Data

Where reservoirs are considered to have a significant impact on flow regimes within a catchment, time series information on levels and releases from the reservoirs and depth volume curves are likely to be required for model calibration, and in developing flood frequency curves. This data should be obtained from the reservoir operator. For reservoirs with a retained volume of 25,000 m³ or greater details of the reservoir operator can be obtained from the public register.

5.8.5 Sea Level Data

5.8.5.1 Gauge Data

Tide gauge data is available from SEPA, the British Oceanographic Data Centre (BODC) and port/harbour authorities.

Data from the national tide gauge network can be obtained free of charge from BODC https://www.bodc.ac.uk/data/online_delivery/nts1f/. There are 43 gauges within this network of which Leith, Aberdeen, Wick, Lerwick, Kinlochbervie, Ullapool, Stornoway, Tobermory, Port Ellen (Islay), Millport and Portpatrick are in Scotland. Both the measured sea level and the residual or surge (difference between the measured sea level and the astronomical tide) are supplied. Time series and monthly extremes are available.

Information on the location of SEPA gauges is available from datarequests@sepa.org.uk.

Data from harbour or port authority gauges should be requested directly from the relevant port authority.

Time series of measured sea level are required for calibration of coastal models and for the tidal areas of fluvial models. Extreme series of sea level are used to develop design water levels, however in most cases design sea levels in the Environment Agency Report Coastal Flood Boundary Conditions for UK mainland and islands (McMillan, et al., 2011), described in section 5.8.5.3 are used. Extreme sea level series are therefore only needed if it is wished to extend the analysis to sub-annual events or areas within estuaries or sea lochs which are not covered by the study.

5.8.5.2 Tide Tables

Astronomical tide curves and harmonic constants are available from the Admiralty Tide Tables, Admiralty Total Tide and other suppliers such as C-Map.

5.8.5.3 Sea level boundary conditions

Design sea levels are given in Environment Agency Report Coastal Flood Boundary Conditions for UK mainland and islands (McMillan, et al., 2011). The design sea levels are developed from a statistical analysis of extremes from the class A tide gauge network together with data from a small number of other sites. The study gives extreme still water levels and representative surge shapes for 1, 2, 5, 10, 20, 25, 50, 75, 100, 150, 200, 300, 500, 1000 and 10 000 year return period events. The study applies to the open coast only, and the further analysis required to develop design sea levels within estuaries is discussed in section 6.5.1. Levels from the Coastal Flood Boundary Project have already been supplied to Local Authorities by SEPA. Surge shapes from the Coastal Flood Boundary Project should be requested from SEPA.

The SEPA Coastal Hazard Mapping Project (Royal Haskoning DHV and JBA, 2013) extended the extreme sea level analysis from the CFB study to sea lochs and estuaries within Scotland but did not derive representative surge shapes for these locations. Where surge shapes are required within sea lochs and estuaries, a hydrodynamic model may be required to model how the shape of the surge changes within the estuary, section 6.5.1.

5.8.6 Wave Data

Wave observations for some sites are free to download from websites including those referenced in Table 5-5, however, there are limited gauge sites and, for the majority, only a short record is available, limiting use of the data to model calibration and validation.

In the absence of long duration wave observations time series data at wave model offshore boundaries are typically taken from **wave model hindcasts**. Wave model hindcasts are also used to generate AMAX and POT series for design event analysis and are available on request from the organisations noted in Table 5-6.

Organisation	Web Address
Cefas Wave Net	http://www.cefas.defra.gov.uk/our-science/observing-and-modelling/monitoring-programmes/wavenet.aspx
BODC	https://www.bodc.ac.uk/data/online_delivery/waves/

Table 5-5: Organisations providing wave observation data.

Organisation	Time Period Data Available	Contact Address
Met Office	1980-2014	enquiries@metoffice.gov.uk (Nb. Local Authorities should contact SEPA in the first instance)
NOAA	1979-2007	http://polar.ncep.noaa.gov/waves/CFSR_hindcast.shtml

Table 5-6: Organisations providing wave hindcast data.

Contractors should not request data directly from the Met Office to avoid being charged commercial rather than government rates. The NOAA model also covers the UK and is available from the NOAA website although it is not calibrated specifically for the UK.

The **available data from these models is typically wind wave, swell and resultant (wave and swell combined) waves, significant wave height, mean period and mean direction;** the complete frequency spectrum is not usually available.

On large, costly projects consideration should be given to installing additional wave buoys to collect data, this can be expensive, but will may increase confidence preventing over-design with resulting cost savings.

5.8.7 Wind data

Time series of wind data may be required for calibrating coastal models and for generating wind wave boundary conditions. Wind observations are primarily available from the Met Office although data may also be available from local weather stations. To avoid being charged commercial rather than government rates, government bodies (including local authorities) should request radar data directly from the Met Office enquiries@metoffice.gov.uk and include the phrase “Government Enquiry” in the subject line. Contractors should not request data directly from the Met Office.

5.9 Other Data

5.9.1 Sewer Network Data

Scottish Water is the organisation responsible for the design and management of Scotland’s sewerage systems. It can therefore provide information on the sewer network, including the location of outfalls. Data should be requested from the Scottish Water Area Asset Manager. Sewer network data can be useful in identifying catchment boundaries in urban areas where catchments may be significantly different from the natural catchment boundaries due to the surface water drainage network.

5.9.2 National Coastal Change Assessment

For coastal studies the National Coastal Change assessment <http://www.dynamiccoast.com/> provides information on the susceptibility of the coast to erosion. This can provide an indication of whether the potential for coastal erosion to contribute to flood risk should be considered in flood studies.

5.9.3 Water Framework Directive Status/Pressures

Information on Water Framework Directive (WFD) Status and Pressures as identified in the River Basin Management Plans can be found on the SEPA Water Environment Hub <http://www.sepa.org.uk/data-visualisation/water-environment-hub/>. This information should be reviewed at scoping stage to identify potential opportunities for studies and measures with a joint WFD and Flood Risk Benefit, and to assist in identifying structures (including informal flood defences) which would need to be included in any channel survey.

5.9.4 Mapping Data

Mapping data has several uses in flood modelling. At the scoping stage, maps are used to identify structures and other features which may influence flow pathways and possible receptors. During model build, maps are used to identify building footprints, and areas likely to have different roughness, or loss of water to the drainage network. Maps are also used in communicating model results. Sources of mapping data typically used in flood modelling,

and their principle uses are given in Table 5-7. Ordnance Survey data is available to Public Bodies under the One Scotland Mapping Agreement⁹, and the license conditions also allows public bodies to pass data to their contractors, subject to conditions.

Map Type	Location	Notes
OS Colour Raster Maps	https://www.ordnancesurvey.co.uk/	Display of model outputs Identification of structures and features.
OS Mastermap		Building footprint identification. Identification of roughness zones.
Historical Maps	http://maps.nls.uk/index.html	Identifying former paths of watercourses, potential culvert routes and artificially drained areas. This is useful when developing a conceptual model.
Land Cover Map 2007	http://www.ceh.ac.uk/landcovermap2007.html	Identification of roughness zones. Identification of rural and urban areas.
Scottish Government Urban Rural	http://www.gov.scot/Topics/Statistics/About/Methodology/UrbanRuralClassification	Identification of rural and urban areas.
Aerial photographs	Various sources	Display of model outputs Identification of structures and features. Identification of roughness zones.

Table 5-7: Map data used to support flood modelling studies.

⁹<https://www.ordnancesurvey.co.uk/business-and-government/public-sector/mapping-agreements/one-scotland-mapping-agreement.html>

6 Boundary Conditions

6.1 Introduction

Hydrological analysis is required to determine design flows and probability of a flood. These are used as input boundary conditions for hydraulic models.

Estimates of probability are not static but may change over time due to changes in climate or catchment and due to changes in the data record or best practice flood frequency analysis techniques. This means that it is important to review the hydrology for any new flood study, even if a hydrological analysis has been carried out for a previous study.

Hydrometric data in the UK are generally of high quality; however uncertainty is inherently present when conducting flood frequency estimates due to the length of record compared to typical design probabilities of interest, the range of different analysis methods available, and the coverage of the gauge network.

This chapter aims to:

- Give a brief description of the methods which can be used for hydrological analysis of fluvial, pluvial and coastal flooding.
- Describe the outputs which would be expected from a hydrological study.
- Describe the circumstances in which SEPA may seek to support a review of hydrological analysis.

Key points for Responsible Authorities

- All flood frequency estimates are inherently uncertain and subject to change.
- The hydrology should be reviewed for any new flood study.

6.2 Terminology

Key points for Contractors

- Where possible, flood studies should use the **annual exceedance probability** terminology rather than return period.

Two terms are commonly used to describe the flood frequency in the UK, the return period and the annual exceedance probability.

- The **return period** of an event is the average interval between years containing an event of the same or greater magnitude. A similar measure is the **average recurrence interval**, which is the average period between events of a same or greater magnitude.
- The **annual exceedance probability (AEP)** is the probability that an event of the same or greater magnitude will occur in any one year. This is the reciprocal of the return period.

Use of the terms return period or average recurrence interval can cause some confusion amongst non-specialists who can misinterpret it to mean that events occur at fixed intervals. For this reason use of annual exceedance probability, rather than return period is preferred.

Return Period (years)	Average Recurrence Interval (years)	Annual Exceedance Probability (%)
2	1.44	50.0%
5	4.48	20.0%
10	9.49	10.0%
30	29.50	3.3%
50	49.50	2.0%
100	99.50	1.0%
200	199.50	0.5%
1000	999.50	0.1%

Table 6-1: Different ways of presenting flood probability.

6.3 Fluvial

Key points for Responsible Authorities

- Design flows should not be finalised or signed off by either the Responsible Authority or SEPA before model calibration and reconciliation is complete, and should be reviewed and revised as a modelling study progresses.
- Identify key locations (reconciliation points) where it is important for flows in a hydraulic model to match hydrological estimates, and agree the locations at the inception meeting.
- The variation in design flows along a catchment should be physically justifiable and explained in the modelling report.
- It may be necessary to run multiple model scenarios for the same AEP event in order to match the design flow at different points in the model.
- Ensure that contractors allow time for appropriately experienced staff to review any hydrological analysis. Encourage use of the supplied check list in Appendix C.2 .

Key points for Contractors

- Determine the robustness of all hydrometric data in consultation with local SEPA Hydrometric teams.
- Compare flow estimates from statistical (single site and pooling) and rainfall-runoff methods.
- Consider the method used to derive hydrograph shape and run large catchment models for multiple storm durations if required.
- The modelling report should include sufficient details of the analysis to enable an experienced hydrologist to reproduce the flow estimates.
- Further detail on approach to hydrological analysis is available in SEPA's Technical Guidance for Stakeholders.
- Refer to specific guidance in the FEH.
- Document the approach used for reconciliation in the modelling report, and give values for any scaling factors.

For all fluvial flood studies the hydrological analysis will need to produce design flow estimates. For studies involving unsteady modelling the hydrological analysis will need to produce design hydrograph shapes. For catchment scale studies the analysis will also need to consider the distribution of inflows.

In most cases hydrological analysis should be based on the methods in the Flood Estimation Handbook (FEH) (Institute of Hydrology, 1999) which provides the industry standard methods and guidance for fluvial flood estimation within the UK. The FEH largely supersedes the Flood Studies Report (Institute of Hydrology, 1975) and its associated reports. The FEH provides a framework for flood estimation, however user expertise and experience is required to judge the most appropriate methods / data to use in any individual circumstance. No single method is considered superior to others for all situations and in some cases other flow estimation methods than those in the FEH may be appropriate depending on the catchment characteristics. However, if FEH methods are not used a comparison with FEH methods should be made with justification provided as to why the FEH methods were not considered appropriate.

Responsible Authorities should note that hydrological analysis may be more complicated or uncertain in the following cases:

- Urbanised catchments;
- Small catchments < 25 km²;
- Catchments containing reservoirs, lochs and hydroschemes;
- Pumped catchments;
- Assessment of natural flood management measures (Chapter 12).

This means that more time may be required to be allowed for the analysis, and/or there may be lower confidence in the results. Where these factors exist within a catchment the approach taken to deal with these cases should be discussed in the report.

An appropriate hydrological analysis is one of the most important parts of a flood study. Responsible Authorities should ensure that contractors allow time for appropriately experienced staff to review any hydrological analysis and encourage use of the check list in Appendix C.2 .

6.3.1 Review of Hydrometric Data

All data received to support a flood study should be independently reviewed and checked against the quality statements and advice of the data provider. This also applies to hydrometric data. Before undertaking a hydrological analysis any hydrometric data supplied for the project should be reviewed in full. SEPA makes every effort to ensure that all hydrometric data supplied by SEPA is accurate however it is possible that some issues and inconsistencies may only become apparent through use in a detailed flood modelling study. As a minimum the data review should cover:

- Robustness of the rating for any gauges used in the statistical analysis e.g. variation of the rating with time, hysteresis, location of any discontinuities
- Catchment changes which may mean that sections of the data series are no longer valid e.g. construction of reservoirs.
- Gaps in the hydrometric data series.
- Suitability of the data for use in hydrological analysis. This should include a review of whether the NRFA FEH indicative suitability is correct.

Any apparent anomalies should be discussed with the local hydrometric team.

6.3.2 Design Flows

The relationship between flow and probability is known as the flood frequency curve. There are two common approaches to estimating the flood frequency curve: (i) statistical analysis of flood peak data (single site or pooled analysis) and (ii) the design event method using a rainfall-runoff model. For many catchments, either approach can be applied however they can produce very different results.

For catchment or local scale models flow estimates using both approaches should be compared and the adopted method justified. For all methods sufficient details of the analysis should be given in an appendix to the modelling report to enable an experienced hydrologist to reproduce the flow estimates.

Design flow estimates are required at the upstream boundary of any modelled watercourses and at reconciliation points where it is important for the flow in a model to match the hydrological estimates. Reconciliation points are typically chosen at:

- All gauging stations in the model domain
- Downstream of major confluences
- Key receptors such as urban areas
- Any points where the SOP of a flood defences is required.

Reconciliation points should be agreed between the Responsible Authority and the contractor at the inception meeting.

Design flow estimates should be reviewed and revised as a modelling study progresses and should not be accepted or signed off by either SEPA or the Responsible Authority commissioning the study until calibration and reconciliation of any models is complete. Where possible a combined hydrological- hydraulic approach should be adopted for model calibration, as the following could indicate both problems with design flow estimates or missing processes and errors in a hydraulic model:

- Problems representing the observed flood history e.g. annual flooding is observed and the 50% AEP event is in bank, or 50% AEP shows flooding in an areas with no flood history.
- Inconsistencies in design flows along the catchment, e.g. increases/decreases in design flow estimates downstream which cannot be explained by increase in catchment area/ attenuation.

6.3.2.1 Statistical Method (single site and pooled analysis)

The statistical method is generally the first choice method where there is a long record of gauged flood event data available. The method involves the construction of a flood frequency curve based on the estimation of QMED (the median of the set of annual maximum flood data with an annual exceedance probability of 50%) and a growth curve which gives design flows for other return periods as a function of QMED.

For gauged locations QMED is typically estimated from the AMAX or POT series at the gauge, and these data series are discussed in section 5.8. For ungauged locations QMED is estimated using another, usually nearby, catchment with similar catchment characteristics, a process known as donor transfer, or from catchment descriptors. Other less common approaches include the use of channel dimension data or continuous simulation.

The FEH describes 6 methods to estimate QMED. In addition, a revised method of estimating QMED based on catchment descriptors is described in the study by CEH (Kjeldsen, et al., 2003). While the choice of method(s) used in the study should still be justified, SEPA recommends that the revised QMED estimation method is considered and that a precautionary approach is taken when estimating QMED and the subsequent derivation of the design flood.

Where only short gauged records are available these may be used to support estimates of QMED.

The method for estimating the growth curve depends on the length of the gauged record for which data is available and the required return period, there are two methods a single site analysis based on local gauged data, or a pooling group analysis which estimates QMED and the growth curve from a group of gauging stations on other similar catchments. For gauged catchments with a sufficient length of record a comparison of the single site and pooling group analysis should be made. For ungauged catchments only the pooling group method will be appropriate.

Where level only gauges are available, or where no high flow rating is available, it may be possible to extract a rating from a hydraulic model provided that the gauge is surveyed and modelled in sufficient detail. In this instance SEPA should be contacted to discuss survey requirements, gauge history and available information for calibration.

6.3.2.2 Design Event Method (Rainfall-Runoff Method)

The FEH Rainfall-Runoff method uses a design storm based on the FEH DDF model discussed in section 5.8.2. This is then run through a simple catchment model (based on the Unit Hydrograph and a loss model) to produce a design flow estimate Figure 6-1. This approach produces a full flow hydrograph as opposed to a peak flow produced by the statistical method. As a result, this method is usually applied when flood volumes or durations are important such as in the design of flood storage areas or reservoir spillways. **This method is potentially most applicable to small catchments especially where they are ungauged.**

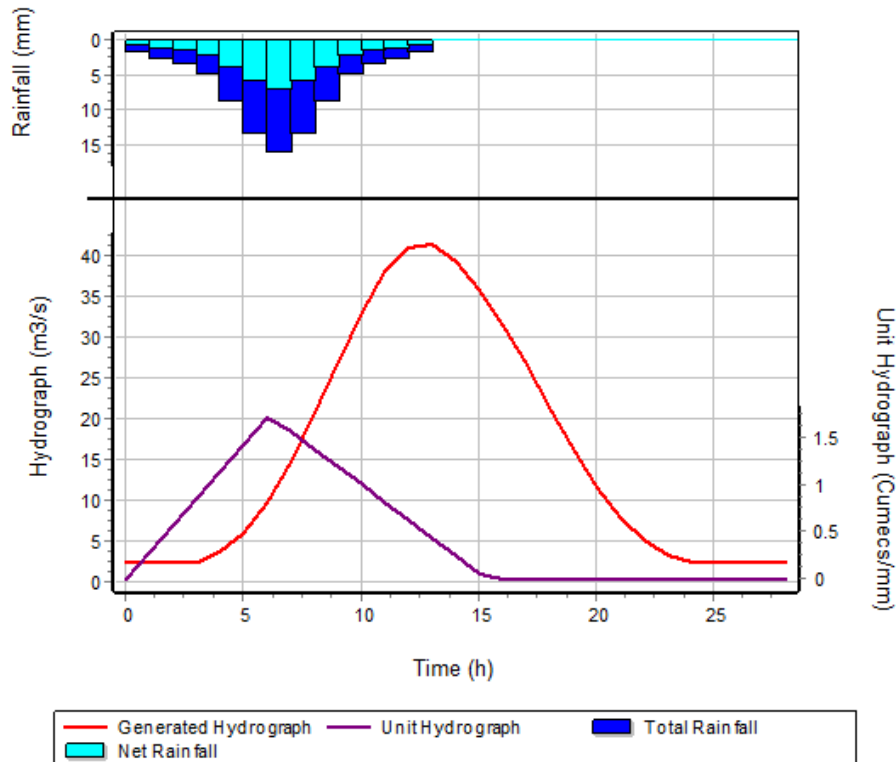


Figure 6-1: FEH Rainfall Run-off model. The model consists of a losses model which describes the proportion of rainfall falling on the catchment which runs off rapidly (net rainfall) and a unit hydrograph which describes the response to the net rainfall.

A new conceptual rainfall-runoff model called the Revitalised Flood Hydrograph Model version 2 (ReFH2) has been developed which supersedes the FSR/FEH Rainfall-Runoff Method. Recent improvements to the method have now rendered it applicable for design flow estimation within Scotland however the methodology has been calibrated to catchments without significant storage (i.e. lochs and reservoirs). The methodology is still being assessed and, like any other flood estimation methodology, it should only be used in combination with others for comparison. Note that ReFH version 1 is not considered suitable for use in Scotland due to the limited number of Scottish gauges and lack of Scottish specific calibration.

As discussed in Section 5.8.2 a new version of the FEH DDF model FEH 2013 has recently been published and should generally be used over the previous version, FEH 1999 due to the improvements in data and techniques. The differences between FEH 2013 and FEH 1999 may also have implications for previous design flood estimates carried out using rainfall-runoff models.

Both the FEH and ReFH2 rainfall models are **lumped** hydrological models (i.e. they use a single unit to represent a catchment and model parameter values are averaged across the catchment). More complicated **distributed** hydrological models allow factors such as soil type or rainfall to vary across a catchment. Distributed hydrological models are not commonly used for flood estimation in Scotland and **would not usually be accepted by SEPA for design flow estimates**; however they are potentially useful for some NFM studies. This is discussed in chapter 12.

6.3.3 Hydrograph Shapes

The shape and duration of a hydrograph is determined by a variety of factors such as drainage efficiency, catchment shape, channel characteristics, vegetation cover, land use,

soil type and storm patterns. Hydrograph shapes are required for unsteady modelling (Table 3-3).

For ungauged catchments the hydrograph shape should be generated using a rainfall-runoff model, as in section 6.3.2.2

Where there is gauged data available close to the model boundary a hydrograph shape can either be derived by either:

- standardising hydrographs by their peaks and averaging (Archer, Foster, Faulkner, & Mawsdley, 2000),
- using a hydrograph from a large observed flood event or
- using a rainfall-runoff model

In order to identify a representative large observed event or suitable events for the averaging approach, 15 minute times series data will be required as discussed in Section 5.8.1.

In all cases the hydrograph is forced to fit the design flow estimate, either by adjusting the rainfall runoff model parameters or by scaling the derived hydrograph shape.

The method used to derive the hydrograph shape and why it was chosen should be discussed in the hydrology report.

6.3.4 Catchment Schematisation/Boundary Locations

For local assessments, a single upstream boundary with a flow estimate and hydrograph based on the catchment upstream of the site may be appropriate provided there are no significant inflows within the study extent. However, for catchment or strategic scale studies where the flow may be reasonably expected to increase throughout the model, inflow hydrographs are required at several points throughout the study area. In this case the catchment is split into sub-catchments and the hydrograph for each sub-catchment is routed through the model. A map of the catchment schematisation should be included in the hydrology report together with the FEH catchment descriptors for each sub-catchment in an appendix.

It is not physically realistic for different duration critical storms to occur at different points in the same catchment at the same time. Where a catchment has been split into sub-catchments the same design storm is applied to each sub-catchment, and the model is run for a range of storm durations to find the critical storm duration which produces the worst case flow or level at the site of interest.

6.3.5 Flow Reconciliation

For large catchments the AEP of a flood event may vary throughout the catchment. This means it is not always possible to apply a consistent design storm across the catchment so that the flow in a hydraulic model matches the design flow estimates at the reconciliation points. In this case it is necessary to adjust the boundary conditions so that the flow in the model matches the design flow at the reconciliation points. This process is termed **flow reconciliation**, and should be undertaken **after model calibration**, chapter 8. There is no single method to achieve this but typical approaches include:

Adjusting the storm duration: Different critical storm durations may be identified for different parts of the catchment. Generally the critical storm duration will increase downstream; any decreases in critical storm duration downstream should be justified in the model report (e.g. confluence with major tributary with steeper/more urbanised catchment).

Adjusting the hydrograph shape: Different hydrograph shapes may be required to match design flows at different points in the catchment, or for different AEPs. If this approach is taken it would be expected that a higher volume hydrograph would be used for larger flood events or for reconciliation points lower in the catchment. Where this is not the case this should be justified in the modelling report.

Scaling tributary inflows: Different scaling factors may be required for different reconciliation points and for different storm durations. Typically the same scaling factor is applied to all tributary inflows for the same model run for simplicity. In most cases scaling factors will reduce the flood peak from the design flow estimates on the tributaries, as downstream of a confluence the flood peak is likely to result from a combination of more frequent events on the tributaries. Although in some instances design flows may decrease downstream due to attenuation, and the AEP of a particular observed flood event may increase downstream, it is not possible to require a lower probability flood event to occur on a tributary in order to generate a higher probability flood event downstream.

Adjusting the phasing of tributary inflows: The start time of tributary inflows may be adjusted to make them more or less coincident. This would typically be used where a combination of gauged data and rainfall-runoff boundaries have been used for model inflows.

It may be necessary to run **multiple model scenarios for the same AEP event** in order to match the design flow at different reconciliation points. The confidence in hydrological flow estimates and the ability of the hydraulic model to reproduce any attenuation in the design flows should be considered in determining to what extent the flow in the hydraulic model should be constrained to match the design flow. The approach used for reconciliation should be described and justified in the modelling report.

6.3.6 Climate Change

A discussion of climate change allowances for fluvial modelling is given in Chapter 10.

6.4 Pluvial

Key points for Contractors

- If necessary model several storm durations to identify the worst case.
- Describe and justify the method used to determine infiltration and drainage losses.
- Undertake sensitivity analysis if the approach adopted is not demonstrably conservative.
- The modelling report should include sufficient details of the analysis to enable an experienced hydrologist to reproduce the rainfall estimates.

Boundary conditions for pluvial models need to consider how much rainfall falls on the surface and how much of this rainfall is lost due to infiltration into the ground or is carried away by the surface water drainage network.

6.4.1 Rainfall Models

It is suggested that representative rainfall applied over a model domain is constructed based on the FEH 2013 Depth-Duration-Frequency model (section 5.8.2). FEH 2013 should generally be used over FEH 1999 due to the improvements in data and techniques between

FEH 2013 and FEH 1999. As in many cases depths in FEH 2013 are higher than in FEH 1999, use of FEH 1999 could lead to an underestimation in rainfall depths. The DDF model gives total rainfall depth for a given probability of occurrence and flood storm duration. The storm duration which causes most flooding for a given probability of occurrence will depend on the catchment being modelled, and it may be necessary to model several storm durations to identify the worst case; SEPA's pluvial hazard maps used 1 hour and 3 hour duration storms.

Standard rainfall profile shapes are given in the FEH and used to generate rainfall profiles from the DDF model. The FEH provides two standard profiles; winter and summer (Figure 6-2), which do not vary with duration or location. The summer profile has a more pronounced peak, representative of the convective storms more common in summer, and is generally recommended for application to urban catchments where a shorter period of high intensity rainfall is generally more critical. The summer storm profile was used in SEPA's pluvial hazard maps. The choice of rainfall profile should be justified in the modelling report.

Point to Note:

A **summer storm profile** presents a shorter duration but higher intensity storm and is generally recommended for application to urban catchments.

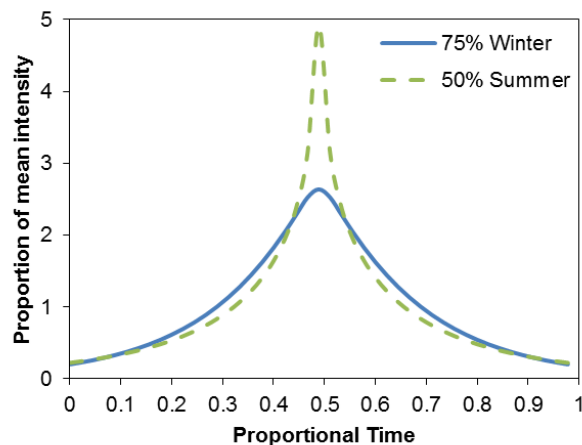


Figure 6-2: Standard FEH Hyetograph Profiles, based on Faulkner, (1999).

6.4.2 Losses

Two types of losses need to be considered in surface water modelling; infiltration into the ground and loss of water into the urban drainage system.

Infiltration rates should vary between urban and rural areas to account for the effect of extensive impermeable surfaces in built-up regions. The FEH handbook advocates the use of 70% runoff for impervious areas (Institute of Hydrology, 1999). Within an urban area there will be a component of the catchment which acts as natural and has lower run off rate. The percentage of the urban area which is impermeable varies according to the

Point to Note:

SEPA's pluvial hazard maps use a conservative approach in its assumptions.

Runoff rates:

- 100% of the urban area is impermeable
- **Urban** runoff rate of 70% and **rural** of 55%

Drainage loss allowance:

- National models: 12mm/h
- Regional models: average 20% AEP (1 in 5) rainfall loss

physical characteristics of the area and the scale and accuracy of the mapping used to define the urban extent. The FEH handbook assumes that 61.5% of the urban area is impermeable based on the digital land cover maps used to define urban extents in FEH (URBEXT). Impermeable areas may be defined at higher resolution using aerial photography or from large scale mapping. SEPA's pluvial hazard maps use a conservative approach, assuming that 100% of the urban area is impermeable and then applying a flat runoff rate of 70% in urban areas and 55% in rural areas¹⁰. Other, more detailed, approaches are possible, such as using the losses model from the ReFH rainfall runoff method which allows the percentage runoff to vary with time, or by specifying different infiltration rates for different surfaces. The method used to determine infiltration losses should be described and justified in the modelling report and sensitivity analysis may be advised if the approach adopted is not demonstrably conservative.

In urban catchments it may be appropriate to incorporate a realistic **drainage value** to remove a proportion of the rainfall input. This is not required if the drainage network is represented explicitly in the model (i.e. an integrated catchment study). Research conducted by the Environment Agency during the creation of The Flood Map for Surface Water advocates the application of drainage loss rates of 12 mm/hr. If there is sufficient information on the drainage network it may also be possible to define a local loss value.

An alternative approach is to assume a given service level for the drainage system. SEPA's national pluvial mapping assumed a 12 mm/hr loss to the drainage system whilst the regional pluvial mapping assumed an average 1 in 5 year rainfall event loss (Figure 6-3). Where a level of service is assumed, the loss applied may be constant or may vary with time, Figure 6-4.

The approach taken to determine losses to the drainage system should be described and justified in the modelling report. In general no loss to the drainage system should be considered for rural catchments.

6.4.3 Climate Change

A discussion of climate change allowances for pluvial modelling is given in Chapter 10.

¹⁰ Urban areas in SEPA's regional pluvial modelling are defined using the Land Cover Map 2007 (LCM2007) and urban areas in the national pluvial maps are defined using the Scottish Government Urban/Rural Classification

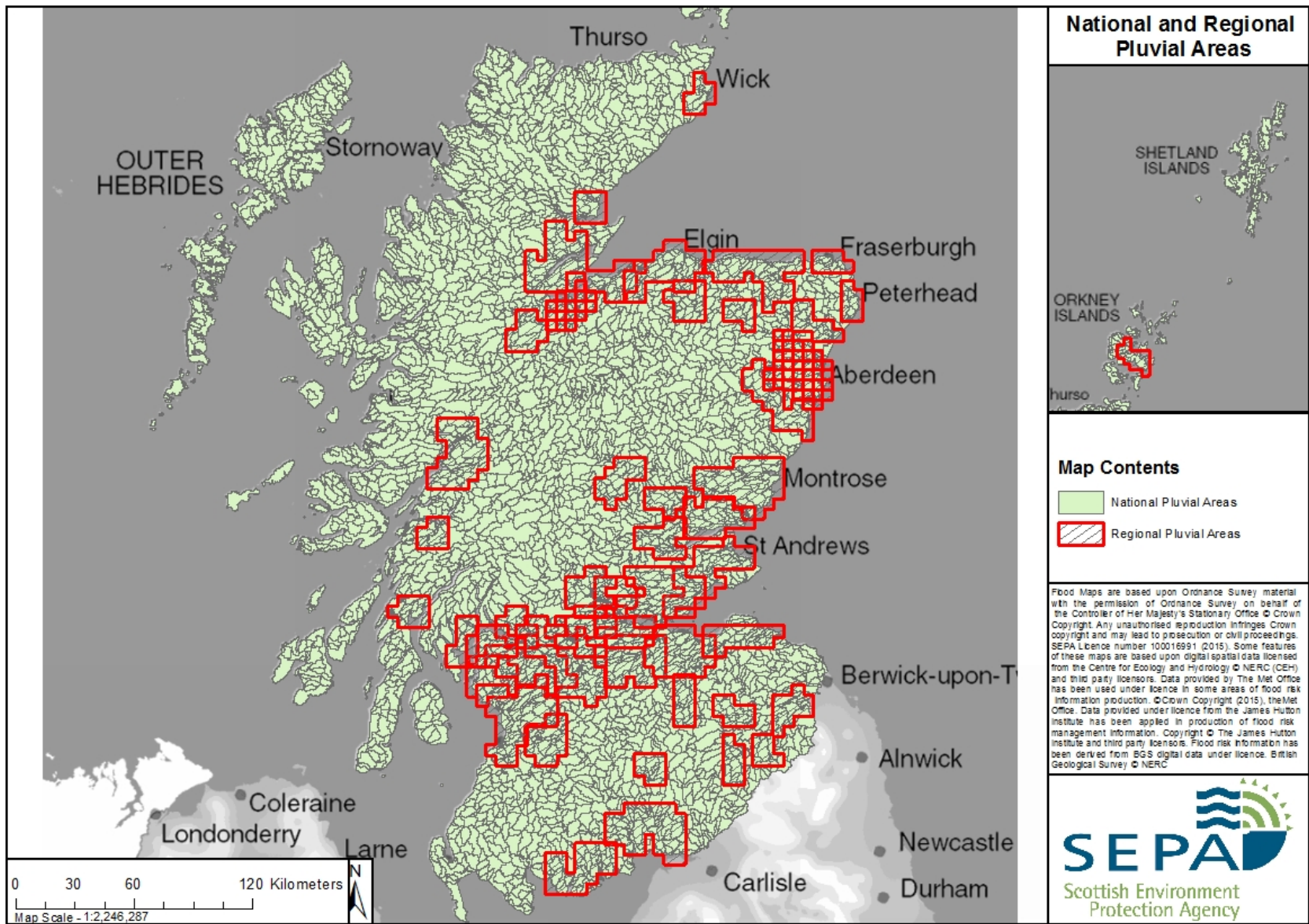


Figure 6-3: Areas covered by SEPA's national and regional pluvial modelling.

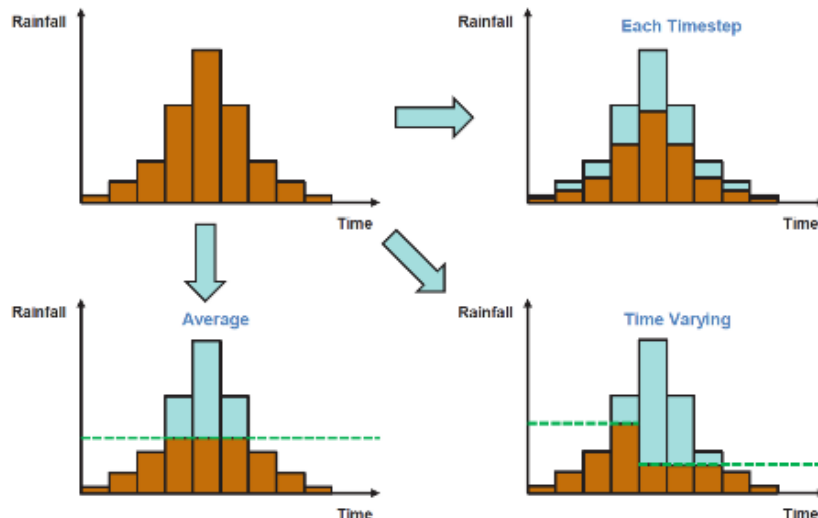


Figure 6-4: Example of Different Methods to Remove 5 year Drainage Allowance (JBA Consulting, 2014).

6.5 Coastal

Key Points for Responsible Authorities

- Coastal flooding is due to a combination of astronomical tides, surge and waves. Interactions between these elements should also be considered. The conceptual model should identify which processes are important for coastal flooding at a study location.
- Responsible Authority coastal flood studies should seek to adopt a more detailed approach than that used to derive SEPA's national hazard mapping. This may involve the use of several models.

Coastal flooding is due to a combination of astronomical tides, surge and waves. The combination of astronomical tide and surge is referred to as the still water level. Still water levels and waves are often treated separately however, waves may increase still water levels at the coast due to a process called wave setup. In turn still water levels influence where waves break and hence the total amount of overtopping. The key processes leading to coastal flooding for a particular study location should be identified through the conceptual model of the study area; see section 3.3.

Section 5.8.5 describes available sea level data and section 5.8.6 describes available wave data. Information on extreme still water levels is not generally available within lochs and estuaries and wave data is usually only available offshore. This means that further modelling is often required to bring boundaries inland and, in complicated areas, generating boundary conditions for coastal inundation models may require:

- A hydrodynamic model to look at how surge and tide change as they move up sea lochs and estuaries.
- A wave transformation model which looks at how waves change as they move inland.
- A wave overtopping model to look at the rate of water overtopping flood defences.

Inland flooding due to still water levels may be modelled by applying a level boundary to an inland flood model or else the hydrodynamic model used to model surge and tide may be extended in land. Inland flooding due to wave overtopping is usually modelled by applying a flow boundary to an inland flood model. The different factors which need to be considered in developing boundary conditions for coastal flood models are given in Figure 6-5.

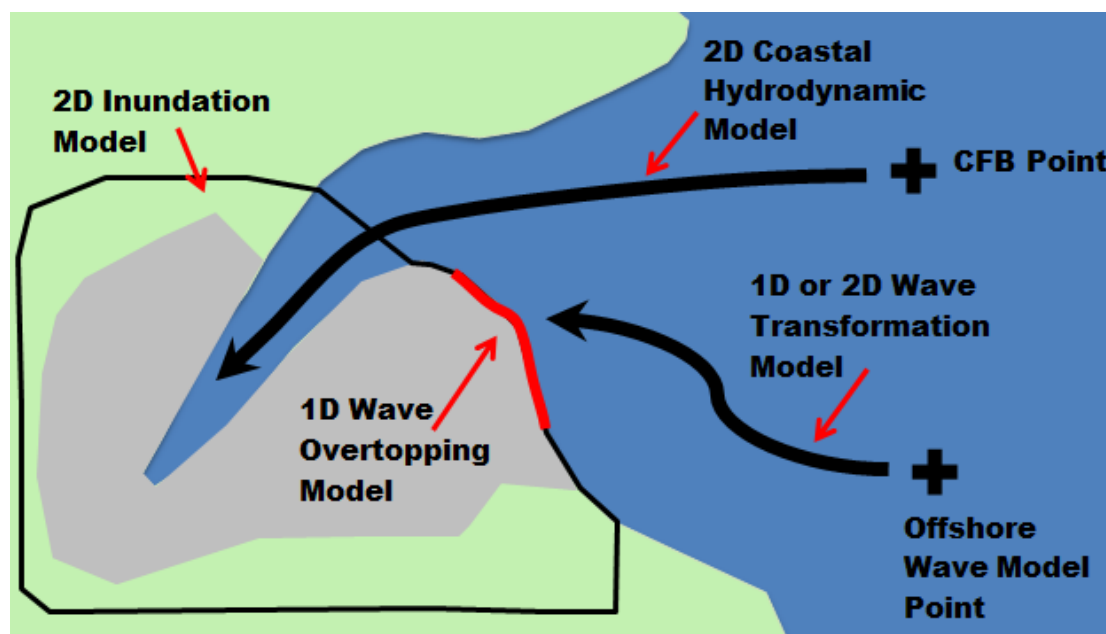


Figure 6-5: Factors to be considered in developing coastal boundary conditions.

The SEPA Coastal Hazard Mapping Study mapped flooding due to extreme still water levels only for the entire of the Scottish coast. This strategic level study was based on level projection of these water levels only and did not consider the duration for which the levels were high. It is expected that any coastal flood study undertaken by a Responsible Authority will be more detailed; probably with time-varying still water boundaries and wave boundary conditions. More information on coastal modelling techniques and their applicability to Scotland is given in (Stokes, Masselink, & Conley, 2016).

6.5.1 Still Water Boundary Conditions

Key Points for Contractors

- For the open coast use boundary conditions from the Environment Agency Project Coastal Flood Boundary Conditions (CFB) for UK mainland and islands (McMillan, et al., 2011).
- For sea lochs and estuaries review the method used to extend to the CFB dataset inland for the SEPA Coastal Hazard Mapping Project (Royal Haskoning DHV and JBA, 2013) to determine if it is appropriate for a more detailed study.
- The base year for the study levels should be documented in the report.

Development of still water boundary conditions needs to consider:

- Extreme water levels, surge and tide shapes on the open coast;
- The change in extreme water levels & surge and tide shapes within estuaries and sea lochs;

- The effect of wind and wave set up on still water levels.

The conceptual model of the study area should identify which of these factors are important, and the modelling report should contain a discussion of the reasoning behind including or excluding these factors from the study.

For locations on the **open coast** boundary conditions should be taken from the Environment Agency Project Coastal Flood Boundary Conditions (CFB) for UK mainland and islands (McMillan, et al., 2011). This gives extreme still water levels for 16 annual exceedance probabilities at 2 km spacing around the open coast of Scotland, England and Wales and provides guidance on developing standard storm tide curves to be used with extreme sea levels at each location. These storm tide curves may be applied directly as a level boundary for inland flood models for locations on the open coast if wind and wave set up are not considered important. The report should state the CFB point used, which surge shape was used to generate the boundary and how the base astronomical tide was derived.

The CFB dataset extends into the outer parts of some **estuaries and sea lochs** but not the inner parts of estuaries because local bathymetric effects can significantly affect tide levels within estuaries. The SEPA Coastal Hazard Mapping Project (Royal Haskoning DHV and JBA, 2013) extended the analysis from the CFB study to sea lochs and estuaries within Scotland using a combination of observed data not included in the CFB study, local modelling studies and relationships between open coast and estuarine locations from similarly shaped and aligned estuaries. For local flood studies in areas covered by the SEPA Coastal Hazard Mapping Project a review should be undertaken of the method used to extend the CFB dataset to determine both if the level of confidence in the levels is appropriate for a more detailed study and if storm tide curves can be derived. This review should be documented in the modelling report. The location of points taken directly from the CFB study and the SEPA study are shown in Figure 6-6.

If the SEPA Coastal Hazard Mapping Project is not suitable for providing boundaries a hydrodynamic model of the estuary or loch may be required. This will usually be 2D, but in some instances a 1D model may be sufficient for narrow estuaries and it may also be possible to include inland flooding within the same model. Detailed bathymetric data is required for constructing a coastal hydrodynamic model and possible sources of data for this are described in Section 5.5.6. Where possible the model should be calibrated against observed tide levels or admiralty tide tables and this is discussed in Section 8.2.2. The relevant CFB storm tide curve should be used as a boundary for the hydrodynamic model. Construction and calibration of any coastal hydrodynamic model used to generate boundary conditions should be documented in the modelling report.

The CFB boundaries and the SEPA Coastal Hazard Mapping levels include the effect of storm surge but do not take into account **wave setup** which may increase sea levels on a downwind coast. In some locations wind set up is also not accounted for. Where this effect has been identified as important in the conceptual model it may be necessary to carry out a joint probability analysis for surge and wave and wind setup, and to add wave and/or wind boundary conditions to any hydrodynamic model used to bring surge inland. In this case additional modelling may also be required for the open coast. Any analysis used to determine the effect of wind and wave setup should be documented in the modelling report.

Sea levels in the CFB and SEPA Coastal Hazard Mapping study are referenced to 2008. The base year for the study and the adjustment made for climate change since 2008 should be documented in the report.



Figure 6-6: Location of CFB points.

6.5.2 Waves

There are two different types of waves:

- **Wind waves** (also referred to as sea waves). These are generated by the local wind, have a shorter period and are often irregular.
- **Swell waves**. These waves are generated by more distant weather systems, have a longer wave period and are more regular.

The sea state is the combination of wind waves and swell. Both components need to be considered in wave overtopping studies..

A description of available wave data is given in section 5.8.6. There are few long time series observations available so, in most cases, the best available data are hindcasts from wave forecast models. Forecasts points from these models are some distance offshore, and need to be transformed inshore, usually through use of a numerical wave transformation model. Extreme still water levels and extreme wave conditions may occur independently however, the worst case situation for flooding is likely to be when large waves occur at high tide or during a high tide and surge, so a **joint probability analysis of extreme waves and extreme still water levels is required**. Wave conditions inshore cannot be used as a direct input into a hydraulic model, and run up and overtopping models are needed to determine the rate of flow over the defences, which can then be used as an input to an overtopping model. Developing wave boundary conditions for input into a flood inundation model therefore requires:

- Offshore design wave conditions
- Joint probability analysis of still water levels and extreme wave conditions
- Wave transformation modelling
- Overtopping Modelling

Case Study – Eyemouth Flood Study

Wave overtopping studies can be complex. The Scottish Borders Council Eyemouth Wave Overtopping and Flood Study (Royal HaskoningDHV, 2013) used three models to generate inflow hydrographs for a flood inundation model from the offshore results from the Met Office wave model.

Waves were transformed inshore using a regional Firth of Forth wave model, and then further inshore using a local Eyemouth wave model, both of which were developed for SEPA's Firths of Forth and Tay flood warning scheme. The results from the Eyemouth model were used as boundary conditions for an overtopping model of the Eyemouth sea wall.

6.5.2.1 Offshore design wave conditions

Offshore design wave conditions are derived from an extreme value analysis of a wave model hindcast (Section 5.8.6). This is carried out for the range of direction sectors (typically in 30° increments) which may be incident on the coast. Results for all wave direction sectors analysed should be tabulated in the report, and sufficient detail of the analysis should be given to allow the results to be reproduced.

Typically the Met Office wave model hindcasts are used for the UK. As with all models, wave model hindcasts are not perfect and may systematically over or under estimate the extreme wave conditions of interest for flood studies. Where possible the performance of any model

used for boundary conditions should be assessed against observed data. In all cases a literature review should be carried out to ensure that known limitations in the model are understood, and these should be documented in the modelling report.

6.5.2.2 Joint probability of extreme still water levels and extreme wave conditions

Extreme still water levels are discussed in section 6.5.1. A joint probability analysis of extreme still water level and wave height should be undertaken. Different approaches for joint probability analysis are given in DEFRA guidance FD2308 (Hawkes & Svensonn, 2005) (Hawkes, 2005), including a desk study approach which is simple to apply and will be sufficient in many cases. However since publication of the DEFRA guidance new techniques have been developed which may be more appropriate for complex areas or where full uncertainty analysis is required (Gouldby, Méndez, Guanche, Rueda, & Mínguez, 2014).

Results from the extreme value analysis and joint probability analysis should be tabulated in the report for the different wave direction sectors considered. Again sufficient details of the analysis should be provided to allow the results to be reproduced. To obtain the worst case flood extents it will generally be necessary to consider a number of different wave and SWL scenarios, each with the same joint probability of occurrence.

6.5.2.3 Wave transformation modelling

Forecast wave model points are usually some distance off shore, while flood modelling requires wave conditions at the coast. Wave conditions from the wave forecast points must be therefore transformed inshore in order to provide wave conditions at the coast and this is carried out using a numerical wave transformation models.

Wave and water level boundary conditions used for the wave transformation modelling come from the joint probability analysis discussed in Section 6.5.2.2. Wind boundary conditions may also be required and are usually developed using a simple regression analysis between wind speed and significant wave height from the wave model hindcast.

Development of a wave transformation model requires good quality bathymetric survey and shore survey (see section 5.5.6). For complex regions multiple wave transformation models may be required, with a coarse resolution regional model covering a larger area used to provide boundary conditions for higher resolution nested models of inshore areas, Figure 6-7. In this case joint studies may be cost effective. SEPA has several wave models developed for flood warning schemes which may be made available for Responsible Authority studies.

Where possible the wave transformation model should be calibrated using observed data, and the set up and calibration of any wave transformation model used should be described in the modelling report.

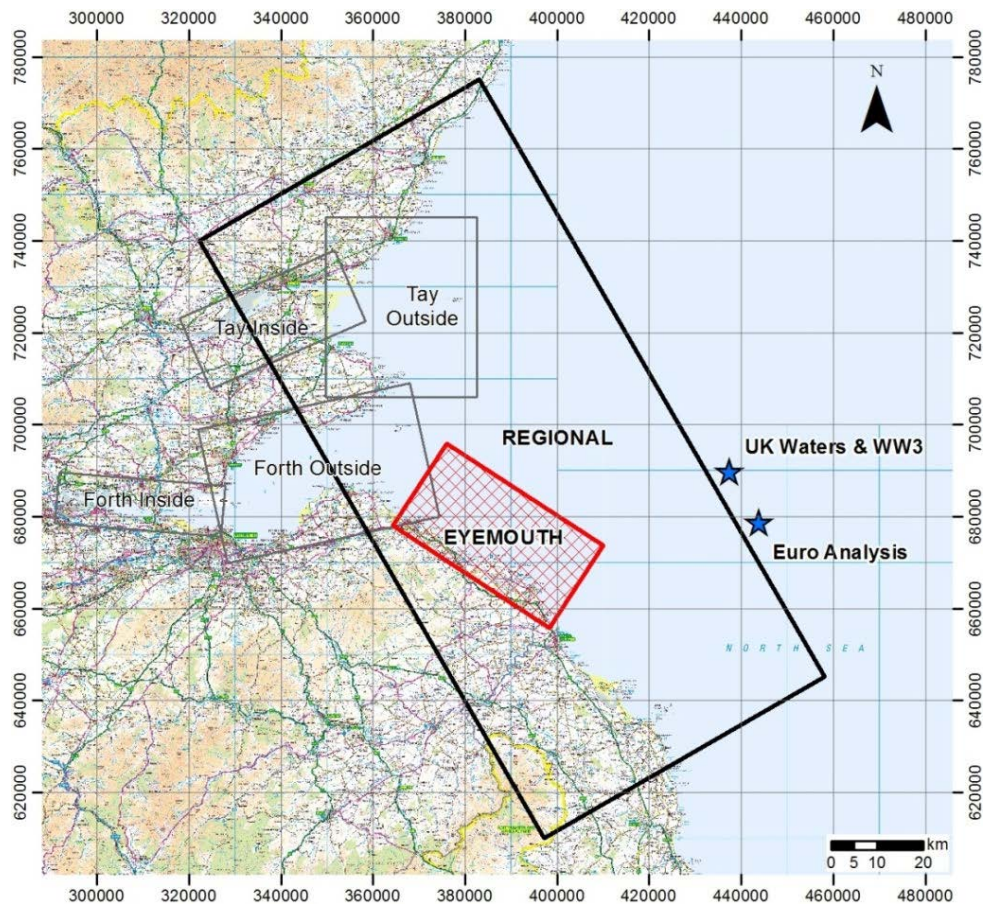


Figure 6-7: Wave transformation model domain for the Firth of Forth developed for SEPA's flood forecasting scheme. To generate boundary conditions at Eyemouth 2 nested model domains are used. Figure from Royal HaskoningDHV (2013)

6.5.2.4 Wave Overtopping

Wave overtopping models are used to calculate an overtopping rate from:

- Inshore wave and still water level conditions, and
- Detailed information on the flood defence or beach profile. Typically the **crest height, toe level and profile or type of the defence** is required.

Several different overtopping models are available (e.g. Pullen, et al., (2007), Hedges & Reis, (1998)) and the most suitable model may change according to the defence and beach type. (Stokes, Masselink, & Conley, 2016) provide a review of different approaches which may be relevant to different types of coastline around Scotland. The modelling report should justify the overtopping model used with reference to the available literature.

6.5.3 Climate Change

A discussion of climate change allowances for coastal modelling is given in Chapter 10.

6.6 Joint Probability

6.6.1 Extreme Sea Level and Fluvial Flows

Joint probability analysis to investigate the potential combined effect of extreme sea levels and high fluvial flows may be required for river reaches which are tidally influenced. The worst case scenario would involve the concurrence of high tide, a surge and high fluvial flows. Joint probability analysis typically includes running a model with different combinations of downstream tidal boundary and fluvial inflow boundary conditions. Consideration should

be given to the backwater influence of the tidal boundary on upstream water levels as this can have an effect further upstream than the tidal limit. Joint probability analysis should be according to the methodology in the DEFRA/Environment Agency Project FD2308 Joint probability: dependence mapping and best practice (Hawkes & Svensonn, 2005) (Hawkes, 2005)

6.7 Groundwater

Currently there are few confirmed instances of groundwater flooding in Scotland and a recent scoping project suggests that it is not as widespread a problem in comparison to other parts of the UK. However, groundwater flooding is possibly underrepresented in Scotland because of the difficulty of differentiating it from other types of flooding.

If groundwater is perceived to be an issue it can be investigated through desk studies or on-site ground investigations and groundwater level monitoring in conjunction with other hydrological data.

6.8 Uncertainty

All flood frequency estimates are inherently uncertain due to the length of record compared to typical design probabilities of interest, the range of different analysis methods available and the incomplete data coverage. This can be one of the largest sources of uncertainty in a modelling study and understanding this can help in making decisions such as the level of freeboard to apply to a defence based on modelled water levels.

Where the analysis method permits, error bounds should be given on estimates of design flows or levels; and design flows or levels should not be reported with a higher level of precision than is justified by the data or analysis. The impact of the effect of uncertainty in flood frequency estimates should be addressed through sensitivity testing. This is discussed in chapter 8.

7 Model Schematisation

7.1 Introduction

This chapter provides guidance for Responsible Authorities wishing to critically review models received from contractors. It describes:

- The options which can be considered when schematising different features within a hydraulic model and how these may affect the results.
- Common errors and problems with hydraulic models.
- Expected good practice in model building.

7.2 1D fluvial Models

Key Points for Responsible Authorities

- 1D models cannot be used to give flow velocity on the floodplain
- The floodplain schematisation determines the out of bank flow routes possible in the model.
- There are several common issues with 1d models which need to be checked for during a model review.

Key Points for Contractors

- Comments should be added to the model giving the source of any data, the reasons for any structure representation, and the location of structures and cross sections.
- Sensitivity testing should be carried out for roughness, structure blockage, and structure representation.
- The modelling report should explain the choice of flood plain representation, the channel and floodplain roughness values

In a 1D model the channel is represented as a series of cross sections. A single flow and level value is calculated for each of these sections and velocity is averaged over the depth and cross section width. As there is only a single level at each cross section, all points below the calculated water level are wet simultaneously, even if there is no connection between one area of the cross section and another, Figure 7-2. This also means that 1D models cannot be used directly to give flow velocity in the channel and on the floodplain, or variations in level across a section for instance, due to superelevation at a bend. Where flow is not predominately 1D, typically at structures, different equations have to be used to calculate energy losses through the structure.

Key factors to consider in schematising a 1D model are the representation of the channel between hydraulic structures, the representation of any hydraulic structures and the floodplain representation.

7.2.1 Channel representation

7.2.1.1 Cross Sections

Cross sections are required at all points of interest, upstream and downstream of structures, where there are significant changes in channel shape or slope and at the model boundaries. Elsewhere the model cross section spacing must be sufficiently close to capture variations in the hydraulic properties; and rules of thumb for cross section spacing are given in Figure 7-1. Too sparse cross section spacing can result in numerical instability and unphysical attenuation of the hydrograph. Where **survey sections are too far apart** most hydraulic modelling software has an option to increase the spacing by interpolating between upstream and downstream survey sections. This is acceptable provided that there are no major changes in channel shape and slope between the survey sections.

For a cross section spacing Δx , the following rules of thumb apply

1. $\Delta x \approx kB$, where B is the top width of the channel, and k is a constant with a recommended range from 10-20.
2. $\Delta x < 0.2 \frac{D}{s}$ where D is the bank full depth and s is the slope.
3. $\Delta x < \frac{cT}{N_{gp}}$ where c is the speed of the flood wave, T is the period of the flood wave and N_{gp} is a constant between 30-50.

Figure 7-1: Rules of thumb for cross section spacing in hydraulic models (from Castellarin, Di Baldassarre, Bates, & Brath, 2009).

If **cross sections are too close together**, this can also cause problems with numerical stability and lead to long model run times as the model has to be run with a small time step. This may mean that a modeller has to exclude some surveyed sections if the survey is very closely spaced.

Braided channels or split flow paths can be modelled either as a single set of cross sections covering both flow paths, as in Figure 7-2, or separate cross sections can be used for each branch of the channel with some representation of the flow pathway between the cross sections. Where a single section is used the 1D methodology means the calculated water level in both channels is the same and the flow split between the channels is not calculated. The approach taken will depend on the level of detail required and the local hydraulics. For strategic or catchment level models use of a single section may be appropriate especially if there is significant flow between the channels during all flood events of interest. For local or design models, or where there are receptors between the flow paths, use of separate sections may be more appropriate.

Comments should be added to the model giving the source of the cross section data (including surveyed date) and any modifications made during the model build. This can prevent or help identify potential problems if the model is reused in future, for instance, steps in the bed due to a different survey datum or loss of channel capacity due to siltation between surveys. Where it is not clear from looking at the model if a section is from survey or has been interpolated, this should also be recorded. In addition, useful information such as nearby street names or location identifiers should be included as comments where available.

For new models in software which requires cross section names to be entered (e.g. FloodModeller), names should be logical and based on the chainage from a downstream confluence with a larger watercourse or the tidal limit. This can help in identifying errors with

cross section locations, and adding any additional survey to a model at a later date. This is described further in Appendix F.

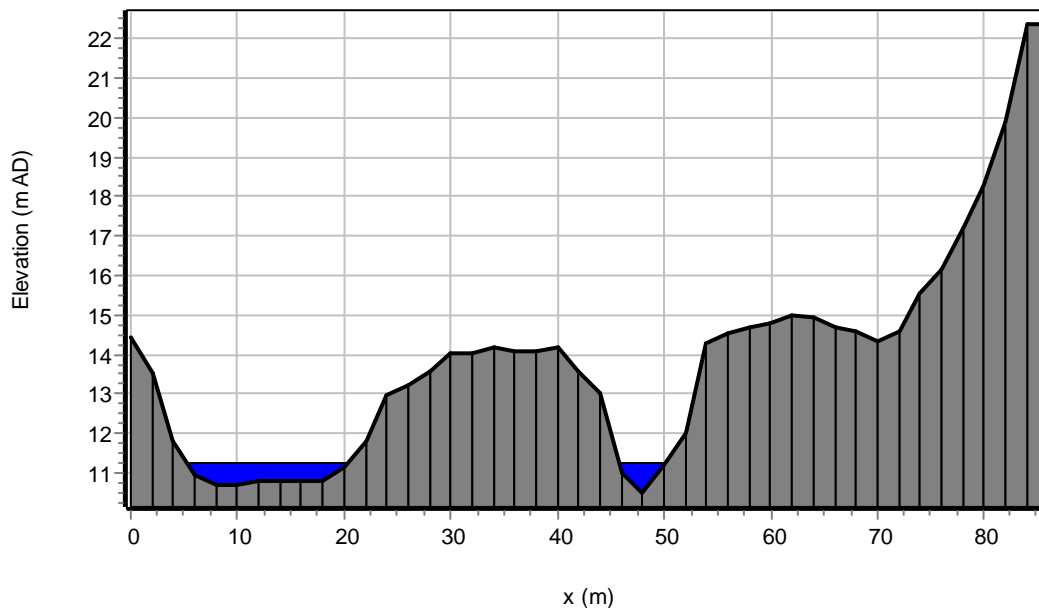


Figure 7-2: Example of split channel modelled as single section.

7.2.1.2 Roughness

Hydrodynamic models include estimates of the surface roughness for the channel and the floodplain areas (right and left¹¹) at every cross section in the model (1D model) and for every cell grid in the model (2D). The most common representation of roughness is in the form of Manning's coefficient (n). Factors that affect roughness include: the nature of the channel bed material, channel bed forms, channel structure, any obstructions (e.g. debris) and the time of the year (i.e. vegetation cover). For free open flowing rivers roughness decreases with increased stage and flow but if the banks of the river are rougher than the channel bottom then the composite ' n ' value will increase with increased stage.

Estimation of roughness is generally subjective based on modeller expertise, site visits or photographs and look up tables for example Chow (1959) or the Conveyance Estimation System (CES) roughness advisor (Fisher & Dawson, 2003). The subjective estimation of roughness means that it is one of the most uncertain variables in a hydraulic model.

- Roughness values should be reasonable and defensible and able to withstand independent review.
- Sensitivity testing to roughness should be carried out as in section 8.4.
- The modelling report should document the values used for roughness and the reason for selection.

7.2.1.3 Hydraulic Structures

Around structures where flow is 2D or 3D, 1D models have to use different sets of equations or parameterisations to represent the flow. Depending on the software used and the structure in question these parameterisations may be purely empirical, based on laboratory and field tests, or they may be based on physical equations. Most 1D modelling software has built-in representations for a range of structure types with options to switch between

¹¹ Right and left are defined as viewed downstream

different equivalent representations of some structures. The precise details of how a structure is represented in a hydraulic model will depend on the software and on the structure; however, there are some general factors which have to be addressed.

Structure coefficients or parameter values In almost all cases representing a structure in a 1D model involves estimation of parameter values by the modeller. This estimation is usually based on user experience, site visits, photographs and survey drawings as it is unusual for detailed measurements to be available at a structure at during flood flows. This introduces uncertainty into the model and sensitivity testing should be carried out for structure coefficients especially where there is high uncertainty in the value to be used or the output of the modelling is expected to be sensitive to the parameter value.

Inclusion of all flow paths There may be multiple flow paths around a structure, particularly during flood events. For instance there may be flow over a bridge deck or out of bank around the side of a weir. All relevant flow paths should be represented. Where a particular flow path has been excluded from the representation this should also be commented upon (e.g. if the flow pathway over the bridge deck is not included as it is above the level of the largest event modelled).

Level of detail The level of detail will determine which hydraulic structures are included in the modelling. For a strategic or catchment level model it may be appropriate to omit some structures such as small footbridges, however these may need to be included for a detailed or design model. Further guidance on this is given in Table 5-2.

Angle to flow Where structures are skewed across the channel this should be accounted for in the structure representation. If the modelling software cannot effectively account for the decrease in effective length due to drowning then different models may be required for high and low flows to ensure that both the drowned and the undrowned states are appropriately captured.

Blockages Where structures have been identified as being at risk of blocking the effect of blockages should be investigated through sensitivity testing; further details on this are given in section 8.4.

Comments should be added to the model giving the location of the structure to aid identification, the reasons for the structure representation used if several options are available, the source of the structure data and how any parameter values were chosen or calculated.

7.2.1.3.1 Bridges

Flow in the vicinity of bridges may be a combination of **free surface flow** where flow is below the bridge deck, **pressurised or surcharged flow** where the flow is in contact with the deck and weir flow over the bridge deck. The bridge schematisation should be sufficient to represent all modes of flow which occur in reality. This may involve the use of multiple model units to represent the bridge (e.g. a bridge unit and a weir or spill unit to represent flow over the bridge). Most forms of hydraulic modelling software have several available bridge representations for each mode of flow – a review of representations available in different software packages is given in Samuels (2004). Typically there is no suitable calibration data available and the choice of representation used is largely based on user experience. If necessary, sensitivity tests to different bridge representations can be carried out.

7.2.1.3.2 Culverts

The hydraulic analysis of flow in culverts is complicated and reference should be made to industry guidance e.g. CIRIA's Culvert design guide (Balkham, Fosbeary, Kitchen, & Rickard, 2010). All culvert models should contain representation of the inlet losses, outlet losses and losses due to friction along the culvert barrel; where a culvert changes shape, bends or is obstructed due to service crossings additional losses should be included to represent these. Losses due to trash screens, where present, should be included in the representation of the culvert inlet.

For detailed or local models it may be necessary to include representations of manholes and surface water sewer connections although in most cases these can be omitted from catchment level models.

Culverts can be particularly prone to blockage and for detailed or local studies sensitivity testing to sedimentation of the culvert barrel and due to inlet blockage should be carried out as set out in the Culvert Design Guide (Balkham, et al., 2010).

Short culverts, where the effect of friction along the length of the culvert can be neglected, can also be modelled as an orifice. This can increase model stability in some cases.

7.2.1.3.3 Weirs and Gates

For structures involving several gates and openings such as mills it may be appropriate for strategic and catchment level modelling to only model the main flow path through the structure, rather than including each sluice individually. Where gates are operated during flood events this can be included in a hydraulic model through use of control rules.

7.2.2 Floodplain Representation

There are three primary methods for representing out of bank flow in 1D models: **extended channel sections**, **storage areas** and **parallel channels** Table 7-1. The most appropriate method depends on the floodplain geometry and several methods may be combined to represent the floodplain in a single 1D model. The floodplain schematisation determines the out-of-bank flow routes possible in the model so care should be taken to ensure that the schematisation is appropriate. The choice of floodplain representation should be covered in the modelling report.

Where the cross section survey does not cover the full width of the floodplain the floodplain representation is typically based on a DTM (section 5.5.5). Difficulties may arise in all methods if there is a discontinuity between the cross section survey and the DTM. Where this occurs it is unlikely that it can be resolved without collection of further out of bank survey.

	Description	Comments
Extended Sections	Cross sections are extended across the full width of the floodplain until they intersect with high ground (Figure 7-3).	<p>Not suitable for embanked watercourses; as there is only one value for stage across a cross section extended sections allow the area behind the embankment to flood before the embankment is overtopped.</p> <p>Cross sections must be perpendicular to the flow direction and for meandering rivers they may be kinked, with different reach lengths being set for the channel, left and right banks.</p> <p>Cross sections should not cross each other.</p> <p>Care must be taken to ensure that there are no significant floodplain changes between surveyed cross-sections.</p>
Storage Areas	Depth area relationships are defined for areas of the floodplain. Flow between these areas and the channel is controlled by the weir equation (Figure 7-4).	Most suitable for flat areas with negligible out of bank flow. Only one elevation value is calculated for the storage area so, if the areas are large or steeply sloped, other areas of the storage area may become wet before the areas next to the channel.
Parallel channels	A separate 1D channel is added parallel to the main river. Flow between the main channel and the parallel channel is controlled by the weir equation.	There may be stability issues associated with the parallel channel drying out, particularly at the start of the modelled event.

Table 7-1: Methods for floodplain representation in 1D models.

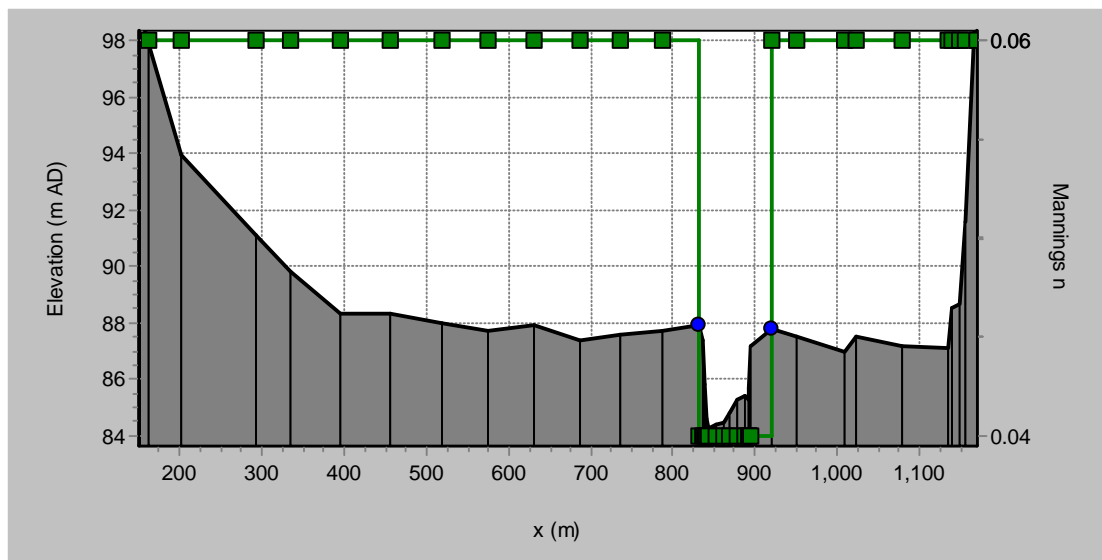


Figure 7-3: Example of extended section in Flood Modeller Pro.

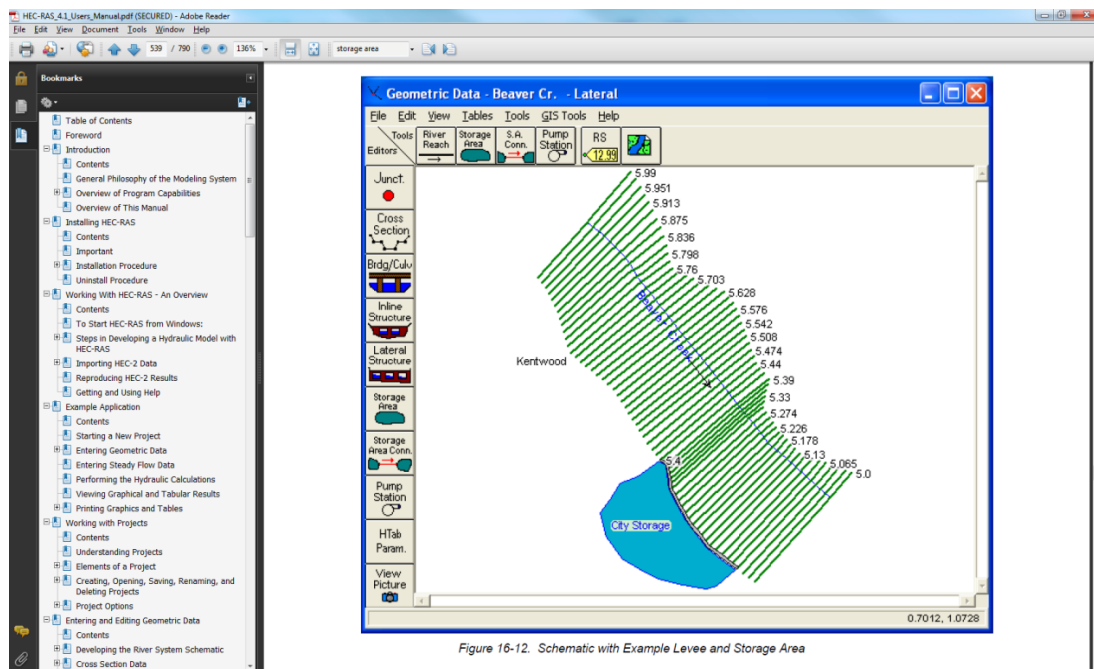


Figure 16-12. Schematic with Example Levee and Storage Area

Figure 7-4: Example of storage area configuration in HEC-RAS from Brunner (2010).

7.2.3 Common Problems with 1D Models

Several common issues may arise with 1D models which should be checked at the model review stage.

Data entry errors 1D models can require significant amounts of manual data entry particularly at structures as there is no single survey or input file format which can be used to read structure data into all hydraulic modelling software¹². This is a potential source of model error and a detailed check on structure data entry against the original survey data should be carried out.

Inappropriate choice of structure coefficients Structure coefficients should be checked to ensure that they are within normal ranges and are physically realistic based on the available evidence.

Glass walling Where 1D models exceed the maximum level in a cross section the modelling software will automatically add a vertical wall at the end of the section to allow water to rise above the section level. This leads to increased water levels within the section as the water cannot spread over the floodplain. Where this occurs the floodplain representation should be extended, unless there is a reason for allowing the model to glass wall (e.g. to represent a very high defence).

Embanked sections If 1D model cross sections contain embankments the area behind the embankment will become wet in the model before the embankment is overtopped. This may be acceptable in some circumstances, for instance if the embankments provide a very low standard of protection or if there is a small area behind the embankment in a catchment or strategic level model. In HECRAS, for example, levees can be used to prevent areas behind the levee becoming wet before it is overtopped. Other software may require the cross sections to be cut back to the top of the embankment and a different representation for the area behind the embankment.

¹² The EACSD file format aims to address this issue, but uptake amongst software providers has been low.

Numerical stability 1D models can be prone to numerical instability. This often manifests as unphysical spikes or oscillations in the water levels or flows. The model log file should be examined for any reports of numerical instability, hydrographs should be examined for unphysical features at each cross section and a long section should be animated to check for unphysical oscillations.

7.3 2D models

Key Points for Responsible Authorities

- 2D models can give depth-averaged velocity on the floodplain but may not represent channel flow well if the resolution is insufficient, particularly around hydraulic structures.
- The model resolution affects the computational effort required to run a model. Balance the need for increased detail due to higher resolution and understanding uncertainty in the modelling through more sensitivity tests and scenarios.
- Future use of the model should be considered in choosing the software as this affects whether the model resolution can vary through a model domain, whether it can be linked with 1d model at a later date and how structures can be represented within the model.
- There are several common issues with 2D models which need to be checked for during a model review.

Key Points for Contractors

- Avoid representing buildings using mesh voids or full height buildings as these representations cause problems when undertaking depth damage calculations using the model results.
- The approach taken to represent any hydraulic structures or linear features in the DTM should be described in the modelling report, together with the data used.
- The roughness values assigned to different land uses should be described in the modelling report, together with the data used to determine the land use.

2D models calculate water level and depth-averaged velocity over a regular or an irregular 2D grid. Schematisation of 2D models is similar for coastal, fluvial and pluvial flooding, with the main difference being in the type and location of boundary conditions applied.

Key factors to consider in schematising any 2D model are the grid type and resolution, the representation of features within the DTM and the roughness. There are also several considerations regarding schematisation which have to be made in choosing 2D modelling software before deciding on the schematisation within a particular software package.

Grid Type – Models may have regular or irregular grids. Irregular grids allow resolutions to vary across the model domain so that higher resolutions can be used only where required, such as for urban areas, steep slopes and along channels, however regular grids may be easier to set up.

Shock capturing – Shock capturing models are better at capturing hydraulic jumps and discontinuities in flow. This is important for dam break modelling and breach analysis.

Computational efficiency and software architecture – Different model codes use different software architecture, which can affect model run times and the number of concurrent simulations which can be run. Shorter model run times are beneficial if large numbers of scenarios or multiple calibration runs are required.

Linkage with 1D models – If the model can be linked with a 1D model at a later date. This is most likely to be a consideration for fluvial models.

Structure Representation – Different packages have different methods to represent features smaller than the model grid such as kerb lines, fences or underpasses, or hydraulic structures such as bridges.

DTM manipulation – The ease with which the DTM can be modified to produce a good representation of the ground surface for modelling (e.g. to include buildings or walls can vary significantly between software packages).

7.3.1 Model Resolution

The model resolution depends both on the scale and objectives of the modelling and the physical characteristics of the study area.

A rule of thumb is that 3-4 grid cells are required to resolve major flow paths. This limits the minimum resolution which can be used for modelling watercourses in 2D. For instance, modelling a 5 m wide channel in 2D would require a minimum 2D grid resolution of around 1.5 m whereas, for a 30 m wide river, a 10 m resolution may be adequate.

For modelling the floodplain of large rivers in rural areas the resolution *does not* have to be high enough to resolve features such as drainage ditches, as these tend to have more influence during low flows than flood flows. Embankments, where present, do usually affect flood flows however; these can be incorporated through forcing elevations in the DTM or incorporation of 1D structures (see section 7.3.2.2). It does not necessarily require a higher resolution. **SEPA's national hazard maps use a resolution of between 5 m and 20 m in rural areas.** In urban areas this resolution is sufficient to resolve flow paths along roads; however, a higher resolution may be required to model flow paths between buildings.

Adequate representation of detailed urban flow pathways (e.g. flows between buildings or even obstructions to flow due to kerb heights) requires a finer spatial resolution. SEPA's fluvial hazard maps use a resolution of 5 m in urban areas and SEPA's pluvial maps use a resolution of 2 m or 5 m in urban areas.

The computational effort required to run a model is largely dependent on the resolution and halving the grid cell size typically results in an increase of run times by a factor of 8. If computing resources are limited it may be necessary to balance the desire for finer grid resolution with the need to run multiple scenarios or sensitivity tests.

Point to Note:

The available DTM affects the model resolution as it cannot usefully be increased beyond the DTM resolution.

A rule of thumb is that 3-4 grid cells are required to resolve major flow paths.

The computational effort required to run a model is largely dependent on the resolution

Where higher resolution is only required in part of a model domain, for instance an urban area within a larger catchment model, this can be achieved either through nested grids in models with a regular grid or through decreasing the element size in models with an irregular grid (examples of these are shown in Figure 7-5). Some nested grid approaches do not conserve momentum at grid boundaries and this can lead to unphysical flow patterns around the boundary. Where nested grids are used the boundaries between grids should be located far enough away from the area of interest so that they do not affect the results; to ensure this is managed appropriately, results near the boundary should be reviewed.

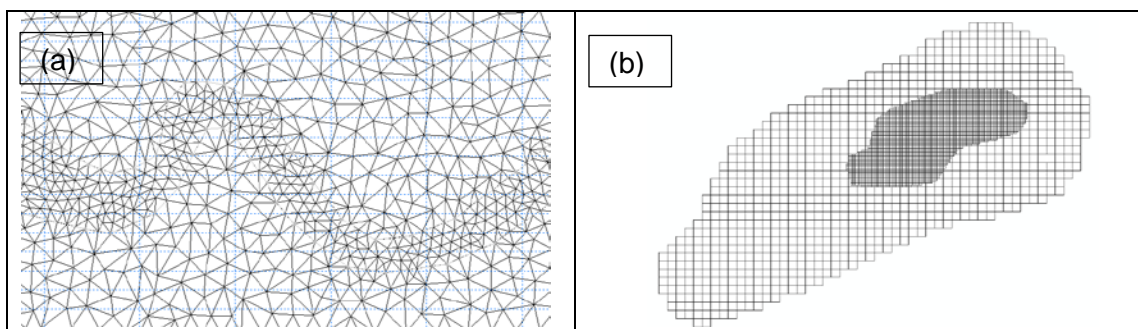


Figure 7-5: Examples of locally increased resolution; (a) an irregular grid with higher resolution along a watercourse and (b) an example of a regular nested grid, in this case a higher resolution grid covers an urban area.

The available DTM also affects the model resolution, as **the resolution cannot usefully be increased beyond the DTM resolution**. However, if other considerations identify that a higher resolution model is required new data should be collected to increase the DTM resolution.

7.3.2 DTM

The basis of the DTM should be stated in any modelling reports, as well as the date it was collected. An assessment of accuracy should also be provided.

7.3.2.1 Building representation

There are several options for representing buildings within 2D models and a review is given in Syme (2008). Common representations include:

Voids Buildings are left as void polygons in the mesh where no values are calculated. This is a conservative approach as storage within the buildings is not accounted for but it may overestimate the obstruction to flow caused by a building. As the model does not calculate within buildings, the depth outputs required for damage calculations are not available as a model output. Instead, depths within buildings have to be interpolated from the water level adjacent to the building and the threshold level which can be problematic if there are differences in water level around the building. Due to the difficulties in interpolation to get values at building centres, **this method is not recommended where depth damage calculations are required**.

Full Height Buildings Buildings are represented as blocks at their actual height. This has similar limitations to voids and **the method is not recommended where depth damage calculations are required**.

High Roughness Buildings are represented by increasing the roughness over the building footprint. This allows buildings to store water and gives depths within buildings. There is limited guidance available on the appropriate roughness value to use however; values

should be significantly higher than the surrounding roughness class. **This approach was used for SEPA's national fluvial hazard maps.**

Stubby Buildings Buildings are represented by raising the DTM within the building footprint to the threshold level. Typically thresholds are assumed to be 0.3 m above the bare earth DTM. The roughness may also be increased over the building footprint. **The stubby buildings approach without an increase in roughness was used for SEPA's regional pluvial hazard maps.**

Porous Walls Buildings are represented as partially porous walls, with the porosity and height of the walls specified by the modeller.

In most cases OS Mastermap data is used to identify building footprints however, other datasets such as detailed ground-based survey may also be used. The method used to represent buildings in the DTM should be stated in the modelling report together with the data used to identify building footprints.

Consideration should be given to future use of the model when choosing the building representation as both the void and full height building methods do not allow depth-damage calculations to be carried out. In particular depth-damage calculations are required to inform Flood Risk Management Strategies so models using these building representations will not be used to inform future Strategies.

7.3.2.2 Hydraulic Structures and Linear Features

Linear features such as raised flood defences or road and rail embankments or drainage channels may or may not be picked up automatically in a DTM depending on both the model and the input DTM resolution. To ensure that features are represented in the model at the correct height most modelling software contains options either to set the height of grid cells along a line or to add a 1D weir type structure into the model.

Bridges, culverts, underpasses and similar features are likely to appear as false blockages, or complete obstructions to flow in the DTM. This can result in over estimation of flooding by the model upstream of the structure but underestimation downstream as not enough flow is passed forward. Some representation of these structures in the DTM is required. Depending on the software, different options are available; a review of structure representation in TUFLOW is given in Syme (2001).

Lowering DTM through the structure This allows flow to pass but does not represent a constriction to flow due to the soffit of the structure. Depending on the scale of the structure and grid resolution some changes in velocity due to constriction/expansion at the *entrance* and exit may be captured, but constriction due to the *soffit* is not included. This method can be implemented quickly with limited structure information and is appropriate for strategic scale modelling.

Use of a 1D structure Most 2D modelling packages contain the option to include 1D representations of structures. This has advantages as most 1D software has in-built representations available for a wide range of structure types. Constriction due to the soffit and constriction/expansion losses can be accounted for through the choice of loss coefficients as in a 1D model although they may need to be reduced if some of the changes in the flow patterns are captured in the 2D model. Due to the 1D-2D link momentum is not conserved through the structure and this reduces the accuracy with which flow patterns around the structure are modelled.

Use of 2D structures Some 2D packages have the ability to model structures in 2D by partially constricting flow along cell sides and at the soffit. Some changes in velocity due to constriction/expansion at the *entrance and exit* are by captured by the change in 2D flow paths but there is usually also an option to add a “form loss” which accounts for changes which are not modelled either due to the 2D grid resolution or because they involve 3d flow. There is limited guidance available on determining loss coefficients in 2D models and a check against other methods is required.

It may also be necessary to modify the DTM to ensure there are flow paths between buildings or other closely spaced structures and to ensure that forested or heavily vegetated areas have not been picked up as obstructions in the DTM.

The approach taken to represent any hydraulic structures or linear features in the DTM should be described in the modelling report together with the data used.

7.3.2.3 Roughness

In 2D models roughness can vary across the model grid. Typically the model domain is split into different land use classes using information from land cover layers such as OS Mastermap and a roughness value assigned to each class. The roughness for some land use types may depend on resolution for example; if features such as buildings and walls are not resolved in the DTM a higher roughness may be set for general urban areas to account for this. The roughness values assigned to different land uses should be described in the modelling report together with the data used to determine the land use.

7.3.3 Numerical precision

Rounding errors can lead to mass balance problems if the numerical precision is not sufficient. This is most likely to be an issue for pluvial modelling where very small depths of water are added to each model grid cell.

7.3.4 Common Problems with 2D Models

Several common issues may arise with 2D models, which should be checked at review stage.

False Blockages Blockages in the DTM which cause an obstruction to flow where in reality there is a flow path.

Leaking Embankments Embankments or walls which are not picked up properly in the DTM and allow flow through where, in reality, there is no flow path.

Glass walling Where 2D flows reach the edge of a model domain and no boundary condition has been defined to allow the water to flow out, the model can insert a vertical wall. This leads to ponding and increased water levels at the edge of the model domain.

Numerical stability 2D models can be prone to numerical instability, particularly if the timestep is too long or the domain is very steep. This can show up as oscillations in velocity and water level. The model log file should be examined for any reports or numerical instability, and the results animated and examined for nonphysical flow patterns.

Mass Balance Errors The model may gain or lose mass, particularly if there is frequent wetting and drying, or if the inflow at each grid cell is small. The mass balance files should be checked to ensure the mass balance is within acceptable limits, usually within $\pm 1\%$ cumulative error.

7.4 1D-2D models

Key Points for Responsible Authorities

- 1D-2D models can give a depth averaged velocity on the flood plain and are able to represent channel flow well, but they can take significant time and resources to set up.
- There are several common issues with 1D-2D models which need to be checked for during a model review. In particular models can be prone to mass balance errors and models should not be accepted without evidence of mass balance checks.

Key Points for Contractors

- The mass balance should be reported in the modelling report.

Coupled 1D-2D models use a 1D model component to represent river channels and/or the surface water drainage network and a 2D model component to represent the floodplain. Flow is dynamically passed between the 1D and the 2D components. This approach is used where there are complex floodplain flow paths which cannot be represented in 1D and where increasing the grid resolution to resolve the channel in a purely 2D model would be impractical or where there are hydraulic structures which can be best represented in a 1D model. Coupled 1D-2D models are most commonly used for fluvial flood modelling or for detailed surface water drainage network models; however they may also be used within estuaries. Despite the advantages of 1D-2D models of representing both the channel and floodplain, **they are not recommended if a purely 1D or 2D model will deliver the desired objective** as they are complex to set up and prone to numerical instability which can take significant time and resources to solve.

The guidance for 1D models in section 7.2 and 2D models in section 7.3 applies to the 1D and 2D components of coupled models. The other considerations are the features represented in the 1D and 2D components of the model and the type of link.

It is also possible to have a 1-way link using the output from a 1D model as the inflow into a 2D model. This approach is only suitable where flow is away from the system represented in 1D and is not as prone to numerical instability.

7.4.1 Common Problems with 1D- 2D Models

In addition to the problems which can occur with separate 1D and 2D models there are potential issues which may arise with coupled 1D-2D models which should be checked at review stage.

Elevation of links If the wrong link elevation is set for lateral links between 1D and 2D models this may lead to flow across the link before the bank is overtopped.

Numerical stability can be a problem for 1D-2D models particularly if there is frequent exchange of water across the link. This can show up as oscillations in velocity and water level in both the 1D and 2D components. The model log file should be examined for any reports or numerical instability and the results animated and examined for nonphysical flow patterns.

Mass Balance Errors can be a particular problem for 1D-2D models. The mass balance files for the 1D component, 2D component and combined model should be checked to ensure the mass balance is within acceptable limits, usually within 1% cumulative error. The mass balance should be reported in the modelling report.

7.5 Boundary Types and Locations

All models only cover a particular area of interest. Boundary conditions are required to define what happens at the boundary between this area and the area outside. Defining the location and type of any boundary conditions is an important aspect of model schematisation. The type of boundary condition depends on the source of flooding and the dimension of the modelling.

7.5.1 Fluvial Models (1D and 2D)

An **upstream boundary** condition is required at the upstream end of any modelled river reaches. These conditions are generally specified as a flow hydrograph for unsteady models, or a constant flow for steady models.

A **downstream boundary** condition is required at the downstream end of any river reaches. These conditions are generally specified as stage hydrograph, flow hydrograph, single valued rating curve, normal depth or critical depth boundary. If the flow reaches the domain boundary other than at the defined downstream boundary the model extent should be examined.

Additional inflows can be added to models between upstream and downstream boundaries to account for any increase in flow between the upstream and downstream boundary. **Lateral inflows** trickle flow in gradually along a reach and are typically used to account for the increase in catchment area along a reach while **point inflows** add flow at a specific point and are typically used to represent tributary inflows.

Upstream and downstream boundary conditions should be located a sufficient distance from the area of interest so that any errors in the boundary will not significantly affect predicted water levels at the study area.

- A rule of thumb $L=0.7D/S$ (where D = bank full depth and S = river slope) can be used when considering the location of downstream boundary from the study site.
- If possible, the downstream boundary should be located where relationship between level and flow is well defined e.g. weir
- If the downstream boundary is tidal; the downstream boundary should be located where a tidal curve can be defined.

7.5.2 Pluvial Models (2D)

Typically a depth of rainfall is applied to every grid cell in the modelled area at each time step. The edges of the model domain are usually set so they are sufficiently far away from the area of interest so as not to have an impact on results.

7.5.3 Coastal Models (2D)

For coastal inundation models a level boundary is typically defined along the coast for still water flooding. Flow due to wave overtopping is usually added as a flow hydrograph. The inland boundary should be sufficiently far inland to be outwith the coastal flood extents.

7.6 Initial Conditions

Initial conditions describing the state of the system before the start of the flood event are required for all types of model. The initial conditions consist of flow and level information at

each point in the model (1D cross sections and storage areas and at each 2D grid cell); although typically for 2D models the flow velocity is assumed to be zero at the start of the simulation.

If the initial conditions are incorrect this may lead to instability at the start of the model run or storage areas having the wrong volume of water in them at the start of a simulation. The model initial conditions should be checked during review of the model. Particular care should be taken in situations where there are significant amounts of storage or artificial drainage.

8 Calibration, Validation & Sensitivity Analysis

8.1 Introduction

Model calibration and validation is important for determining the degree of confidence which can be placed on model results. Sensitivity analysis is important for understanding the level of uncertainty in the modelling. These affect the practical use the model can be put to and the confidence in decisions which are based on the modelling. This chapter describes:

- What calibration is and why it is important;
- Expected good practice in model calibration;
- What sensitivity analysis is and why it is important;
- Expected good practice in sensitivity analysis.

8.2 Calibration

Key Points for Responsible Authorities

- Specify the number of calibration events and target criteria for model calibration in the SoR. A minimum of 3 calibration events and one validation event is recommended.
- Additional sensitivity testing and uncertainty analysis should be carried out if limited calibration data is available. In some cases installation of additional gauging to enable a higher level calibration may be appropriate.
- Review model calibration reports critically to ensure common issues with model calibration are avoided.

Key Points for Contractors

- The calibration process should be fully documented in the modelling report. Changes to parameters and the rationale for revising must be clearly documented.
- Models must not be forced to fit the data by varying parameters outside physical ranges or in ways which are not supported by the available data.
- Consider the possibility of data errors and changes to the study area since the calibration event.
- Carry out additional sensitivity testing if it possible that several parameter combinations may give the same fit to the observed data.

Calibration is the process of adjusting model parameters, such as the surface roughness, within physically defensible ranges until the resulting predictions give the best possible fit to a selected observed event. A model is said to be **validated** if it is able to provide accurate predictions against other observed events (i.e. non-calibration events) within acceptable limits. Model calibration and validation provides an understanding of the appropriateness of the model considering observed flow/stage data. The main objective of model calibration and validation is to provide a demonstration of the quality of model predictions. If calibration is not carried out, confidence in the model application will be significantly reduced.

Model calibration appropriate to the level of study should be carried out where sufficient data is available. The quantity, quality and type of observation has a primary influence on model reliability and confidence in outputs and, as discussed in section 3.4, the data available for calibration should be considered in setting the study extent. Where stage and flow calibration data is not available a reality check on the predicted outlines and levels for an event should be carried out using other historic flooding information such as photographs and anecdotal descriptions of flooding. It is important that the reliability of the data is checked prior to use.

The level of calibration which would be expected for different levels of study is given in Table 8-1.

Level of Study	Gauged	Ungauged
Strategic	Sensitivity testing. Check of design events against historic record at sufficient locations to understand limitations in the method.	
Catchment	Calibration against gauged data	<ul style="list-style-type: none"> • Reality check against historic data. • Sensitivity testing
Local		<ul style="list-style-type: none"> • Reality check against historic data. • Sensitivity testing. • New data collection.

Table 8-1: Suggested level of calibration for gauged and ungauged catchments for different levels of study. Target calibration levels for gauged study areas discussed for different sources of flooding in section 8.2.1, 8.2.2 and 8.2.3 .

The main information required is recorded flows and/or water levels and flood extent from observed events; however a range of different types of data may be used in calibration and reality checks as listed below;

- Observed extents from survey ;
- Aerial photography (particularly if taken at the flood peak of the event);
- Historic flood levels;
- Trash lines;
- Anecdotal reports of which properties/streets flooded, anecdotal reports of depths of flooding experienced (this may be in the form of descriptive terminology e.g. “waist deep” etc.);
- Photographic evidence for example of levels at structures during events;
- Information on structure operations and blockages during the event.

The number of calibration events should be specified in the Statement of Requirements (SoR). It is recommended that a minimum of 3 calibration events and one validation event are used for local and catchment scale studies. However, model confidence can still be improved by calibration/validation for fewer events if sufficient calibration data is not available for more events. After calibration, performance of the model (and adjusted parameters) should be validated through simulation of at least one separate observed event. Possible calibration events should be identified in the SoR, but it may be necessary to use other events if there are issues with the data record or the identified events are not considered representative (e.g. flooding mechanisms such as ice jams or culvert blockages or multiple sources of flooding).

In some areas calibration data may only be available for a short period of time, with no significant events. Calibration and validation of models under these circumstances can still

be useful (e.g. to check the performance of a wave transformation model or flows predicted by a rainfall runoff model). In some cases installation of additional gauging to enable this level of calibration may be appropriate, and the costs of installation and maintenance should be considered against the project aims and required accuracy.

Target calibration acceptance criteria should be defined in the SoR or early in the project. Typical requirements are set out in the template SoR which can be made available on request, appendix A.

The calibration process should be fully documented in a report and should include calibration event dates and measurements and locations of historic floods. Changes to parameters and the rationale for revising must be clearly documented.

8.2.1 Fluvial

River models should be calibrated for flow and levels at gauging stations. It is strongly recommended that, where possible, the study extent covers at least one and preferably two or more gauges to assist in calibration.

The hydraulic parameters which are usually varied during model calibration are the surface roughness (e.g. Manning's n) and structure coefficients. **Model boundaries**, including parameters in hydrological models, may also be varied, for instance the parameters in the rainfall run off model. Where possible a combined approach to hydraulic-hydrological model calibration should be undertaken.

The calibration events should cover both in-bank and out-of-bank scenarios to ensure that both the channel and the floodplain are modelled correctly. Although inclusion of larger events is important, not all the events need not have caused extensive flooding as it is also valid to show the model correctly predicts water not reaching particular locations. Utilising recent events may minimise the impact of recent changes in hydraulic structures or catchment characteristics.

Specific data requirements for each calibration event are:

- 15 minute flow and level time series for any gauges within the study reach, including tributaries. Particular care should be taken in extrapolating rating curves.
- 15 minute rain gauge data for any gauges within or surrounding the catchment.
- Tide gauge data if the downstream boundary of the model is tidal.

If the ReFHv2 rainfall run off model is used, the following are also required:

- MORECS/MOSES evapotranspiration and soil moisture data for 2 years prior to the event.
- Daily rainfall for any gauges within or surrounding the catchment.

Case Study – Hydraulic model calibration for Selkirk

Selkirk has a history of flooding, with notable recent events in 1977, 2003, 2004, 2005, and 2009. Following these events Scottish Borders Council categorised Selkirk as a high priority for investment in flood protection measures and between 2002 and 2011 a phased programme of modelling and investigation was undertaken in order to inform the flood protection measures.

In order to have confidence in the hydraulic model predictions of flood levels, the model was calibrated using a combination of gauged data and historic flooding information. Four events were identified where there was suitable recorded data, observed flood levels and/or anecdotal evidence to be used as calibration events; October 1977, January 2005, October 2005 and November 2009 (Halcrow, 2011).

Flow records from the 2 gauges within the study reach were used to derive model inflows, and the hydraulic model was calibrated by adjusting individual model parameters in order to obtain a good correlation between predicted and observed water levels. The final phase of the study reported a reasonable fit to observed data for all four events, with discrepancies of less than 0.2 m recorded for the majority of locations across all calibration events. In instances where larger discrepancies were noted, further investigation was undertaken in the form of sensitivity testing. This helped to refine the conceptual model of the catchment by identifying factors which could increase flood levels which had not previously been considered. One such case was at the Riverside footbridge in the November 2009 event, where sensitivity testing identified that a 40% blockage of a bridge was required in order to reproduce observed water levels, and whilst this was initially considered high, this was supported by a review of the observed data for this event.

The calibration was revisited at different phases of the work following updates and expansion of the model. This ensured that confidence in the model outputs at each stage was understood, and provided confidence in the use of the model for the design of the Selkirk Flood Protection Scheme and alleviation.

The calibration criteria should consider;

- peak water level;
- overall hydrograph shape; and
- timing of the peak level.

Target accuracy in the calibration should be set using tolerances of both peak water level (e.g. +/- \pm X mm) or less and in the timing of peak level (e.g. within X hours or less).

For *catchment scale studies* it is recommended that tolerances for **peak water level at measured locations are in the order of +/-300 mm or less** and that, for *local scale or detailed studies*, it is recommended that tolerances for **peak water level are in the order of +/-150 mm or less** depending on the application. This can be considered to correspond to medium and high confidence in the outputs respectively.

Target accuracy in the **timing of the peak level** will depend on the hydrograph duration; for most purposes a target accuracy of 30 minutes would be appropriate however a larger tolerance may be acceptable for catchments with a long time to peak and a 15 minute tolerance may be required for very quickly responding catchments.

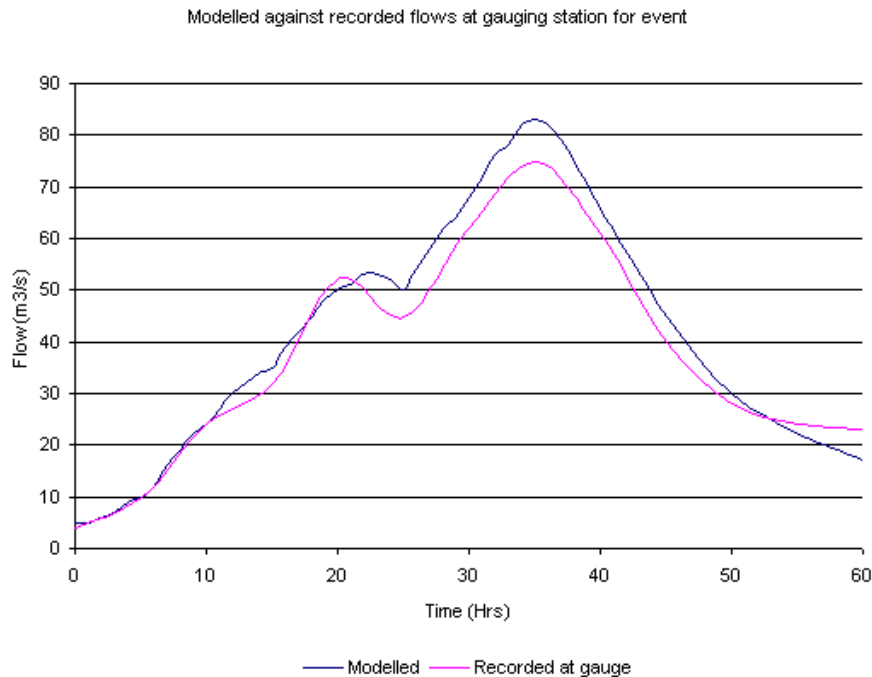


Figure 9-1: Example of a calibration plot comparing modelled and observed flow

Calibration plots can be produced comparing modelled flows with those recorded at the gauging station for an event. Tables can also be used to present a comparison of observed and modelled peak flow, time to peak and stage at particular locations.

8.2.2 Coastal

Hydrodynamic models used to bring extreme still water estimates inland should be calibrated for level at tide gauges. Where tide gauges are not available performance should be checked against tide tables over a spring neap cycle, while installation of additional temporary gauging may be considered. The hydraulic parameters which are usually varied during model calibration are the **bed roughness** and **eddy viscosity**. Changes may also be made to **model boundaries** and **bathymetry**.

Wave transformation models should be calibrated for significant wave height at wave buoys. Where these are not available, installation of temporary gauging should be considered. Calibration should be over a sufficient period to cover all wave direction sectors. The hydraulic parameter usually varied during model calibration is the bed roughness, although boundary conditions may also be adjusted.

It is unlikely that sufficient data will be available for calibration of wave overtopping and coastal inundation models.

It is recommended that tolerances for coastal hydrodynamic models are that:

- **Levels are within ± 0.1 m** at the mouth of firths, estuaries and sea lochs and **± 0.3 m at the head.**
- Directions are **within ± 22.5 degrees**
- **Timings** of high water are within **± 15 minutes**

The Environment Agency document Best Practice in Coastal Flood Forecasting (HR Wallingford, 2004) classifies wave and surge models as having high, medium and low confidence if predictions of height are within about $\pm 20\%$, $\pm 30\%$ and $\pm 40\%$ respectively. For

shoreline models of overtopping rate and probability of breaching, the same document classifies models as having high medium and low confidence if most predictions are expected to be within factors of about 5, 15 and 50, respectively, due to the much lower expectation of accuracy in these models. This corresponds to expected accuracy for the area flooded within about $\pm 30\%$, $\pm 45\%$ and $\pm 70\%$, respectively if overtopping or breaching has occurred.

8.2.3 Pluvial

A detailed pluvial model with explicit representation of the surface water drainage network should be calibrated according to the UDG guidance (WaPUG, 2009), which is used in the collaborative Scottish Water and Local Authority Integrated Catchment Studies (ICS). Data requirements for calibration are also given in this guidance.

There is unlikely to be sufficient data available to calibrate strategic and catchment scale models. In this case a reality check against observed data should be carried out.

8.3 Common Issues with Calibration

It should be noted that **no model will ever give a perfect fit to data**. The differences between the calibrated model and recorded data should be acknowledged in the technical report and any areas or events where the fit is poor should be explained. **Models should not be forced to fit the data** either by making unphysical changes to parameter values or by making changes to model parameters at a spatial scale which cannot be supported by the data. At best this will lead to an inappropriate level of confidence in the model and, at worst will hide model and data error leading to the incorrect conclusions being drawn from the study. This in turn could lead to poor investments and decision making. A list of common issues is highlighted below.

Point to Note:

Despite best efforts, **no model will ever give a perfect fit to data**. From model calibration it should be clear as to the quality of the model and the confidence upon which decisions can be undertaken based on its output.

Model calibration parameters should only be adjusted within published and accepted ranges For instance accepted Manning's roughness coefficients for cultivated areas are between 0.020 and 0.050 depending on the crop condition (Chow, 1959); so changing the roughness coefficient to 0.1 for areas covered by cropland would not be appropriate.

Data errors should be considered a possibility during model calibration For instance an incorrect gauge datum would lead to a mismatch between model and data and although it might be possible to adjust model parameters to improve the fit to data this would lead to an error in the model.

Changes to parameter values should be appropriate given the available data For instance if roughness classifications have been based on land use maps it would not be appropriate to vary roughness between individual fields with the same land use class unless other information such as a site visit or aerial photography provided evidence for different roughness. It would however be appropriate to vary roughness for the entire land use class within published and accepted ranges. Similarly changing bridge coefficients based on a single wrack mark upstream of a bridge may be inappropriate, as several other parameters may affect water levels upstream of the bridge.

Missing flood mechanisms should be considered during calibration For instance a fluvial model may not reproduce observed flood extents if surface water or groundwater

flooding contribute to recorded flooding. In this case it would be incorrect to adjust parameters of the fluvial model to reproduce the observed flooding.

Catchment changes since the recorded flood event should be considered For instance if flood defences have been constructed at a location the model would not be expected to reproduce flood extents prior to the defences being constructed. It may be necessary to construct a model of the historical condition of the catchment to assist in calibration however, where changes have been extensive, the resulting calibration may be of limited use for the present day case. It should also be noted that not all catchment changes will be documented.

Calibration runs should always be driven using observed data A comparison of a 0.5% AEP design event against an observed 0.5% AEP event would be a useful reality check but would not constitute calibration as the design event may differ from the observed event in several ways (e.g. hydrograph shape, combination of waves and tides, etc.).

The possibility of several parameter combinations giving the same fit to the observed data should be considered Typically with flood models there are many fewer measurements available for calibration than there are model variables. For example, in a 1D fluvial model variables include roughness at each cross section and coefficients at each hydraulic structure, while in a 2D pluvial model, variables could include roughness and evaporation loss at each grid cell. Conversely flow measurements may only be available for a single point within the catchment. Where there are more variables than measurements, the problem is said to be “underdetermined” and there may be more than one combination of parameter values which gives the same fit to the calibration data. These combinations of parameter values may exhibit different sensitivity and give different results for extreme conditions outwith the range of the calibration data. Where this is considered a possibility, sensitivity tests should be carried out to assess the impact of choosing different plausible parameter sets. This is particularly important for some hydrological models which may have many more parameters than either 1D or 2D flood models.

Calibration data are not always available and, in such circumstances, greater emphasis should be put on understanding the model sensitivity and model uncertainties.

8.4 Sensitivity Analyses

Key Points for Responsible Authorities

- Model sensitivity tests should be undertaken for all modelling studies in order to give the modeller, reviewer and users an understanding of what parameters affect the model and in what ways. The required sensitivity tests should be specified in the project SoR.

Key Points for Contractors

- Results from the sensitivity analyses should be presented in the modelling report.

Model sensitivity tests should be undertaken in order to give the modeller, reviewer and users an understanding of what parameters affect the model and in what ways. Sensitivity testing involves varying an element of the modelling and assessing how this alters the model results. This helps develop an understanding of the confidence in the model and its outputs. Sensitivity analysis is particularly important where limited data is available to validate or calibrate the model or where there is large uncertainty in model parameters or input data.

There are two types of sensitivity analysis that should be carried out; sensitivity to parameters which may affect the numerical solution (which is discussed in Chapter 14) and sensitivity to physical parameters, which is discussed below.

Sensitivity to the following are typically tested:

- Boundary conditions e.g. a 20% increase in design flow
- Surface roughness e.g. increasing or decreasing the Manning's n used in the model.
- Location and type of upstream and downstream boundary conditions to ensure there is no impact on results within the area of interest.
- Blockage of critical structures such as culverts and other hydraulic structures which may be prone to blockage during flood events. Models can be run with full and/or partial blockage to better understand the impact of these processes.

Additional sensitivity testing of the following may be required, depending on the specifics of the model:

- Model resolution e.g. increasing or decreasing the cell size e.g. 20 m -> 5 m.
- Key structure coefficients e.g. at bridges and weirs.
- Banktop/floodplain spill coefficients
- Initial conditions/initial water levels in storage areas such as ponds and flood storage reservoirs
- For pluvial modelling, testing the sensitivity of the model to the storm duration used may be appropriate.
- Wind boundary conditions, particularly for coastal surge models.
- For wave overtopping models beach/defence profile and overtopping model parameters.

The required sensitivity tests should be specified in the project SoR. Where information is missing or uncertain, additional sensitivity testing may be valuable such as for example influence of floodplain embankments.

The following sensitivity tests were carried out on SEPA's strategic level national fluvial hazard mapping models. More detailed studies may consider a wider range of tests in addition to these.

- Sensitivity to a 20% increase in flow for the 1 in 10 and 1 in 200 year defended and 1 in 1000 year undefended scenarios.
- Sensitivity to a 40% increase in roughness for the 1 in 10 and 1 in 200 year defended scenarios.
- Sensitivity to blockages for the 1 in 10 year defended and 1 in 1000 year undefended scenarios

Results from the sensitivity analyses should be presented in the modelling report. Sensitivity analyses results can be presented in several ways. For 1D models the analyses are usually presented by displaying the different sensitivity model run results on a long section plot. Alternatively plots showing difference in water level against chainage for each of the sensitivity runs or tables showing the predicted level at key locations or model nodes of interest for each of the runs can be produced.

8.5 Confidence

Key Points for Responsible Authorities

- Uncertainty is inherent in all models. Understanding the level of uncertainty in a modelling study helps inform decisions based on the study outputs. Understanding the sources of uncertainty can reduce uncertainty in future studies by targeting the largest sources of uncertainty.
- There are a range of existing methods for analysing uncertainty which vary in complexity and effort required. Use a risk-based approach to uncertainty analysis where the level of risk informs the level of uncertainty analysis required.
- Consideration of the type and level of uncertainty analysis required should be made at scoping stage and the level and form of uncertainty analysis required for the project should be specified in the SoR.
- Further information on uncertainty is available in SEPA's Uncertainty Framework which can be made available to Responsible Authorities.

Key Points for Contractors

- Uncertainty should be considered in all flood studies. The modelling report should contain a description of the uncertainty analysis undertaken together with identification of potential sources of uncertainty and an indication of the level of uncertainty. Decisions or judgments made about the uncertainty, including any assumptions, should be documented.
- Use the FRMRC Framework for addressing uncertainty in Fluvial Flood Risk Mapping to determine the appropriate level of assessment for catchment or local scale studies.
- Ensure that the quoted level of precision in any outputs is appropriate given uncertainty in the modelling, and include error bounds on study outputs where appropriate.

Uncertainty is inherent in all models. Uncertainty arises at each level or stage in the process of modelling flood risk and from a range of sources. Figure 8-1 shows examples of potential sources of uncertainty in flood risk models.

The level of **confidence** in the output will reflect the uncertainties within each of the stages of assessment, such as within the input data, parameters, the model and the way the outputs may be transformed (Walker, et al., 2003).

Guidance from the Scottish Government (Scottish Government, 2011) states that "Uncertainty should be clearly presented in flood risk assessments showing what approaches have been used to quantify them and how decisions have been influenced by uncertainties. Any assumptions made should be clearly set out".

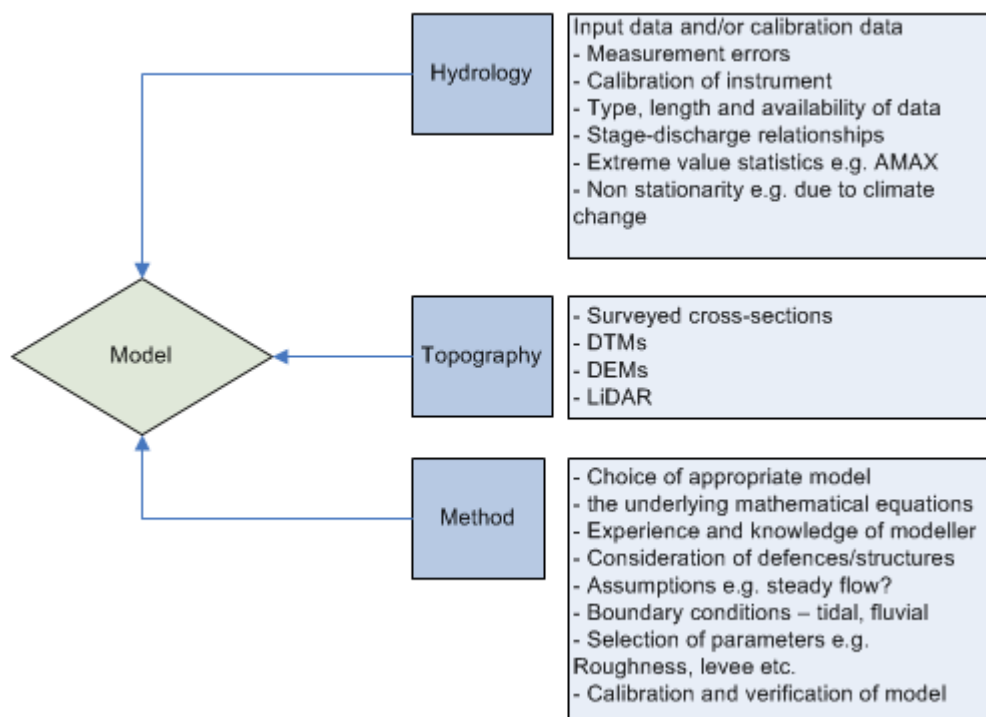


Figure 8-1: Examples of potential sources of uncertainty in models¹³

The level of uncertainty analysis should be proportional to the costs and potential benefits. Detailed uncertainty analysis, with associated resource and time implications, may be justified where the level of confidence in the model predictions would affect the outcome of a decision or where the product would be used in evaluation of significant investment, such as construction of a major flood defence scheme (Beven, 2011).

Consideration of confidence should reflect the purpose of the model and the decisions which it is intended to inform. It should also consider the level of detail and modelling methods applied at each level of modelling. In this way, **a risk-based approach** should be followed (i.e. the level of risk informs the level of modelling which then informs the level of uncertainty analysis required).

Identification of the relative importance of different sources of uncertainty, related to the magnitude of the impact on the final output, may be useful since the largest future reductions in uncertainty could be gained through targeting the largest sources of uncertainty (e.g. through collecting cross section data to improve a DTM, or additional gauging to improve the investigation of inflow boundaries).

There are a range of existing methods for analysing uncertainty including both qualitative and quantitative methods. These range from simpler forms of analysis (e.g. sensitivity analysis and approaches which qualitatively score uncertainty), to complex approaches (e.g. formal, expert elicitation where the opinion of several authorities on the subject is used to inform confidence intervals, Bayesian methods, regressions and approaches involving defining distributions for propagating the effects of different sources of uncertainty to see how these influence model output). The ability to conduct detailed evaluation of uncertainty may be affected by the availability of data required.

¹³ Sources of uncertainty identified in: (Apel, Thielen, Merz, & Blöschl, 2004); (Apel, Aronica, Kreibich, & Thielen, 2009) (Maier & Ascough, 2006), (Bales & Wagner, 2009)

Generally, detailed or complex quantitative approaches are expected to be most applicable at the detailed modelling scale where there is potential for significant investment in measures, meaning that a detailed indication of the potential uncertainty is of particular benefit. **Quantitative** approaches can provide a fuller insight into how uncertainty in inputs propagates through models (to the outputs) and, in some cases, detailed information about uncertainty in different sources can be produced in the form of probabilities of outcomes, confidence intervals and/or probability distributions. Quantitative uncertainty analysis may be used to inform calculation of freeboard levels for flood prevention schemes.

Qualitative approaches focus on identification and grouping of the sources of uncertainty. They then characterise the uncertainty usually using judgements about the level of uncertainty. Qualitative estimates and/or sensitivity analysis may be the selected way of assessing uncertainty where the approach is constrained by available data (e.g. where no historical data are available in order to constrain estimates of uncertainty).

At the catchment to local modelling scales, the decision flow diagrams contained within the [FRMRC Framework for addressing uncertainty in Fluvial Flood Risk Mapping](#) (Beven, 2011) may assist in determining which methods of uncertainty analysis are appropriate. It is recommended that at the outset of the project there should be consideration of the form of uncertainty analysis required for the project and this should be specified in the SoR.

For all studies a description of the uncertainty analysis undertaken should be provided, together with identification of potential sources of uncertainty and an indication of the level of uncertainty. Decisions or judgments made about the uncertainty, including any assumptions, should be documented.

9 Scenarios

Key Points for Responsible Authorities

- To maintain consistency with national maps and appraisal methods, SEPA recommends a particular set of model scenarios to be provided to enable an update to national flood hazard maps.
- Running additional scenarios may add to the cost of a flood study however, this is likely to be cheaper than running additional scenarios at a later date.

9.1 Introduction

The range and number of scenarios run through a model will depend on the use of a flood study. For example, a flood risk assessment according to SEPA's Technical Guidance for Stakeholders only requires the 0.5% annual exceedance probability (1 in 200 year) event while a minimum of 5 flood events spanning a range from high to low probability are required for detailed damage calculations (Penning-Rowell, et al., 2013). Natural flood management techniques are expected to be most effective for frequent flood events so an NFM study may require consideration of more frequent flood events than a design for a hard flood defence scheme.

Running additional scenarios is likely to increase the cost of a flood study but future use of the model and results should be considered when specifying the required scenarios as the costs of contractors rerunning the model at a later date to produce additional scenarios is likely to be greater due to;

- additional project management costs;
- the risk that models may not run, or produce different results in newer versions of modelling software meaning significant work is required to run the additional scenarios;
- additional time required for a different modeller to familiarise themselves with the model if the original modeller is no longer available, or creating the additional scenarios is awarded to a different contractor.

Extending the range of scenarios to cover more frequent events may improve confidence in the modelling, as there is more likely to be data available for validation including anecdotal evidence on the frequency of flooding.

The science on how climate change may affect flooding is still developing and recommended allowances for climate change may go up or down in future. Estimates of present day extreme flows and levels may also change as new data is collected or analysis methods are improved. A wider range of scenarios can provide a measure of future proofing for a study as new flow estimates may correspond to a scenario which has already been run.

SEPA's national hazard maps use a consistent set range of scenarios across each source of flooding which provide a suitable spread for the damage calculations used to inform the Flood Risk Management Strategies. To maintain consistency, SEPA requires the same scenarios to be provided for any update to the national hazard maps. This chapter sets out the minimum scenarios required for an update to SEPA's hazard maps. Additional scenarios may be required in some instances, depending on the study area and the purpose of the study.

9.2 Fluvial

The scenarios used for SEPA's hazard maps are given in Table 9-1. To maintain consistency the core scenarios are required for any study used to update SEPA's fluvial hazard maps. The methodology used to develop SEPA's national fluvial hazard maps only considers out of bank flow so SEPA does not currently publish flood maps for a 50% or 20% AEP event. However, including these scenarios is strongly recommended as for many UK rivers the bank full capacity is the 50% AEP event so this can provide a useful sense check on model results, particularly in the absence of historical flood information. Sensitivity tests are discussed in section 8.4.

		Core Scenarios			Sensitivity Tests		
Annual Exceedance Probability (%)	Return Period	Defended	Undefended	Climate Change	+40% Manning's n	Blockage sensitivity	+20% Flow
50	2	✓					
20	5	✓					
10	10	✓			✓	✓	✓
3.33	30	✓	✓	✓			
2	50	✓					
1	100	✓	✓				
0.5	200	✓	✓	✓	✓		✓
0.1	1000		✓			✓	✓

Table 9-1: Scenarios used in SEPA's national fluvial hazard mapping.

9.3 Coastal

The scenarios used for SEPA's hazard maps are given in Table 9-2. To maintain consistency these scenarios are required for any study used to update SEPA's coastal hazard maps.

SEPA's coastal flood maps do not include the effect of waves. For wave overtopping studies, a joint probability analysis of waves and extreme still water level should be undertaken as there will be multiple combinations of wave and extreme still water level which could constitute for example a 0.5% AEP event. This may mean that a range of combinations of extreme water level and waves need to be run for each flood probability.

Annual Exceedance Probability (%)	Return Period	Undefended	Climate Change
10	10	✓	
4	25	✓	
2	50	✓	
1	100	✓	
0.5	200	✓	✓
0.1	1000	✓	
0.01	10000	✓	

Table 9-2: Scenarios used in SEPA's national coastal hazard mapping.

9.4 Pluvial

The scenarios used for SEPA's pluvial maps are given in Table 9-3. To maintain consistency these scenarios are required for any study used to update SEPA's pluvial hazard maps.

Annual Exceedance Probability (%)	Return Period	Undefended	Climate Change
10	10	✓	
3.33	30	✓	
2	50	✓	
1	100	✓	
0.5	200	✓	✓
10	10	✓	
3.33	30	✓	
2	50	✓	
1	100	✓	
0.5	200	✓	✓

Table 9-3: Scenarios used in SEPA's pluvial hazard maps.

9.5 Integrated Catchment Studies

The scenarios used for Integrated Catchment Studies should be agreed with Scottish Water.

10 Climate Change

10.1 Introduction

Key Points for Responsible Authorities

- An investigation of the impact of climate change on flood risk should be included in all modelling studies.
- Detailed information on climate change, including appropriate allowances for different purposes, will be produced by SEPA's flood risk and climate change group and this chapter updated as appropriate.

The Climate Change (Scotland) Act, 2009 places duties on public bodies regarding climate change, including acting in the best way calculated to deliver the Scottish Government's adaptation programmes, and to act in the way they consider the most sustainable. Consideration of climate change is also a key part of the FRM Act. An investigation of the impact of climate change on flood risk should therefore be a component of any modelling study.

Information now available on potential climate change and its impacts on flows in our rivers and the sea level at our coasts provides a clearer consideration of the probable range of change across Scotland's regions than ever before. The provision of regional climate impacts in a probabilistic manner represents a significant change from the long-term approach of considering the impact of climate change as a single figure uplift applied flatly across the country.

The new information provides greater flexibility to consider climate impacts in a risk-based framework although it could, initially, appear confusing. The change of approach warrants further, specific guidance which will be forthcoming. **This chapter of this guidance, however, deals specifically with the consideration of climate change for strategic modelling issues in support of FRM actions** and summarises the latest information on climate change impacts on flows.

This chapter;

- Summarises available climate change information for changes in peak river flow, short duration rainfall, and sea level rise
- Discusses the approach used for these variables in SEPA's national hazard maps and whether this is still considered appropriate.

Detailed information on climate change, including appropriate allowances for different purposes will be produced by SEPA's flood risk and climate change group, and this chapter will be updated as appropriate following the discussions of the group. The chapter will also be updated as appropriate to take account of new studies and scientific recommendations.

10.2 UKCP09 Projections

The leading source of climate information for the UK is the UKCP09 climate projections. The projections are probabilistic, quantifying uncertainty in climate change projections arising from the representation of climate processes and the effects of natural internal variability in the climate system. A user interface allows users to easily access information relevant to a geographical area or for a particular climate variable. The projections and associated

scientific reports are available from the UKCP09 website <http://ukclimateprojections.metoffice.gov.uk>. Projections are available for high, medium and low emissions scenarios for different time horizons until 2100.

Although the UKCP09 projections were published in 2009, the guidance document “Flood and Coastal Defence Appraisal Guidance FCDPAG3 Economic Appraisal Supplementary Note to Operating Authorities - Climate Change Impacts” (DEFRA, 2006) has continued to be used in many cases in Scotland due to the difficulties of directly relating changes in river flow and sub-daily duration rainfall to the UKCP09 results. Recent SEPA and UKWIR projects provide updated guidance on these areas, making use of the DEFRA (2006) study no longer appropriate to inform strategic decision making. There have also been recent improvements in understanding how climate change may affect mean sea level since the publication of UKCP09.

The Met Office is currently developing a new set of UK climate projections, UKCP18, which will update UKCP09. The projections are expected to provide improved information on how climate change may affect short duration rainfall and sea level rise. Publication is due in March 2018, and this guidance will be updated to reflect this and any other improvements in scientific understanding.

10.3 Fluvial

Key Points for Responsible Authorities

- New information on how climate change may affect river flows is available. This information is probabilistic, and varies between river basin regions.
- SEPA’s fluvial hazard maps used the 2080 high emissions scenario 67th percentile (i.e. uplifts in peak flow that are “unlikely to be exceeded”

SEPA commissioned CEH to assess the vulnerability of Scottish river catchments to climate change (Kay, Crooks, Davies, & Reynard, 2011). The study comprised a sensitivity analysis to determine how catchments would respond to changes in temperature and the amount and seasonality of rainfall. Projections for rainfall and temperature from the UKCP09 projections were combined with the sensitivity analysis to produce a set of probabilistic estimates for change in river flow for river basin regions across Scotland. These cover high, medium and low emissions scenarios for the 2020s, 2050s and 2080s time horizons. The UKCP09 river basins used are shown in Figure 10-1, together with the corresponding hydrometric areas. Results for the medium emissions scenario for the 2050s are shown in Table 10-1, and results for the low, medium and high emissions scenarios for 2080s are shown in Table 10-2. **It should be noted that uplifts for the medium emissions scenario 50th percentile in 2080s in the west of Scotland are considerably higher than the 20% uplift recommended by the DEFRA (2006) guidance.** A full copy of the report is available from SEPA’s website https://www.sepa.org.uk/media/219493/ceh_report_final_sepa.pdf together with a non-technical summary <https://www.sepa.org.uk/media/219494/ceh-cc-report-wp1-overview-final.pdf>.

SEPA’s **fluvial hazard maps used the 2080 high emissions scenario 67th percentile**; this is a *relatively conservative* approach which is considered appropriate for strategic level mapping. The choice of scenario and probability should be appropriate to the purpose of the study for instance, a modelling study to inform the design of a flood defence around a site of critical national infrastructure may wish to use a more conservative climate change allowance. The scenario or scenarios used should be justified in the modelling report and,

ideally a sensitivity analysis to different allowances should be carried out. If a different climate change allowance is used to that in SEPA’s national hazard maps, the model may need to be rerun with a 2080 high emissions scenario 67th percentile uplift in order to gain a consistent picture of the potential impact of climate change across Scotland. This consistency is required for incorporation into SEPA’s National Flood Hazard Maps and the Flood Risk Management Strategies.

For studies at the coast, climate change projections for sea level rise should be considered as in section 10.5.1.

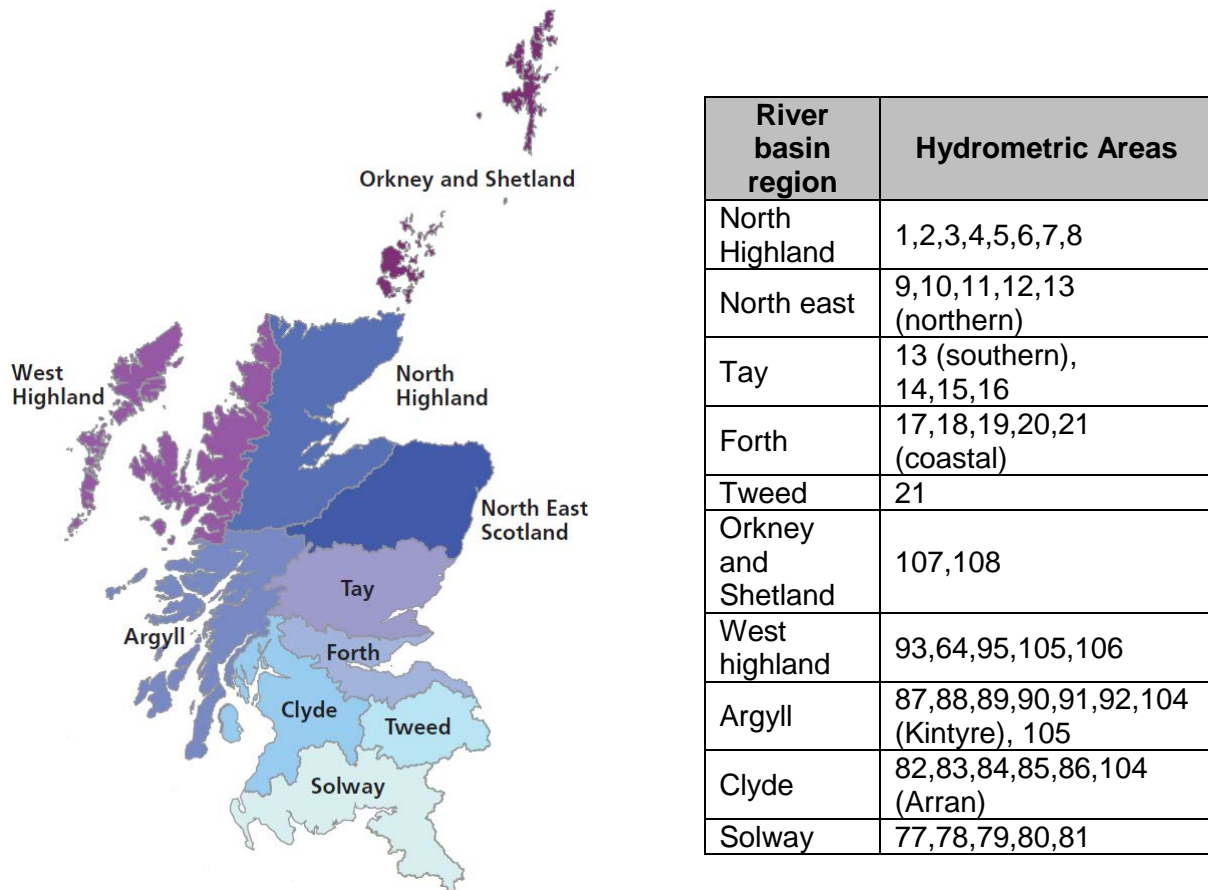


Figure 10-1: UKCP09 river basin regions covering Scotland, for which probabilistic estimates are available. The hydrometric areas falling within each river basin region are given in the table.

Scenario	Probability (%)	Exceedance Likelihood	% change in flood peak (thresholded based on exceedance likelihood)									
			Orkney/ Shetland	N Highland	W Highland	NE Scotland	Argyll	Tay	Clyde	Forth	Solway	Tweed
MEDIUM	10	very likely to be exceeded	13	7	11	2	11	6	7	6	7	4
	33	likely to be exceeded	19	13	19	9	20	11	14	12	13	10
	50	is as likely as not to be exceeded	25	16	25	12	26	14	18	16	17	13
	67	unlikely to be exceeded	29	20	31	15	31	18	23	20	21	17
	90	very unlikely to be exceeded	34	29	42	21	42	27	32	29	30	24

Table 10-1: Percentage uplifts for the medium emissions scenario 2050s, results from Kay, Crooks, Davies, & Reynard (2011).

Scenario	Probability (%)	Exceedence Likelihood	% change in flood peak (thresholded based on exceedence likelihood)									
			Orkney/ Shetland	N Highland	W Highland	NE Scotland	Argyll	Tay	Clyde	Forth	Solway	Tweed
LOW	10	very likely to be exceeded	15	7	12	2	12	4	8	5	6	5
	33	likely to be exceeded	20	14	23	10	23	12	16	13	13	11
	50	is as likely as not to be exceeded	27	18	30	13	30	16	20	17	18	14
	67	unlikely to be exceeded	30	24	36	16	36	20	26	22	23	19
	90	very unlikely to be exceeded	38	33	50	24	50	31	35	32	35	28
MEDIUM	10	very likely to be exceeded	16	10	15	3	15	7	11	7	8	6
	33	likely to be exceeded	27	18	29	11	29	15	20	16	16	13
	50	is as likely as not to be exceeded	30	23	36	14	37	20	27	21	22	17
	67	unlikely to be exceeded	34	29	44	18	45	25	32	27	28	22
	90	very unlikely to be exceeded	45	40	60	28	60	37	45	40	45	32
HIGH	10	very likely to be exceeded	18	12	20	4	20	11	15	11	13	9
	33	likely to be exceeded	29	23	36	12	36	20	27	22	25	18
	50	is as likely as not to be exceeded	33	29	45	17	45	26	34	28	32	23
	67	unlikely to be exceeded	41	37	56	24	56	35	44	40	44	33
	90	very unlikely to be exceeded	53	50	>60	33	>60	50	60	54	60	45

Table 10-2: Percentage uplifts of the high, medium and low emissions scenarios for the 2080s, results from Kay, Crooks, Davies, & Reynard, (2011). Values shown in bold are those used in SEPA's national fluvial hazard maps.

10.4 Pluvial

Key Points for Responsible Authorities

- New information on how climate change may short duration rainfall events is available.
- SEPA's pluvial hazard maps used a 20% uplift for extreme rainfall for the 2080s. The new information suggests a larger uplift may be appropriate for future, strategic studies.

The models used to develop the UKCP09 climate projections did not have sufficient resolution to analyse the type of rainfall events typically responsible for surface water flooding. SEPA's pluvial hazard maps therefore used a 20% uplift based on DEFRA guidance (DEFRA, 2006), which represented the best understanding at that time.

A recent study by UKWIR, Rainfall Intensity for Sewer Design, provides new recommendations for percentage uplifts in sub-daily duration rainfall depths for climate change scenarios (Bennett, Blenkinsop, Dale, Fowler, & Gill, 2015). This study used two approaches to estimate predicted changes in rainfall depths;

- A comparison of the present day rainfall with that at a "climate analogue", another location which has a current climate similar to the projected climate. This was undertaken for selected locations only, and results for Glasgow and Newcastle are advised for use in the west and east of Scotland respectively;
- Analysis of a high resolution climate model simulation which is of sufficient resolution to resolve the type of rainfall responsible for pluvial flooding. The model used does not cover Scotland or Northern England, but has similar results to the "climate analogue" approach elsewhere.

The study provides **low, central, and high projections**. The *central* projection is an average of the climate analogue and high resolution model projections, while the low and high projections give the spread in projections from the different approaches (note that the high and low projections do not constitute a full probabilistic assessment and may not capture the full spread of possibly changes). Uplift values from the UKWIR study for use in Scotland are given in Table 10-3.

Location	Water & sewerage company applicability	Duration (hours)	Epoch								
			2030s			2050s			2080s		
			L	C	H	L	C	H	L	C	H
NW (Glasgow)	Scottish Water (west)	1	14	19	25	16	27	37	23	50	88
		3	0	7	10	0	6	11	11	22	29
		6	8	12	18	0	7	20	4	20	36
NE (Newcastle)	Scottish Water (east)	1	20	28	40	24	44	75	45	50	60
		3	12	15	16	18	29	41	35	53	76
		6	5	7	10	8	17	30	33	51	75

Table 10-3: Percentage change in rainfall depth for different locations and different epochs recommended by the UKWIR study, Rainfall Intensity for Sewer Design (Bennett, Blenkinsop, Dale, Fowler, & Gill, 2015). The percentage uplifts are based on a recent climate baseline (e.g. 1981-2010) and for use with the 2015 release of the FEH DDF model and are given for Low (L), Central (C) and High (H) projections.

The central projections for 2080 from the UKWIR study are significantly higher than those recommended in the DEFRA guidance. **Responsible Authorities are recommended to use the uplifts from the UKWIR study for any future surface water studies as these are based on the latest science.** A risk-based approach should be adopted to make use of the high and low estimates. It should be noted that the high and low estimates of change are not absolute, with other sources of uncertainty being present and should be considered.

Changes in mean sea level or river flows may have an impact on the duration and frequency of tide locking of surface water drainage systems. If the conceptual model identifies tide locking as important, it may be necessary to consider climate change projections for sea level rise and river flows, section 10.5.1 and section 10.5.1.

10.5 Coastal

Key Points for Responsible Authorities

- Climate change can affect coastal flood risk through changes in mean sea level or changes in storminess which affects storm surges and waves.
- Recent projections of global sea level rise are greater than those used for the UKCP09 climate projections.
- SEPA used the 2080 high emissions scenario 95th percentile, relative sea level rise for the national coastal hazard maps.
- There are large uncertainties in the projected change in the UK wave climate due to climate change. It is not possible to recommend climate projections for waves however, sensitivity analysis should be undertaken where appropriate.
- The projected impact of climate change on surge is small compared to projected changes in mean sea level and can usually be ignored.

Climate change may impact coastal flooding through changes in mean sea level or through changes in storminess, which affect surge and waves.

10.5.1 Extreme Still Water Level Rise

Climate change can affect extreme still water levels through changes in mean sea level or changes in storminess which may affect the frequency and magnitude of surges.

UKCP09 provides projections of absolute and relative sea level rise. The relative sea level rise predictions are of most use in flood risk management and account for movement in the land surface. Results are available for the 5th, 50th and 95th percentile, high, medium and low emissions scenarios on a 12 km grid around the coast. Projected sea level rises are provided for every year up to 2100 from a base year of 1990.

UKCP09 projections of trends in storm surge are less detailed than for sea level rise. Long term linear trends in mm/yr are provided for the period 1951-2099 for the medium emissions scenario 5th, 50th and 95th percentile only. In most locations the projected change in surge in the UKCP09 results is small compared to the projected changes in mean sea level, and may not be distinguishable from natural variability so that consideration of changes in mean sea level only is sufficient.

Since the UKCP09 climate projections were published, improvements in scientific understanding, particularly in the likely contribution of land ice melt to sea level rise, have led

to higher projections of global sea level rise (IPCC, 2013). The UKCP09 scenarios may therefore underestimate the potential range in sea level rise. A risk-based approach should be adopted in using the UKCP09 sea level rise projections, but the medium emission scenario 50th percentile *should not* be considered a central estimate. Acknowledging the changes in scientific understanding since publication of the UKCP09 sea level projections, **SEPA used the 2080 high emissions scenario 95th percentile relative sea level rise for national coastal hazard maps**. UKCP09 also provides a H++ projection of combined sea level rise and surge which is beyond the likely range but within physical plausibility. The H++ scenario may be appropriate as a sensitivity test, particularly for critical infrastructure in coastal locations.

The CFB boundaries suggested for use in section 6.5.1 have a reference year of 2008, so the change between 1990 and 2008 in the UKCP09 results should not be included if the CFB boundaries are used as a model input.

The UKCP09 sea level rise grids do not cover the upstream extent of some estuaries and sea lochs. If hydrodynamic modelling of the loch or estuary is not undertaken to establish extreme sea levels inland, the adjacent downstream UKCP09 sea level rise grid predictions should be 'borrowed' and used directly at the estuary/loch site of interest. If hydrodynamic modelling is undertaken, the sea level rise estimates should be applied to the offshore boundary of the hydrodynamic model.

10.5.2 Waves

There are large uncertainties in the projected change in the UK wave climate due to climate change; the UKCP09 projections have changes in the annual maxima of between -1.5 m and +1 m (Lowe, et al., 2009). The Marine Climate Change Impacts Partnership report "Impacts of climate change on storms and waves". Woolf & Wolf (2013) reviews current understanding and identifies knowledge gaps, including:

- How changes in the mid latitude storm tracks due to climate change.
- How results from global climate models can be best used to investigate local changes in wave climate.
- How changes in offshore waves have an impact at the coast.

Due to the uncertainty it is not possible to recommend climate projections for waves, however appropriate sensitivity analysis should be undertaken.

11 Defences

Further guidance on modelling defended and undefended scenarios is currently being developed.

12 Natural Flood Management

12.1 Introduction

Natural Flood Management (NFM) is an important component of the FRM Act, which requires it to be considered in the development of flood protection measures. SEPA's Natural Flood Management Handbook (Scottish Environment Protection Agency, 2016) provides a practical guide to the delivery of NFM measures. This chapter is intended to compliment chapters 5 and 6 of the NFM handbook and the rest of this guidance document by providing further information on how NFM may be included as part of a modelling study. The relationship between the modelling process in this guidance and the NFM implementation process outlined in the NFM handbook is shown in Figure 12-1. The following discussion assumes that opportunity areas for NFM have already been identified (step 3 in the NFM implementation process).

Despite recent research there are still gaps in scientific understanding of how the potential effects of NFM measures may be assessed, particularly for measures in the wider catchment. Dealing with these knowledge gaps may require innovative approaches to be adopted for NFM studies other than those considered here, and this chapter will be developed as scientific understanding improves.

12.2 Modelling Approaches for NFM Studies

Key Points for Responsible Authorities

- Any modelling should be proportionate to the study objectives, the likely scale of impact of the NFM measures and the achievable confidence in the approach and outcomes.

Modelling may be required at 3 stages of the NFM implementation process, short listing of measures (part of the NFM scoping stage), options appraisal/detailed assessment and detailed design. At all stages the investment in any modelling should be proportionate to the study objectives, the likely scale of impact of the NFM 3 measures and the achievable confidence in outputs.

12.2.1 Short Listing of Measures

Where resources permit, modelling can be undertaken at this stage to determine how much change in flood flows or levels NFM measures would have to deliver in order to achieve a given reduction in flood risk. A possible approach to this is scenario testing with catchment scale hydraulic models to assess the changes in inflow hydrographs which would be necessary to deliver a given reduction in flood risk. Further information on this is given in the NFM handbook. Hydraulic models used for this approach should be unsteady and should be calibrated for flows, levels and travel times where data permits. If models are not calibrated, an indication of impact is still possible but there will be a reduced level of confidence in the results. Either 1D or 1D-2D hydraulic models could be used for this type of assessment, although the longer runtimes of 1D-2D models may prevent sufficient numbers of scenarios being tested. A combination of hydraulic and routing models may also be used.

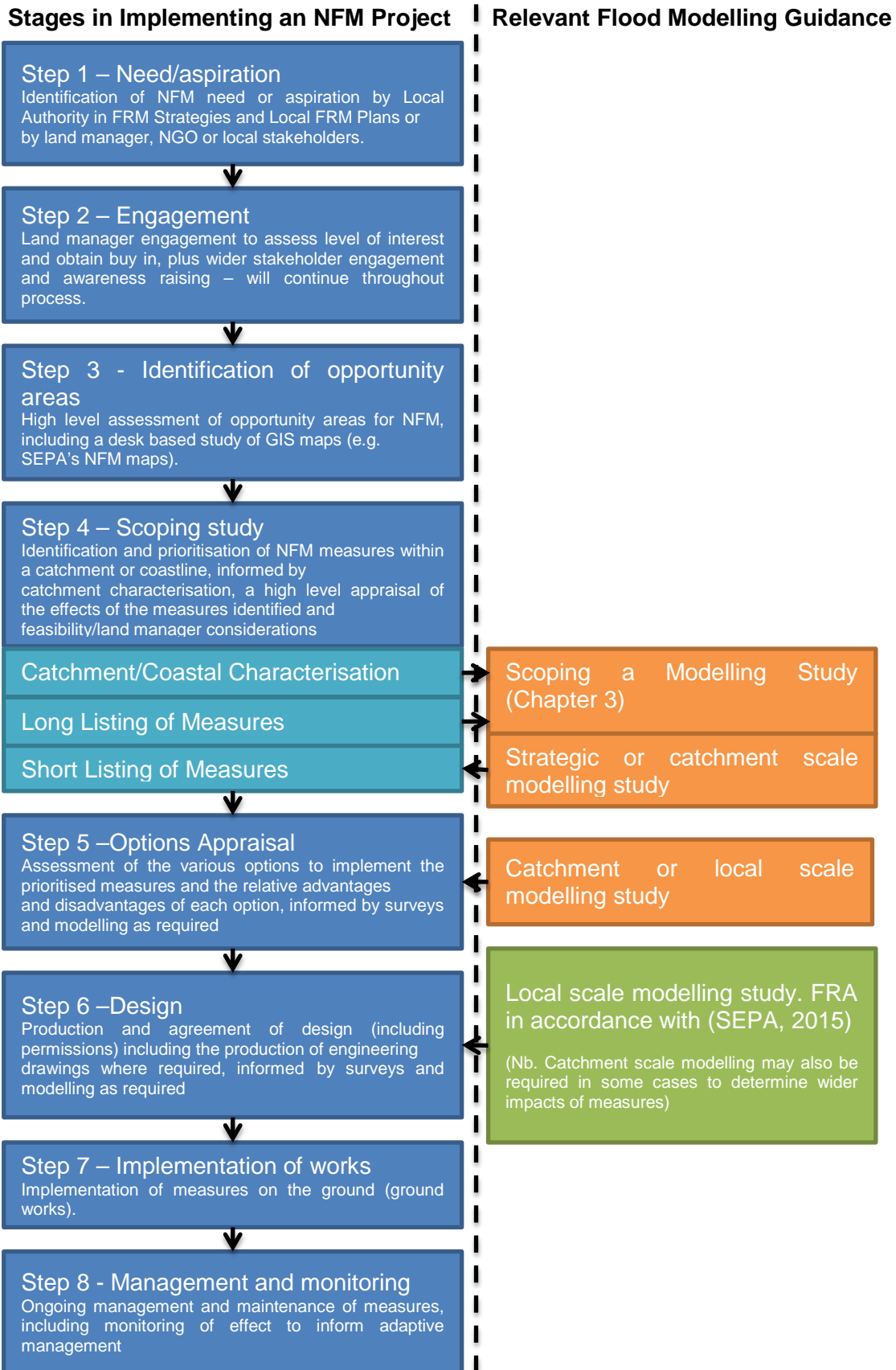


Figure 12-1: Relationship between the modelling process as set out in this guidance document and the NFM implementation process set out in the NFM handbook.

Expert judgement can be used to compare the required changes in inflow hydrographs with that likely from long listed NFM measures. This could also be informed by sensitivity testing using hydrological models to determine a plausible range of changes to peak flows and hydrograph shape resulting from the implementation of NFM measures. Hydrological models may also be used at this stage to give an indication of the areas in the catchment where NFM measures may be most effective.

In some cases the same scenario testing process can also be used to inform short listing of hard engineering measures.

12.2.2 Options Appraisal

Modelling should generally be undertaken to inform options appraisal. The NFM handbook provides guidance on the type of modelling tool which may be appropriate for assessing different types of NFM measure.

For measures which are in or adjacent to a river channel, hydraulic modelling can be used to provide a quantitative estimate of the effects of the NFM measure on water levels, hydrograph timing, flood extents and damages relative to the baseline scenario.

For measures in the wider catchment, hydrological modelling can be used to provide a qualitative indication of the effect of the NFM measure on peak flood flows and hydrograph timing. **Current limitations in scientific understanding and assessment tools mean that a quantitative assessment of NFM measures in the wider catchment is not possible.**

12.2.3 Detailed Design

At this stage a flood risk assessment complying with SEPA's Technical Flood Risk Guidance for Stakeholders (SEPA, 2015) should be produced. Further detailed modelling may also be required to inform the design. Modelling and flood mapping showing the effect of the measure may be used to inform visualisations with and without the measure in place.

12.3 Consideration of NFM within Flood Studies

Key Points for Responsible Authorities

- Consider NFM at the scoping stage for any modelling study.
- Undertake the catchment/coastal characterisation and long listing of potential measures described in the NFM handbook prior to commissioning any modelling, and use this to inform the scope.

NFM should be considered at the scoping stage of flood modelling studies, as the location and type of possible NFM measures may affect the modelling approach taken and the study area. Developing a conceptual model of a catchment is particularly important for NFM studies as measures designed with a poor understanding of catchment flooding mechanisms could inadvertently increase flood risk, for example, through increasing the synchronicity of flood peaks or increasing the risk of structure blockages. The study area should be sufficient to cover all upstream and downstream effects of proposed NFM measures.

It is recommended that the catchment/coastal characterisation and long listing of potential measures described in sections 6.4.1 and sections 6.4.2 of the NFM handbook is undertaken and delivered prior to commissioning any modelling. This characterisation can be used to inform the scope of any modelling and to determine whether investment in any modelling is required. Contractors used for the catchment/coastal characterisation and long listing of measures may also be asked to scope any modelling study.

Case Study – Floodplain reconnection upstream on the River Nith

The Whitesands area of Dumfries experienced significant flooding from the River Nith in 1962, 1977, 1982, 2009 and 2013. There are extensive agricultural flood embankments on the Nith upstream of Dumfries and breaching these to reconnect the flood plain and provide additional storage was identified as a potential NFM option to reduce flood risk within the town.

To assess this option a model of Dumfries was constructed covering the proposed areas of flood plain reconnection and the town of Dumfries. The model showed that although breaching the embankment reduced water levels in the town for 10% and 4% AEP events they were increased for 1% and 0.5% AEP events. The breach in the embankments allowed the water to flow into the storage area, behind the embankment before the peak of the event so as the event peaked, the storage area, which was already full, was unable to store more water, causing the water in the storage area to flow back into the watercourse. Without the breach the area behind the embankments only flooded during the peak of the event reducing water levels downstream during the peak (Mouchel, 2011).

Considering potential NFM options during scoping allowed the study area to be extended to cover the area identified for the NFM measures. The unexpected detrimental effect of this NFM option during larger flood events highlights the importance of developing a conceptual model of the catchment flooding mechanisms in order to identify all possible effects of a measure. In other situations the conceptual model may identify positive impacts of NFM which otherwise may not have been identified during scoping.

12.4 Hydraulic Modelling as part of an NFM Study

Key Points for Responsible Authorities

- NFM is expected to be most effective for more frequent flood events so these should be considered in the flood modelling study.
- Representation of some NFM measures in hydraulic models is uncertain so additional sensitivity testing may be required.

Key Points for Contractors

Where hydraulic modelling is being used to assess NFM measures;

- The hydrological analysis should be extended to cover flow events which occur more than once a year on average.
- The scenarios run should be sufficient to determine if there is a change to the frequency of out of bank flows or the depth or duration of flooding during frequent events.
- The scenarios run need not include less frequent flood events if the measure has no measurable effect for more frequent events (e.g. if a measure has no effect in a 3.3% AEP event and a 2% AEP event it would not be necessary to model a 1% AEP event. However, a 0.5% AEP event will usually be required for a flood risk assessment at detailed design stage in line with (SEPA, 2015)).
- Results for the 50% AEP event and more frequent events should be mapped for the baseline model. These maps should be compared with landowner or land manager knowledge of frequent flooding.
- The schematisation used to represent NFM measures should be described in the modelling report, and justified with reference to available research literature.
- Sensitivity tests should cover;
 - The schematisation of each NFM measure. This should consider the full range of plausible parameter values.
 - Seasonality and maturity of the NFM measure, where relevant.
 - Blockages at key structures downstream of the measure if the NFM measure may increase debris supply.

The guidance in chapters 6, 7 and 8 on model schematisation, boundary conditions and calibration uncertainty analysis also applies to developing models used to assess the impact of NFM measures. In general, to assess the effects of measures **within the channel**, a 1D or 1D-2D model is required while, for measures **adjacent to the channel**, a 1D-2D or 2D model would be required. All models used for NFM studies should be unsteady.

The benefits of many NFM measures are likely to be greatest for more frequent events while some will have no measurable impact during major flood events. Some NFM measures may affect the frequency, depth or duration of flooding of agricultural land which is already subject to frequent flooding; providing an indication of the scale of these effects may also assist in consultations with landowners. Where data is available, calibration of the baseline model without any NFM measures in place should be as described in chapter 8. Landowner and land manager knowledge should be used as an additional source of historic flood event data for model verification.

Schematisation Uncertainty in Hydraulic Models

For many NFM measures there is a limited body of scientific research available to support model schematisation, so modellers have to use expert judgment in choosing how to represent NFM measures. For instance debris dams could potentially be represented in a 1d hydraulic model by;

- a constriction in individual a cross section,
- increased roughness along a river reach,
- as a weirs, spill or gate

For each of these possible schematisations there are a range of parameter values which may be appropriate (percentage constriction, roughness value, weir coefficients etc).

The level of confidence in the modelling of any particular NFM measure will depend on the type of NFM measure being assessed and the body of scientific research available to support model schematisations and the choice of parameter values. The effectiveness of some NFM measures may depend on the season and the maturity of the measure. For instance vegetation will increase roughness more in summer than in winter, and roughness for established riparian woodland will be greater than for newly planted woodland. There may be concerns that, in some cases, NFM may increase debris supply, which may in turn lead to structure blockages.

12.5 Hydrological Modelling as part of an NFM Study

Key Points for Responsible Authorities

- The additional cost associated with the use of more complicated approaches such as development of bespoke tools or the use of distributed hydrological models should be justified by an expected reduction in uncertainty.
- Contractors should be able to demonstrate sufficient experience in the use of any models or techniques proposed and their application to NFM. This is particularly important for distributed hydrological models which historically have been used primarily for academic research and where engineering and modelling consultants may have limited experience.
- Contractors should be able to demonstrate that any bespoke or new tools have been checked and reviewed and are appropriate to the study.

Key Points for Contractors

- Uncertainty in the modelling should be tracked at an appropriate level for the study so it is clear if predicted effects of the measure are greater than uncertainty in the modelling.
- Sensitivity testing should consider the full range of plausible parameter values for the present day and NFM conditions.
- The approach taken for model calibration should take account of the possibility of multiple sets of parameter values giving the same fit to data and models not being well calibrated for change conditions.
- Any bespoke tools should be checked and reviewed. This should include a check of the code and the scientific assumptions used to develop the tool. A record of the checks carried out should be provided in the modelling report.

With all types of hydrological models there is uncertainty regarding the application to NFM and how model parameters should be modified to represent proposed catchment changes. At present, the use of hydrological models is restricted to providing an indication of the sensitivity to any proposed change and where in the catchment changes are likely to have most effect. There is insufficient confidence in the application of hydrological models to assessing NFM measures to provide predictions in the change in flow due to NFM for a particular rainfall event. The NFM handbook gives examples of three approaches which may be useful in NFM studies;

- FEH and ReFH2 rainfall runoff models (see section 6.3.2.2),
- Use of more complex commercially or freely available distributed hydrological models, or
- Development of bespoke tools.

The approach adopted will depend on the purpose of the study, the available data, the size of the project and the potential impacts. It should be noted that more complex approaches may not necessarily lead to a significant reduction in uncertainty.

Uncertainty in Hydrological Models

Uncertainty analysis is particularly important where hydrological models are used in NFM studies. Uncertainties arise because:

- The relevant physical processes and inputs may vary over a much smaller scale than the available data. There may also be gaps or inaccuracies in the required input datasets.
- The model resolution may not be sufficient to capture local processes, for instance ,in a distributed model there may be several small incised channels within a model grid square.
- Not all relevant processes may be included in a chosen model
- A large number of model parameters may be adjusted through calibration though, typically, only a small amount of calibration data is available. Several choices of parameters may give similar fits to data but they may respond differently to change scenarios. Where models are well calibrated to current conditions, it is not certain that they will remain well calibrated for the future condition with the inclusion of the NFM measure.
- It may not be clear how input datasets should be altered to account for change scenarios.
- Even physically based models which include a detailed representation of hydrological processes involve some form of parameterisation, for example vegetation may be divided into types and certain properties such as canopy storage would be associated with a particular vegetation type. These parameterisations may not be relevant to all catchments.

A further discussion of the issues involved is provided in (O'Donnell, O'Connell, & Quinn, 2004).

13 Flood Mapping

13.1 Introduction

Flood maps can be produced from hydraulic model results to spatially represent data such as flood extent, depth, velocity and hazard for sources such as pluvial, fluvial, coastal and sewer flooding. This chapter;

- describes how flood maps are produced from different types of model;
- describes some of the issues which can occur with different types of maps;
- suggests what should be considered in a review of flood maps;
- describes the post processing required for consistency with SEPA's national hazard maps.

13.2 Fluvial

13.2.1 1D flood Mapping

The method of fluvial flood mapping is dependent on the hydraulic modelling package. Many hydraulic modelling packages include functionality to produce flood maps from 1D results (e.g. Infoworks RS, FloodModeller, MIKE 11) while others such as HEC-GeoRas contain add-ons to GIS packages. Flood maps can also be produced solely in GIS.

The basic data requirements to create a flood extent map include maximum water levels, a DTM and cross section locations. If the model includes reservoir or storage units then these will need to be represented separately in order to represent the water level within the reservoir unit as opposed to the cross section at this location and, in this case, a plan of the reservoir locations is also required.

A triangulated irregular network (TIN) is created from the cross sections and reservoir areas and the water level at each cross section is assigned to the relevant nodes (vertices) of the TIN. This water level is then interpolated between the TIN nodes to create a water level surface. The DTM is subtracted from the water level surface to produce a depth grid. Areas with negative depth are dry and removed from the outputs. Flood extents are then produced by contouring the processed depth grid.

The resolution of the DTM used determines the resolution of the flood maps. As such it should be appropriate for the level of detail in the model and should not lead to excessively large file sizes for the depth grids. It is recommended that 1D flood maps have a maximum resolution of 5 m.

Due to the interpolation of level results between model cross sections several issues may occur in 1D flood maps and a careful check against the 1D model results is required. The maps should be examined for the following features and if, necessary, the model should be amended accordingly.

- Isolated patches of flooding which are not well connected to the river;
- Flood extents which appear constrained by cross section extents or reservoir extents;
- Flood extents which are greater than the area covered by the cross section extents or reservoir extents.

1D flood models do not have the functionality to produce hazard ratings or floodplain velocity. Where these are required a 2D model should be used.

13.2.2 2D Flood Mapping

The production of flood maps from 2D models is simpler than from 1D models as water levels, depth, velocity and hazard can be output directly from 2D models. Flood extents are then produced by contouring the processed depth grid.

For 1D-2D models, flood extents and depth and level grids for the 1D component only should be produced as for 1D models and added to the 2D grid. For consistency with SEPA's hazard mapping the **1D component** should be assigned a value of '200', **velocity** for the 1D component should be assigned a value of '200' for the magnitude and '-9999' for the **direction**.

13.3 Coastal Flood Mapping

13.3.1 Horizontal Projection Method

SEPA's national coastal hazard maps used a basic horizontal projection methodology from still water levels, Figure 13-1. The Coastal Flood Boundary (CFB) dataset was used to provide estimates of design sea levels every 2 km around the coast with some points included within firths and estuaries where available. From each CFB sea level point, a cross section was drawn to link to high ground with land above the relevant return period on the DTM. Everything below this line is within the flood extent. From the still water level data attached to the cross sections, a water surface was interpolated between the sections to give a continuous water surface reflecting the values of the CFB data. Flood depth maps were created by subtracting the DTM containing the ground elevation data from the water surface layer. It should be noted that this method can overestimate flood risk in some areas as it assumes an infinite momentum and volume of water. Flood waters will keep moving inland until they hit the required contour on the DTM. In other areas the method may underestimate if wave action is considered important. This method is suitable for national scale flood mapping projects, but it is not expected that Local Authority flood studies will use the same approach.

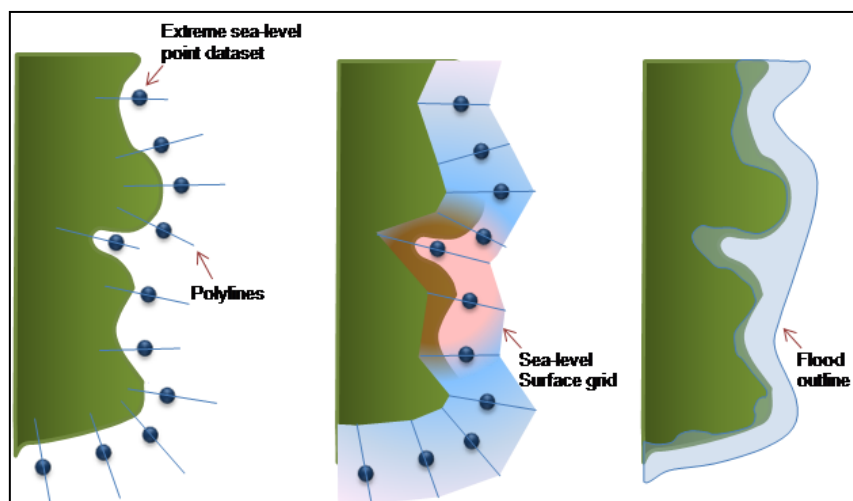


Figure 13-1: Flood map generation from horizontal projection method.

13.3.2 2D Coastal Flood Mapping

As with 2D fluvial flood mapping, water levels, depth, velocity and hazard can be output directly from 2D models and flood extents are produced by contouring the processed depth grid.

13.4 Pluvial Mapping

In general 2D models will be used for pluvial flood mapping and water levels, depth, velocity and hazard can be output directly. Pluvial models involve the application of rainfall to every model grid cell resulting in a shallow depth of water at all grid cells. To produce flood maps which do not show the entire model grid area as flooded it is necessary to threshold the results to remove shallow depths. The velocity, hazard and water level results should also be processed to remove results below the depth threshold. For consistency with SEPA's pluvial hazard mapping a 0.1 m depth threshold should be used.

13.5 Post-Processing

Post processing of flood maps is required to ensure an appropriate representation of flood risk. The requirements of post-processing will vary dependent on the purpose and scale of the flood map; however typically post processing is carried out to:

Remove dry islands below an area threshold as confidence in flood extents at a small spatial scale is likely to be low and these areas would be isolated during a flood event. Numerous small holes also increase the complexity of storing the data in GIS.

Remove puddles below an area threshold as confidence in flood extents at a small spatial scale is likely to be low. However, the reason for the puddles should be understood before any post processing as this can indicate incorrect initial conditions, frequent wetting and drying of the model or general instability. Numerous small puddles also increase the complexity of storing the data in GIS.

Show bridges as wet or dry depending on whether or not there is flow over the bridge deck. This is used to assess flood risk to transport routes. Depending on the DTM, the bridge representation in the model and the method of flood mapping this may require manual post processing.

Depth threshold pluvial model results so that the entire model domain is not included in the flood extent.

SEPA's national hazard maps have been post processed to:

- Remove dry islands and isolated wet areas less than 200 m² which are not connected to the floodplain. Dry islands have been assigned a depth of 0.01 m, a velocity of 0.01 ms⁻¹ and a hazard of 0.1.
- Remove results below a depth threshold of 0.1 m for pluvial flooding

13.6 Quality Checking

Flood maps should be sense checked. Key considerations include (list not exhaustive):

- Are the depths/velocities/water levels reasonable?
- Does the inundation extent reflect the topography?
- Are there any areas with particularly large depths/velocities?
- Is the river included in the floodplain extent?
- Are there any false blockages e.g. areas where flow has been prevented through a structure which would not occur in reality?
- Does the flood extent/depths increase with return period as you would expect?
- Do isolated wet areas connect to the main floodplain through for example a drainage channel?
- Do flood extents extend across structures which would obstruct flow?

14 Quality Assurance and Quality Control

14.1 Introduction

Errors in data, model schematisation and analysis can have a major effect on study results. At worst, if these errors are not identified, decisions can be made based on incorrect modelling, for instance development could be permitted in areas at risk or flood defences could be built to the wrong level. Where errors are identified during a project this can lead to significant rework and result in time delays while, if errors are identified after a project is finished and “accepted” by a Responsible Authority it can be difficult to get contractors to revisit the work.

To ensure good quality output, quality control and quality assurance should be built in to all stages of a modelling project, by both the Responsible Authorities and contractors Figure 14-1. This will require the Responsible Authority to review outputs and provide input at key stages of modelling project.

This chapter recommends quality control and quality assurance activities which may be carried out by contractors and Responsible Authorities at different stages of a modelling project. However, it does not seek to replace Responsible Authorities’ or contractors’ quality assurance and quality control procedures.

14.2 Scoping and Commissioning a Study

Key Points for Responsible Authorities

- Consider quality criteria at scoping stage.
- Ensure the appointed contractor is proposing to use qualified and experienced staff.
- Ensure risks to quality are included in a contractor’s risk register.

The Responsible Authority should consider the required quality criteria for the modelling in terms of calibration tolerances, and this should be stated in the SoR.

The contractor should set out the quality control and quality assurance processes which will apply to the project in their tender. Risks to quality should be included in the risk register.

The Responsible Authority should ensure that the appointed contractor is proposing to use qualified and experienced staff for modelling, hydrology and project management. Identification of less experienced staff as part of a project team is acceptable provided that sufficient time is allocated for more experienced staff to provide technical input. In addition to the core project team a contractor should identify an internal reviewer who is not directly involved in the project.

Where the study involves development or use of novel tools or methodologies to meet Responsible Authority requirements in developing areas of flood risk science such as NFM or Climate Change additional levels of review are likely to be required. The contractor should set out how any novel tools will be or have been reviewed in their tender, including review of the concept, coding and usage of the tool. If there is any concern regarding novel approaches, please contact SEPA.

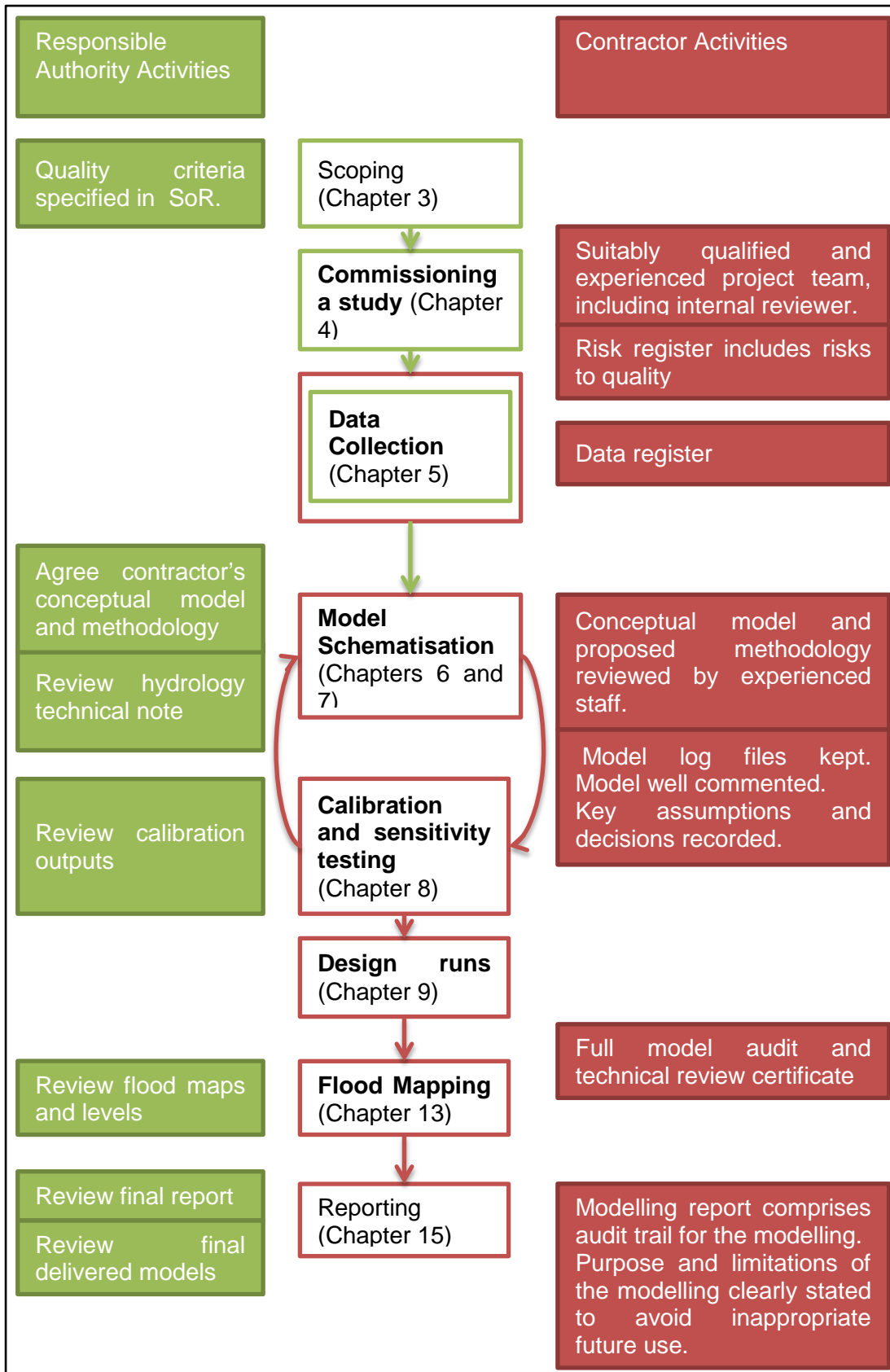


Figure 14-1: Contractor and Responsible Authority QA and QC activities at different stages of a modelling project.

14.2.1 Conceptual Model

Key Points for Contractors

- The conceptual model and proposed methodology should be reviewed and signed off by an experienced modeller and agreed with the Responsible Authority.

The contractor should develop its own conceptual model for the study area and decide on an appropriate methodology also considering the study purpose. The conceptual model and proposed methodology should be reviewed and signed off by an experienced modeller and agreed with the Responsible Authority. A review by suitably experienced staff at this stage should ensure that an appropriate approach is adopted from the start of the study, that potential problems are identified and appropriate mitigation is put in place. This should include identifying key points in the study where an internal technical review of the modelling and analysis by the contractor would be beneficial.

Available data should also be reviewed at this stage to determine if it is suitable to meet the objectives of the study or if there are any issues with data quality and availability. Where the available data is not sufficient to meet the study objectives and quality criteria the contractor should make the Responsible Authority aware of the quality implications.

14.3 Data Collection

A data register should be kept as this can help in understanding any implications to the project output if quality issues are identified with any of the input datasets at a later date. To ensure that any data used for the project is of an appropriate quality the contractor should review all data before use and a record should be kept of any checks carried out and any problems identified.

14.3.1 Model Build

Contractors should ensure that their work procedures for model build follow normal good practice. This includes keeping log files, ensuring file naming structures are logical and including comments in models where appropriate.

14.3.2 Model Audit

Key Points for Contractors

- Carry out an internal review of any models and calculations, using an independent reviewer.

Key Points for Responsible Authorities

- Ask contractors to provide evidence that an internal audit of any models and calculations has been carried out.

Errors in models and calculations can significantly affect study results. The contractor should carry out an audit of the modelling and any calculations. This should be carried out by an experienced modeller who has not been involved with constructing the original model or models. The exact checks carried out will depend on the level of study and the methodology used.

For catchment or local scale studies a detailed audit should be carried out for all calculations and for all models constructed. In some case an external audit by an independent consultant may also be appropriate for some local scale and flood defence design studies.

For strategic scale studies such involving multiple models, such as the nearly 3500 models created for SEPA's national fluvial hazard mapping project, it may not be feasible to carry out a detailed review of all models. In this case it may be appropriate to use automated tools to screen for numerically unstable models and any physically unrealistic or inconsistent results. However, the method used and implementation of the method as well as the results from any screening should be reviewed by an experienced modeller. If automatic checks are used, detailed manual checks should also be carried out on a subset of models to ensure that any systematic errors not identified by the automatic screening are detected.

The Responsible Authority should ask for evidence that this audit has been carried out; this can be in the form of a signed technical review certificate, or a model audit report, with a record of actions taken. An example review certificate from SEPA's regional pluvial hazard mapping is included in appendix C.1. A *pro forma* for a fluvial flood estimate review is given in Appendix C.2.

As a minimum the audit should cover the following areas;

Model schematisation - including roughness, structure representation, boundary conditions and flood plain representation where relevant.

Numerical solution – including mass balance, sensitivity to parameters which affect the numerical solution, model convergence.

Documentation – log file documenting all model version and key assumptions, data register, comments in model etc.

Model Calibration – fit to data, parameters adjusted within physical range.

Results and sensitivity tests - behaviour of model as expected, results consistent between different AEPs.

Due to potential problems with instability of 1D-2D models, Responsible Authorities are advised not to accept models unless the mass balance for all model runs is reported in the model audit and is within acceptable limits.

14.3.3 Responsible Authority Review of Results

Key Points for Responsible Authorities

- Review outputs at key points in a project.
- Ensure you receive all model run and results files.

Review of interim outputs at key points by the Responsible Authority can help identify potential problems. As a minimum it is recommended that Responsible Authorities review the following outputs;

- the contractor's conceptual model and proposed methodology,
- a technical note on the hydrology or tidal/coastal boundary conditions.
- technical note on model calibration,
- flood maps and levels for design runs and sensitivity tests,

- final report and deliverables,
- final delivered models.

In reviewing outputs Responsible Authorities should use their local knowledge to check that results are physically realistic however, they should be aware flood models can show the correct behaviour for smaller events within Responsible Authority experience but may not exhibit the correct sensitivity for larger events. Responsible Authorities should be satisfied in their review of outputs that there is no evidence of the common problems for different types of model described in sections 7.2.3, 7.3.4 and 7.4.1. SEPA may be able to assist with the review of outputs if required.

It is important that complete model run and results files are provided by a contractor as set out in Section 15.4 as it is not possible for a Responsible Authority, SEPA or any external reviewer to review a model only from the modelling report. Any survey data or photographs should also be provided to enable model schematisation to be checked against the survey.

14.4 Reporting

Key Points for Contractors

- The modelling report should clearly state the purpose of the modelling and any limitation.
- There should be sufficient detail in the modelling report and appendices for any experienced modeller to reproduce the analysis.

To avoid inappropriate future use of the study outputs, the modelling report should clearly state the purpose of the modelling. Any limitations of the study, the data and the method used which may affect use of the results should be highlighted, and recommendations for future improvements to the modelling should be made.

The modelling report and appendices should comprise an audit trail for the modelling, providing sufficient detail of the methods and datasets used for any experienced modeller to reproduce the analysis.

15 Deliverables

15.1 Introduction

It is important that the correct deliverables are specified in the statement of requirement (SoR). To enable future reuse of the data this should include all model outputs in a GIS format, full model results, reports and run files. The details of what is required should be explicitly stated in the SoR. Where historic flood events have been used for calibration, results from the calibration models should also be supplied, together with the data used for calibration. For projects involving 2D modelling it is likely to be necessary to supply a hard drive for transfer of the data.

15.2 Reporting Requirements

Model documentation is used by decision makers and other users of models to understand the way in which a model was developed and how a model can be used.

The model documentation should normally consist of four reports:

- Technical report
- Non-technical report or summary
- Model hand over report
- Model audit report

In addition it is recommended that technical notes on hydrology/coastal boundary conditions and model calibration are requested at appropriate points of the project.

15.2.1 Technical Report

The technical report is generally intended for an 'expert' audience. The technical report should address the modelling objectives set out in the SoR. It should provide a record of the hydrological and hydraulic analysis including all key modelling decisions, input data, calibration or sensitivity analysis, a commentary on model confidence and key limitations and recommendations for future development and use of the model.

The report should include appropriate maps of the study area, cross-section locations and plans of the model results. If a separate non-technical summary is not requested, this may be included as a chapter within the main report.

15.2.2 Non-Technical Summary

The non-technical report or summary is generally intended for a 'lay' audience. It will provide an overview of the study, the outcomes and recommendations for the use of the information generated.

15.2.3 Model hand over report

A model hand over report should be produced providing sufficient information for an experienced modeller to rerun the model and interrogate the results.

15.2.4 Audit report

A model audit report or technical review certificate should be supplied to provide confirmation that the model has been assessed and that any issues identified have been addressed. This applies for internal model audits carried out by a contractor and external model audits carried out by either SEPA or a contractor appointed for peer review. See section 14.3.2 for further details.

15.2.5 Format

Model reports should be provided in an appropriate word processing package for use with partner organisation IT systems. A copy of the report and all figures should also be provided in .pdf format for sharing with other organisations. Hard copies of reports may also be requested.

15.3 Results Files

Study outputs and results can be provided in a range of formats. Requesting output in GIS format allows the data to be queried and manipulated after the end of the project.

The specific outputs which are to be received should be stated in the SoR. SEPA recommends that the extent and depth, and hazard, velocity and flow direction (as appropriate) is supplied as a minimum. This should be requested in the relevant proprietary format the Responsible Authority uses and, if being sent to SEPA, ideally within the ESRI shapefile/raster format. It is advised that ESRI geodatabases are not used as compatibility issues with older versions of software may prevent data being shared easily between Responsible Authorities.

15.3.1 Gridded output

The following gridded outputs should be requested as deliverables;

1D models: water level and depth

2D models: water level, depth, velocity (including flow direction) and hazard

These are standard outputs from hydraulic modelling packages commonly used in the UK, and are absolute minimum required for interpreting model results.

To facilitate data sharing between Responsible Authorities, all data should be in a suitable format for import into GIS either ESRI ascii grid format, GeoTIFF or .bil format, and -9999 should be used as no data value.

For direct rainfall (surface water) models where rainfall is applied to every point of the model grid, large areas of the model will be covered by a shallow depth of water. In this case the results should be requested with a 0.1 m depth minimum threshold in addition to the un-thresholded depth results in order to remove large areas of very shallow flooding.

15.3.1.1 Depth and Elevation

Grids of both elevation and depth should be supplied.

Flood depth and elevation grids should not contain no data values at building centroids in order for depth damage calculations to be carried out. This is discussed in section 7.3.2.1.

15.3.1.2 Hazard

For consistency with SEPA's national flood hazard maps, hazard should be calculated using the flood hazard formula in Defra report FD2321/TR1 Flood Risks to People (HR Wallingford; Flood Hazard Research Centre, Middlesex University; Risk & Policy Analysts Ltd., 2006).

$$HR = d(v+1.5)+DF$$

Where: *HR* = (flood) hazard rating;

d = depth of flooding (m);

v = velocity of floodwaters (m/sec); and

DF = debris factor (= 0, 1, 2 depending on probability that debris will lead to a significantly greater hazard)

For consistency with SEPA's flood hazard mapping and modelling the debris factor *DF* should be 0.

15.3.1.3 Velocity

Grids of both speed and direction should be requested. The maximum velocity should be 'maximum velocity', not 'velocity at maximum depth'. Where the models wetting and drying is leading to high velocities for shallow depths of water, a depth threshold for tracking maximum velocity may be applied.

15.3.1.4 Other Gridded Outputs

Several other gridded outputs may be selected for 2D modelling software. The exact range of outputs which can be selected depends on the software. The following may be useful:

- **Flow** for assessing the flow split between out of bank flow paths
- **Froude number** for assessing if flow is sub or supercritical. Some calculation methods are less accurate as flows become supercritical so this may affect model confidence, or help in identifying model issues.
- **Duration of flooding** for emergency planning or detailed damage calculations
- **Time of onset** for emergency planning
- **Bed shear stress** for assessing the potential for erosion.

If additional outputs are required this should be discussed with the contractor prior to starting final model runs as if additional output is not selected at this stage the model may need to be rerun in order to generate the output.

15.3.2 Flood Extents and Area of Benefit

The Area of Benefit should be calculated as the difference between the defended and undefended outlines at the SoP of the defence. An appropriate allowance should be made for freeboard in calculating the SoP.

Flood extents and the Area of Benefit from a flood defence should be requested in ESRI shapefile format, as well as any proprietary format required by the partner organisation's GIS format. ESRI shapefiles can be imported into most other GIS packages and this facilitates sharing of data between Responsible Authorities.

Flood extents and Area of Benefit should not be simplified or smoothed and should match the supplied depth grids.

Flood extents should not show bridge decks as flooded unless there is flow across the bridge deck in the model.

15.3.3 Miscellaneous Outputs

Other outputs which may be requested include time before evacuation routes are cut, or travel times between gauges and receptors. These outputs can be useful for emergency planning.

15.3.4 Animations

Where unsteady modelling has been undertaken, animations of the model output can be requested. These can provide a useful tool in understanding flooding mechanisms and in engaging with the public. Animations may be particularly effective for breach modelling.

15.3.5 Other formats

Contractors may be able to supply data in a number of other formats which may aid interpretation of the results.

Interactive PDFs can provide an improved visual representation of flood risk and understanding into the mechanisms of flooding. They can allow users to click on different scenarios and pre-defined storm durations to allow the user to visualise flood risk. Interactive PDFs can be used for various applications such as flood protection scheme designs, displaying model run information and even combined events i.e. a fluvial and coastal flood events.

3D Visualisations can be used to help convey complex technical information to local communities (e.g. flood prevention scheme designs) and can be used to present different design options and the benefits of each approach or even the complexities involved. However, they can be time consuming and costly depending on the scale and complexity of the visual representation and careful consideration should be made into the level of detail required.

15.3.6 Tables of results and long sections

For 1D models, tables of water elevation and flow at each 1D node should be requested. Long sections and cross sections of modelled water level may also be useful, to allow for the visualisation of the water level across the reach

For 2D models it is possible to select time series output of level, depth and velocity at point locations, and flow through cross section lines. As a minimum, the flow time series should be extracted at all gauges. Locations where point output and flow through cross section lines are required should be discussed with the contractor prior to final model runs. This is because it can be difficult and less accurate to calculate these from the model output files.

15.4 Model Files

Complete sets of raw model results and run files, including check/diagnostic and mass balance files, should be provided for each scenario run including calibration and sensitivity runs. For 1D-2D models the mass balance output should be supplied for both the 1D and 2D components of the model and include the flow across the link.

A description of the files which would be expected to be received for modelling software commonly used in Scotland is given in Appendix E. SEPA can provide assistance in checking that all the expected files have been supplied if required.

A model log file should also be provided stating which run files were used to produce each output.

Comments, including names, of all significant structures within the model should also be provided together with comments on any modification to structure coefficients.

Derivation calculations (e.g. spreadsheets) used for any model inputs (e.g. for boundary conditions) must be supplied. The merged DTM used in construction of the model and for production of flood maps must be supplied. This will allow the model to be re-run and mapped for other scenarios at a later date if required.

15.5 Survey

If a survey is undertaken as part of the contract, the survey should also be included as a deliverable. The survey formats should be as per the EA Technical Specifications.

15.6 Photographs

Any photographs taken in the course of the study (e.g. on site visits) should be supplied along with an appropriate caption / commentary to establish what the photographs depict. These should ideally be georeferenced to the OSGB 1936.

15.7 Other deliverables

If the Responsible Authority wishes to adopt the model and reuse in house, it may be beneficial to specify a model hand over session. Additionally training in the use of the model or software may be included as part of the scope.

Once the deliverables have been approved by the reviewer and approver (i.e. project executive) signoff of the products can be undertaken.

Appendices

A Template Flood Study SoR

Please contact strategic.floodrisk@sepa.org.uk for a copy of the template flood study SoR in an editable format. It is intended to include the SoR here in a later version of the guidance, however SEPA wish to receive feedback on the usefulness and appropriateness of the present version of the SoR prior to making it publically available.

B Example Survey SoR

Please contact strategic.floodrisk@sepa.org.uk for a copy of the template survey SoR in an editable format. Text highlighted in yellow should be amended by the Responsible Authority. This SoR is based on Environment Agency's Standard Technical Specifications version 3.2 (Environment Agency, 2013), and Responsible Authorities are advised to refer to the Environment Agency Specification while developing any SoR using this template. SEPA cannot guarantee that survey according to this SoR will be suitable for all flood studies, and Responsible Authorities should consider their own requirements when developing a survey SoR.

Statement of Requirements

1 Background

Explain the general project background.

2 Introduction

Responsible Authority Name wishes to carry out a topographic survey of a reach of the River XXX, specifically between XXXX and XXXX, along with associated tributaries including the XXXX and XXXX. Cross section spacing and length should be informed by best practice and knowledge. Survey work should be carried out by the use of GPS surveying instruments and methods. All survey work should be carried out in line with best practice and in line with the Royal Institution of Chartered Surveyors (RICS) guidelines for surveying. The information gathered will be used for constructing a computer model of the watercourses and will be used in conjunction with existing LiDAR information to produce a 1D-2D model for the area.

3 Aims and Objectives

The aim of this project is to undertake a topographic survey of a reach of the upper XXXX catchment from XXXX to XXXX including the XXXX and the XXXX. The information gathered will be used for constructing a computer model of the watercourses and will be used in conjunction with existing LiDAR information to produce flood extents for the area.

The study area is outlined in the XXXX Study Location Map – see Appendix A. Costings for the work should be produced.

4 Method of Undertaking Research – Scope of Work

The successful tenderer appointed in due course as the surveyor (the “Surveyor”) shall provide all services required to satisfy the objectives of this study. The services will include, but not necessarily limited to, the main task of undertaking a topographic survey.

5 Land Ownership

Prior to work commencing Responsible Authority Name will obtain the permission of each landowner or tenant to undertake the survey. Responsible Authority Name will also provide in writing, proof that the surveyor is working on their behalf.

6 Quality Assurance

The Surveyor shall apply quality management procedures to ensure that the information and materials provided under this contract adhere to the Specifications and are fit for purpose in terms of quality, completeness, standard of presentation and timely delivery.

The Surveyor shall be responsible for adopting full quality control and assurance procedures at each stage of the work to ensure that mistakes, errors and omissions are identified and corrected prior to the delivery of the results. The Survey shall not be considered delivered until received in a form that complies with the specification.

7 Ecological Considerations

Ecological sensitivities should be considered for the catchment and stated if required – example below.

Consideration will be given to ecological sensitivities in the catchment such as spawning redds and freshwater pearl mussels. Prior to work commencing, Responsible Authority Name will make initial contact with the appropriate associations. The Surveyor shall also be expected to make contact prior to undertaking any survey work and will be required to adopt best working practices that will prevent disturbance.

8 Survey Specification

The following specification should be adhered to, (any deviations not agreed with Responsible Authority Name will possibly involve additional survey work by the surveyor at their own time and cost). Reference should be made to the Environment Agency Survey Specifications (Environment Agency, 2013, National Standard Contract and Specification for Surveying Services Standard Technical Specifications Version 3.2).

8.1 Reference System

- All coordinates shall be related to Grid (OSGB1936)
- All levels shall be Newlyn datum (mAOD)
- The specified measurement tolerance is +/-5cm

8.2 Survey Controls

- Permanent ground marks shall be established on firm ground as required.
- Paint must not be used for marking survey control stations and wooden pegs should not be left protruding from the ground unless they are to be removed on the same day as this creates a hazard. Permission of landowners should be gained before establishing a survey control station.
- Control shall be related to the Ordnance Survey OS Net.
- The planimetric co-ordinates of directly surveyed points shall be correct to $\pm 0.05\text{m}$ RMSE on carriageways and hard surfaces, and $\pm 0.10\text{m}$ RMSE on all other surfaces.

8.3 Definitions and Control of Works

The following definitions shall apply:

- **WATERCOURSE CENTRELINE** is determined from the lowest point in the bed level;
- **A CROSS SECTION** is normal to the watercourse centreline;
- **LEFT and RIGHT** are determined either side of the watercourse centreline when viewed toward the downstream direction of the watercourse;
- **SKEW ANGLES** are estimated clockwise from the direction of stream;
- **CHANNEL WIDTH** is determined between natural river bank edges;
- **HARD BED LEVEL** is that to which a staff, pole or rod with a base area of 0.0005 to 0.0025 square metres can be driven to refusal;
- **SOFT BED LEVEL** is that to which a staff, pole or rod first meets resistance underwater;

SIGNIFICANT CHANGE IN SLOPE is deemed to be noticeable when walking the slope.

8.4 Channel Cross Sections

- Levelled cross sections are to be taken across the channel. Cross sections should be perpendicular to the channel/flow direction and viewed downstream. As a general guide, cross sections should be undertaken at **XXX m** spacing reducing to **XX-XX m** and **X m** and to capture physical changes to the river channel respectively (**Insert location map reference**). All levels shall be accurate to +/- 10 mm. Cross channel chainage shall be accurate to +/- 100 mm and longitudinal chainage between cross sections to be accurate to +/- 1000 mm.
- Where it is not practical to survey a section at the prescribed position or interval the position of the section may be moved. However, the interval between two adjacent sections shall not exceed the prescribed interval.
- Cross section levels shall be taken at straight line normal to the watercourse centreline with all changes in slope recorded. Section survey points should be taken at each significant change in slope and at chainages not exceeding 2 m across the channel
- Cross-sections are to be surveyed viewed downstream. The origin (zero chainage) must be established on the left side of the section.
- Cross sections should extend both sides of the water courses to the true land level, extending 5 m beyond bank top where possible. Where possible, it is essential that all sections are measured into open spaces clear of trees and dense vegetation cover to a maximum distance of 50 m to allow tie in with LIDAR data. In those instances where a bank top is raised above the surrounding ground (flood plain), sections should be measured to 5 m beyond the landward toe of the crest; the crest, defined as the line along the bank top over which water will spill from the river onto the surrounding ground.
- Water level should be recorded at each section on the day of the survey with the date and time recorded each day. Channel bed levels and bank levels either side are to be recorded.
- Bed levels will be measured directly whenever and wherever possible. Where direct measurement is impossible, where, for instance, the water depth is too great or other causes make it impractical, then other methods to be considered include measurement by boat or reading the depth of water against a staff and relating these readings to a measured water level.
- Where silt occurs both the hard bed and the silt top will be measured at the same points. The hard bed will be shown as a pecked line and labelled "H" in the digital data. The silt top will be shown as a solid line.
- Each individual cross-section, including structure sections should be given a unique identifier.
- The sections will be plotted to a vertical scale of 1:100 and horizontal scale of 1:200.

8.5 Flood Plain Sections

- Any flood plain sections required are denoted in **insert cross section location reference**. Flood plain sections will be taken normal to the centre line of the valley

and not necessarily at right angles to the centre line of the channel. Because of this, flood plain sections may appear 'dog-legged' on the key plan. These sections may be defined on the contract mapping.

8.6 Hydraulic Structures

- Cross sections will be taken immediately upstream and downstream of each structure and in the case of bridges ensure that dimensions of bridges openings and flood arches are included. Structures include all those shown on the attached map and drawings as well as any significant bridges, weirs, culverts, mill lades, major pipe crossings and impounding structures identified in the field.
- Where structures extend beyond the top of bank, then the complete upstream elevation will be surveyed with its cross section.

Bridges

- For bridges, the springing level, soffit level, abutments, parapets, deck level and internal arch or flow area dimensions should be recorded and marked on the cross section plan. The Surveyor should survey the bed level where the structure enters the bed. Details of any bridge piers must also be included and the length of the bridge or tunnel is to be measured parallel to the watercourse.
- The downstream elevation will be presented as viewed looking downstream and is required to be surveyed when specifically requested or where it is different from the upstream side. Even when a downstream elevation is not required, the downstream soffit, top of parapet, invert, bed level and bank crests are to be measured and added to the longitudinal section
- Where structures are skewed across the channel, the skew span will be measured together with the appropriate skew angle and marked on the associated topographic drawing. The length of the bridge tunnel will therefore be the channel length through the bridge, not the distance at right angles to the roadway.
- Where a structure extends 10 m beyond the top of bank then the complete elevation will be surveyed with its cross section. Where a bridge spans the flood plain, then all relevant flood arches (and other openings that could take flood water) must be included in the cross section.
- In situations where the bridge is not going to be overtopped and/or reduce conveyance with increasing water depth, a full bridge survey is not required; bridge parapet, soffit and springing levels can be omitted. Bridges identified for survey will be discussed at the inception meeting.

Culverts

- Complete dimensions of the inlet and outlet elevations of culverts are to be taken alongside the channel section as done with the bridge structure. For pipe culverts, internal pipe diameter, invert, soffit and crown of pipe levels should be recorded upstream and downstream. The length of the culvert should also be measured if safe to do so. Details of any trash screen and flaps, including dimensions, number of bars, bar width and bar spacing should be recorded and noted on the cross section plan.

Weirs

- A cross section will be taken along the crest of the weir and structure details will be taken and annotated on the associated topographic drawing. For weirs that do not cross the watercourse in a straight line perpendicular to the watercourse, the actual length of the weir shall be stated clearly on the cross section drawing. A long section of the weir will be produced extending both upstream and downstream to the natural river bed. The weir long section will have the following information:
 - upstream and downstream water level;
 - upstream and downstream bed level;
 - weir crest;
 - upstream and downstream extent of any apron;
 - water and bed levels at the tail of any weir pool

8.7 Longitudinal (top of bank) survey – flood bank level

- A longitudinal survey is required along the top of both banks of all watercourses. Levels will be taken at a minimum of 25 m (or as agreed) or where there are sudden or pronounced changes in ground level e.g. collapsed embankment.
- Where flood defences or embankments are present, this should be taken as the top-of-bank levels and general details on the condition of the flood defences or embankment should be noted i.e. if there is a gap where water could escape.
- Where there is no embankment / wall the ground level should be given:
 - Where the river is fenced, at the fence line;
 - Where a road or path runs along the river, at the centre line;
 - Elsewhere, at 5 m away from the river bank
- Where applicable (e.g. at agricultural embankments) additional longitudinal surveys should be taken; this should include the base of the embankment/wall on both sides (access permitting).
- Photographs of all structures and embankments surveyed will be taken and georeferenced with a time and date.

8.8 Additional Cross Sections

- Additional cross sections should be undertaken at the following SEPA gauging stations:
 - **Insert gauging station and grid reference;**
- At each gauging station there is a minimum requirement for four cross sections across the floodplain; three downstream of the ramp gauge or post and one under the cableway/winch where available. A cross section will be taken at the downstream control of each gauging station. A cross section will also be taken upstream of the cableway/winch.
- Where standard cross section spacing does not cover the above then additional cross sections should be undertaken.

8.9 Data Format and Key Deliverables

- An electronic copy of the survey on CD-ROM in PDF, CSV, 2D and 3D DWG (2013 or earlier) with each surveyed point to have an X, Y and Z value.
- All data to be presented graphically on key plan/section location maps, cross sections, structure sections and long sections should be made available as a CSV xyz file, in DWG format and in a format compatible with Flood Modeller/HEC-RAS software (.txt/.dat and EACSD) – see Appendix B. This cross section data will contain the following:
 - Cross section with unique identifier incorporating chainage from most downstream end of reach;
 - Level (mAOD);
 - Chainage across the sections/structures working from left to right bank (viewed downstream);
 - National Grid northing;
 - National Grid easting;
 - Applicable survey code;
 - Reference to any photographic or anecdotal evidence
- The longitudinal data will contain the following:
 - The deepest bed level at each section, both hard bed (solid) and silt line (pecked).
 - The water level at each section.
 - The bank crest levels derived from crest point levels shown on the cross-sections, the left bank as a pecked line and the right bank as a bold line.
 - The extent and level of any concrete sill or apron together with appropriate label. The section number and chainage of each section and the altitudes of each of the plotted points. The chainage shall be quoted to the nearest metre except when the scale of the survey makes it appropriate to quote the chainage to decimetres.
 - All structure with their critical levels (soffit, invert, deck, crest etc.)
 - Tributary channels should be included where surveyed
 - Where changes in the levels of bank, bed or water level occur between cross-sections, these changes are to be measured and added to the longitudinal section. The longitudinal section should represent an accurate and complete profile of the channel to ensure that low spot and level changes are identified.
- A GIS shapefile clearly showing the survey route, the uniquely identified cross sections and any survey gaps.
- Digital copies of georeferenced photographs of cross section locations, embankments and structures.
- A digital key plan based on suitable Ordnance Survey grid is to be produced showing clearly the extent of survey. In addition, scale, a north point and sheet coordinates are to be indicated.

- A quality statement will be provided detailing confidence in the survey and any associated uncertainties.

9 Data

- The following data will be supplied to the successful tenderer by **Responsible Authority**:
 - Cross section location drawings;
 - Shapefiles of the study area and the cross section locations;
 - Bridge and other structures data including drawings annotating the structures to be included in the survey.

10 Security

- The highest classification of data for this contract will be **OFFICIAL: COMMERCIAL**.
- From the onset of the contract all Consultant staff (or any contractor or sub-contractor appointed by it) who have access to **Responsible Authority** data must as a minimum be fully compliant with the requirements of the Baseline Personal Security Standard (BPSS).
- **Responsible Authority** require confirmation of the office location(s) from where the work will be undertaken both by the Consultant and Sub Contractors for this contract.
- At tender stage details of how project data will be accessed, stored, transmitted and handled within your organisation is required. This should include both electronic and hard copy data and meet the Cabinet Office Security Policy Framework requirements as a minimum.

11 Meetings

An allowance should be made for an inception meeting. Thereafter, contact will be made primarily over email or telephone to discuss progress or any issues that have arisen which may lead to a delay in the delivery date.

12 Delivery Timescales

The tender return should include a programme of work that takes the following milestones and key dates into consideration:

Task No.	Main tasks	Date

13 Budget

The projected cost of the contract is expected to be within the range of £XXXX to £XXXX including VAT.

- Fixed Price

The surveyor shall submit a fixed price. Each price shall be deemed to include, inter alia, the following:-

- All travel and subsistence costs.
 - All media and consumable costs.
 - Field work and data processing.
 - Traffic management and maintenance.
 - Liaison with the landowners / tenants for access.
 - Tender preparation costs.
 - Weather downtime.
 - All post, telephone, fax and e-mail costs.
 - Controls established to OS GPS Network.
 - Where reflector less total station is adopted the surveyor shall include for a detailed visual inspection of the site to ensure all features (e.g. manholes, gullies etc) are included. Any visual inspection and additional survey work shall be deemed to adopt a safe system of work as noted above.
- The tender price should be made up based on the form of data being collected as follows:
 - Channel survey
 - Topographical survey

14 Project Management

The appointed contractor will be responsible for taking and distribution of minutes and agenda for all meetings and telecom's.

Any compensation claim due to change in scope needs to be provided and agreed in writing before commencing work.

Requests for changes to key project staff must be provided in writing for approval.

15 Intellectual Property Rights

All copyright and Intellectual Property Rights (IPR) will be transferred to Responsible Authority Name in accordance with the Terms and Conditions.

16 Sustainability

Responsible Authority Name is committed to working in a sustainable manner. For example, public transport should be used whenever possible for meetings, waste should be kept at a minimum, and a recycling policy should be in use. Paper used as part of the project should be from a variety of sources, including recycled.

17 Tender Submission

Tender submissions should include the following:

- Methodology statement

- Project outputs
- Key staff.
- Costing
- Project programme including timetable taking into consideration the key dates detailed in Section 11.

All tender submissions should cover the above requirements in a maximum of 10 pages.

Schedule 2

Tender Evaluation

Tenders will be evaluated using the following criteria and weightings.

Technical Criteria (overall weighting 80%)

Financial Criteria (overall weighting 20%)

Schedule 3

Price Summary - Template

Tenderers are required to submit a firm price for the service detailed in Schedule 1 excluding VAT. All costs appropriate to the proposal must be included or summarised here. Costs which appear elsewhere in the proposal but which are not summarised here will be presumed to have been waived.

Activity	Person Hours	Price £ (excl. VAT)
Total Price (excl. VAT)		£

Tenderers must also provide a breakdown of the staff involved in this contract.

Personnel		Hours Input	Activity	Hourly Rate
				£
				£
				£
				£
				£
				£

				£
				£
				£
				£

C Quality Control

C.1 Example technical review certificate

TECHNICAL REVIEW CERTIFICATE



Project	SEPA Regional Pluvial Flood Hazard Dataset
Project Number	2012s5757
Analyst	Halina Piorecka
Reviewer	Linda Hemsley
Subject of Review	Model H (Edinburgh, West Lothian, Falkirk/Grangemouth)
Revision	v2 (all 3 catchments)
Project Manager	Caroline Anderton

Before Initial Run - DTM Check

LIDAR on top of NextMap	Yes (HP)
Buildings Applied	Yes (HP)
Buildings Correct Height	Yes (HP)
Cutlines Applied	Yes (HP)

After First Run - Blockage Test

Aspect	Comments																																																																												
DTM derivation log completed (..\DTM Derivation Log Sheets\DTM Derivation Log Sheet - H3.doc)	Yes																																																																												
Use outlines and depth grids to check cutlines	Reviewed by HP																																																																												
Check distribution of depths and velocities	Total number of cells: 202588515 <table border="1"> <thead> <tr> <th>Depth (m)</th> <th>% of cells</th> </tr> </thead> <tbody> <tr> <td>0.00 - 0.10</td> <td>94.77</td> </tr> <tr> <td>0.10 - 0.25</td> <td>3.39</td> </tr> <tr> <td>0.25 - 0.50</td> <td>1.11</td> </tr> <tr> <td>0.50 - 1.00</td> <td>0.51</td> </tr> <tr> <td>1.00 - 2.00</td> <td>0.19</td> </tr> <tr> <td>> 2.00</td> <td>0.03</td> </tr> </tbody> </table>	Depth (m)	% of cells	0.00 - 0.10	94.77	0.10 - 0.25	3.39	0.25 - 0.50	1.11	0.50 - 1.00	0.51	1.00 - 2.00	0.19	> 2.00	0.03																																																														
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Contour areas deeper than 3m and check (scenario 13) ..\ArcGIS\Shapefiles\Lidar 3m Contour Checks\h3_contour_3m.shp	No of contoured areas deeper than 3m: 386 (Edinburgh, Falkirk, West Lothian catchments). 56 no. contoured areas found to be outwith ponds, lakes, quarries, etc. <table border="1"> <thead> <tr> <th>No</th> <th>Contour Numbers (FID)</th> <th>Comment</th> <th>DTM Error Y/N</th> </tr> </thead> <tbody> <tr><td>1</td><td>0</td><td>Area near to water course</td><td>N</td></tr> <tr><td>2</td><td>1</td><td>Area near to water course</td><td>Y</td></tr> <tr><td>3</td><td>4</td><td>garden</td><td>Y</td></tr> <tr><td>4</td><td>5</td><td>garden</td><td>Y</td></tr> <tr><td>5</td><td>19</td><td>Sewage works</td><td>N</td></tr> <tr><td>6</td><td>20</td><td>ditch</td><td>N</td></tr> <tr><td>7</td><td>22</td><td>Grassed area</td><td>N</td></tr> <tr><td>8</td><td>23</td><td>ditch</td><td>N</td></tr> <tr><td>9</td><td>24</td><td>Grassed area</td><td>N</td></tr> <tr><td>10</td><td>29</td><td>Wooded area</td><td>N</td></tr> <tr><td>11</td><td>30</td><td>Wooded area</td><td>N</td></tr> <tr><td>12</td><td>49</td><td>road</td><td>N</td></tr> <tr><td>13</td><td>91</td><td>path</td><td>N</td></tr> <tr><td>14</td><td>99</td><td>Oil storage</td><td>N</td></tr> <tr><td>15</td><td>100</td><td>Area near to road</td><td>N</td></tr> <tr><td>16</td><td>101</td><td>field</td><td>N</td></tr> <tr><td>17</td><td>107</td><td>Area near to water course</td><td>N</td></tr> <tr><td>18</td><td>121</td><td>garden</td><td>N</td></tr> </tbody> </table>	No	Contour Numbers (FID)	Comment	DTM Error Y/N	1	0	Area near to water course	N	2	1	Area near to water course	Y	3	4	garden	Y	4	5	garden	Y	5	19	Sewage works	N	6	20	ditch	N	7	22	Grassed area	N	8	23	ditch	N	9	24	Grassed area	N	10	29	Wooded area	N	11	30	Wooded area	N	12	49	road	N	13	91	path	N	14	99	Oil storage	N	15	100	Area near to road	N	16	101	field	N	17	107	Area near to water course	N	18	121	garden	N
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TECHNICAL REVIEW CERTIFICATE



19	127	culvert	N
20	132	ditch	N
21	138	Low lying area near to railway	N
22	139	Low lying area near to railway	N
23	140	building	Y
24	141	Open area	Y
25	142	Development area	N
26	143	Building	Y
27	148	Building	Y
28	150	Industrial estate	N
29	151	subway	N
30	157	Sewage works	N
31	164	path	N
32	165	path	N
33	166	path	N
34	167	ditch	N
35	168	road	N
36	176	Sewage works	Y
37	178	Sewage works	Y
38	184	road	Y
39	189	subway	N
40	196	Grassed area	N
41	200	ditch	N
42	201	Golf course	N
43	203	Golf course	N
44	204	Golf course	N
45	228	subway	N
46	242	park	N
47	265	railway	N
48	266	railway	N
50	275	Area near to watercourse	N
51	297	Grassed area near to watercourse	N
52	309	Grassed area	N
53	310	ditch	N
54	315	Open area	Y
55	316	Open area	Y
56	352	Car park	Y

DTM Error Log to SEPA

JBA Error Number	Contour ID	Error Issued to SEPA?	Comment From SEPA re-procedure to follow	Action Requested by SEPA	DTM adjusted?
1	1	No	-	-	In watercourse - no action required
2	4	No	-	-	Interpolated
3	5	No	-	-	Interpolated
4	140	No	-	-	Interpolated
5	141	No	-	-	Interpolated
6	143	No	-	-	Ramps off road - no

TECHNICAL REVIEW CERTIFICATE



						action required
7	148	No	-	-	-	Interpolated
8	176	No	-	-	-	Interpolated
9	178	No	-	-	-	Interpolated
10	184	No	-	-	-	
11	315	No	-	-	-	Interpolated as one
12	316	No	-	-	-	Interpolated
13	353	No	-	-	-	Interpolated
14	93	No	-	-	-	Interpolated
15	210	No	-	-	-	Interpolated
16	217	No	-	-	-	Interpolated

After Main Runs

Aspect	Comments
DTM derivation log updated	Yes

Distributions Edinburgh

Depth Grids (m) [no. cells 196381015]						
	0.00 - 0.10	0.10 - 0.25	0.25 - 0.50	0.50 - 1.00	1.00 - 2.00	> 2.00
H_3_depth	97.73	1.41	0.54	0.26	0.06	0.01
H_11_depth	96.00	2.41	0.89	0.49	0.19	0.02
Velocity Grids (m/s) [average no. of cells 192254570]						
	0 - 0.25	0.25 - 0.50	0.50 - 2.00	2.00 - 5.00	5.00 - 10.00	> 10.00
H_3_vel	98.48	1.04	0.47	0.01	0.00	0.00
H_11_vel	96.21	2.63	1.13	0.03	0.00	0.00

Distributions Falkirk

Depth Grids (m) [no. cells 131401015]						
	0.00 - 0.10	0.10 - 0.25	0.25 - 0.50	0.50 - 1.00	1.00 - 2.00	> 2.00
H_3_depth	97.29	1.76	0.60	0.28	0.06	0.00
H_11_depth	95.20	3.03	1.08	0.52	0.17	0.01
Velocity Grids (m/s) [average no. of cells 128178143]						
	0 - 0.25	0.25 - 0.50	0.50 - 2.00	2.00 - 5.00	5.00 - 10.00	> 10.00
H_3_vel	98.58	1.04	0.38	0.00	0.00	0.00
H_11_vel	96.68	2.34	0.96	0.01	0.00	0.00

Distributions West Lothian

Depth Grids (m) [no. cells 203868515]						
	0.00 - 0.10	0.10 - 0.25	0.25 - 0.50	0.50 - 1.00	1.00 - 2.00	> 2.00
H_3_depth	99.01	0.64	0.35	0.00	0.00	0.00
H_11_depth	95.45	2.72	1.06	0.58	0.16	0.01
Velocity Grids (m/s) [average no. of cells 199218684]						
	0 - 0.25	0.25 - 0.50	0.50 - 2.00	2.00 - 5.00	5.00 - 10.00	> 10.00
H_3_vel	97.97	1.40	0.63	0.01	0.00	0.00
H_11_vel	95.31	3.18	1.48	0.03	0.00	0.00

Post Processing Results Check

Data	Checked
dwt grids	Yes (3 and 13)

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dnt grids	Yes (3 and 13)
v grids	Yes (3 and 13)
hr grids	Yes (3 and 13)
hrb grids	Yes (3 and 13)
f01m_exspa shapefiles	Yes (3 and 13)
f03m_exspa shapefiles	Yes (3 and 13)
f01m_wspa shapefiles	Yes (3 and 13)
f03m_wspa shapefiles	Yes (3 and 13)

Preparation of Deliverables

File/Folder	Present and Named Correctly
Folders 1 - 14: dwt grid dnt grid v grid hr grid hrb shapefile f01m_exspa shapefile f03m_exspa shapefile f01m_wspa shapefile f03m_wspa shapefile	Yes (HP)
DTM	Yes (HP)
False Blockages shapefile	Yes (HP)
Technical Review Certificate	Yes
Model Databases	Yes (HP)
Report	Yes
Model Grid	Yes (HP)

PRELIMINARY CERTIFICATE - After Initial Run

(Only required when comments are raised). In respect of the project detailed above, I have carried out a review and consider the technical output sound, subject to the comments listed. Please inform me when you have considered these comments so that I may complete the Final Certificate.

Initial review comments	
	<p>Review undertaken on new initial results - area covers impacted DTM area only.</p> <p>Note: previous initial review undertaken on all study catchment areas.</p> <p>A number of DTM errors from contour check to be up-dated upon approval from SEPA.</p> <p>Visual blockage review check highlights a number of areas where the DTM requires inclusion of additional cutlines to address excessive water depths where culverts and bridges are present.</p> <p>Reference dtm: h3_dtm_v1.</p> <p>It is evident when comparing the DTM and the existing cutline shapefile (H_cutlines) that a significant number of the cutlines have not been accounted for properly in the latest version of the DTM. The result of this is a vast number of high depth areas which, had the cutlines been adopted, would not have been shown as blockages.</p> <p>The details below note areas where additional cutlines are required in addition to those already contained in the 'H_cutlines' shapefile. Where a blockage has been observed upstream of an existing cutline it is assumed that the modeller will ensure these are incorporated into the next set of runs (in addition to those noted below).</p> <p>Edinburgh:</p> <ul style="list-style-type: none"> • Crossing (326571, 664802) • Culvert (327323, 664747) <i>cutline not added</i> • Structure (332518, 662275) • Structure (332305, 663277) • Culvert (333064, 663237) - ~5m of water upstream • Bridge (332595, 664932)

<ul style="list-style-type: none"> • Bridge (332591, 664910) • Road crossing (333245, 665388) • Culvert (333157, 665222) • Bridge (333145, 665718) • Bridge (333305, 665908) • Bridge (333665, 666591) • Newmills Road crossing (333609, 667070) • Road (333921, 667592) • Number of roads to be accounted for (centred at 334829, 668984) • Crossing (334809, 668559) • Number of roads to be accounted for (centred at 336223, 672579) • Road (337452, 672693) • Road (336454, 673102) • Road (336567, 673182) • Crossing (332769, 673130) • Road (332736, 673077) • Crossing (332532, 672934) • A1140 (329957, 674402) • Low point/high depth observed (329072, 675473) - check if correct (<i>HP not enough info</i>) • Road (320967, 676812) • Culvert (316606, 672985) • Road (316493, 672135) • Cutline needs moving further downstream (refer to DTM) (316516, 672064) • Main road (314692, 671671) • Culvert (315177, 671206) • Structure (314830, 671109) • Structure (313896, 670936) • Structure (313757, 670883) • Structure (312451, 670667) • Structure (313770, 670894) (<i>under buildings, cutline not added</i>) • Culvert (317624, 668069) • Low point/high depth observed (318102, 668406) - check if correct (<i>HP not enough info</i>) • Bridge (319136, 668142) • Main road (320475, 668543) • Structure in DTM (322016, 670419) • Cutline needs extending (323288, 671290) • A900 (326439, 674958) • Crossing (328291, 674305) • Road (329028, 674244) • Structure (329897, 671083) • Structure (328435, 669643) • Road (328304, 669193) • Crossing (328528, 668893) • Crossing (327224, 668551) • Crossing (327242, 668571) • Road (333920, 671503) • Road (331975, 664072) • Culvert (327338, 664735) (very long culvert cutline not added) <p>West Lothian:</p> <ul style="list-style-type: none"> • Culvert (306215, 671050) (very long culvert cutline not added) • Culvert (307937, 672389) • Cutline needs extending (311695, 671166) • Road (311700, 671126) • Crossing (311713, 671063) <p>Falkirk/Grangemouth:</p> <ul style="list-style-type: none"> • Water level backing up at tunnel (285265, 679678) • Road (285744, 679077) • Road (285781, 679097) • Road (285865, 679071) • Culvert (285825, 679113)
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	<ul style="list-style-type: none"> • Low DTM point (290132, 676012) - needs to be checked • Structure (293912, 675188) • Road (295974, 675730) • Road (297403, 675822) • Road (299017, 676630) • Structure (301203, 677022) • Main road (301354, 678305) • Road (302689, 679060) • DTM low point (305149, 679795) - needs to be checked (<i>HP not enough info</i>) • Check number of structures along the Carriden Burn (302303, 680688) • Railway and road (298234, 680828) • Culvert (298163, 680642) • Bridge (298580, 680695) • Railway crossing (285861, 684076) • Railway crossing (285890, 683935) • Crossing (285893, 681903) • Crossing (285947, 681855) • Crossing (285979, 681818) • Crossing (288513, 678224) • Crossing (288504, 678205) • Crossing (288712, 678125) • Crossing (288726, 678091) • Crossing (288413, 677203) • Road (288200, 677129) • Crossing (286887, 677491) • Bridge (286901, 678081) • Structure (293161, 676482) • Structure (293545, 676574) • Road (294025, 676674) • Culvert (293795, 676633) • Road (294527, 676910) • Road (294777, 676921) • Structure (295470, 676913) • Structure (295980, 676812) • Tunnel (290443, 678057)
Signed	
Reviewer	Linda Hemsley
Date	22 November 2012

CERTIFICATE ACKNOWLEDGED BY ANALYST	
Analyst comments	The errors were identified in the DTM, 14 local interpolations applied to DTM. Number of cutlines added after the initial run.
Signed	
Analyst	Halina Piorecka
Date	December 2012

FINAL CERTIFICATE - After Main Runs	
In respect of the project detailed above, I have carried out a review and consider the technical output sound, and any comments raised under a Preliminary Certificate have been satisfactorily addressed.	
Signed	
Final Reviewer	Linda Hemsley

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Final Reviewer comments (i.e. discuss visual inspection of results)	
	<ul style="list-style-type: none"> - Cutlines implemented where applicable. - Distribution checks are sensible. - No DTM error corrections were issued to SEPA. - Reference dtm: h3_dtm_v2. - Depth and velocity ranges are sensible, with few high depths, in justified locations e.g. behind disused railway embankments, quarries, woodland, alongside road embankments, waterbodies, etc. - Sense check of 'with' and 'without' small ponded areas shows consistency (f01m_wspa, f01m_exspa, f03m_wspa, f03m_exspa for runs 3 and 13). - Sense check of low and high return period depth results shows increase of flood extent with return period. <p>Edinburgh:</p> <ul style="list-style-type: none"> - Check of dwt_13_1 shows water ponding upstream of the culvert (327323, 664747) upstream of the workings area, as identified during the initial review. There was limited information on which to add a cutline. Therefore the water depths upstream are conservative, indicating a blocked culvert. - Check of dwt_13_1 shows water upstream of a culvert (315177, 671206) as highlighted in initial review. Local track indicates a possible pipe style conduit therefore the results represent this having blocked. Even if a cutline was included the topography local to the track is such that water would still pond upstream. - Check of dwt_13_1 shows water ponding upstream of road (313896, 670936), as per initial review. No information on culvert exit, therefore could not be included. Again, even with a cut through the topography is such that water would naturally pond in this location. - Ponding of water evident (318039, 670909), road not cleaned in DTM. <p>West Lothian:</p> <ul style="list-style-type: none"> - Check of dwt_13_19 shows water ponding upstream of works site (306215, 671050) - as identified in initial review. No details available to inform culvert details/cut-through and not realistic to assume open and flooding of works site. Therefore current scenario is representative of culvert blockage. - As per initial review, no culvert exit details available (307937, 672389) therefore this could not be included. Runoff naturally flows into the river due to the topography directly to the west. <p>Falkirk/Grangemouth:</p> <ul style="list-style-type: none"> - Check of dwt_13_21 shows water contained upstream of the tunnel (285265, 679678) as highlighted in initial review. Without further information it is not possible to introduce a cut through in this locality. The deep water is contained in the lock area and therefore does not have any adverse impact on the surrounding area. - Check of dwt_13_21 shows water ponding to the side of the motorway (301354, 678305), as highlighted in the initial review. The impact is a localised depth of water on the local road. In reality this water would flow under the motorway, therefore resulting in a lower depth of water but over a longer extent of the road, but still local to the opening due to the local topography. - Check of dwt_13_21 shows water ponding alongside the main road (302689, 679060), as highlighted in the initial review. A cutline has not been included to account for the culvert under the road. However the topography in the area shows even with a culvert included the flood extent would still be similar as floodwaters are encouraged to pond along the side of the road over a distance of ~250m. Thus inclusion would result in the depth local to the structure being less deep, but the extent as a whole is likely to remain the same. - Check of dwt_13_21 shows water ponding alongside the local road as highlighted in the initial review (286887, 677491). There is no cutline included to link the local drain system, but

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	<p>aside from this floodwaters would still collect in the same vicinity due to the topography in the area. Water would naturally collect local to the road.</p> <p>- Check of dwt_13_21 shows water ponding upstream of culvert (293795, 676633) as highlighted in the initial review. It is not realistic to implement a cutline over the length of culvert (~250m) as in reality the floodwaters are likely to build up behind the culvert, especially in a high flow event when blockage is also likely to occur. Implementing a cutline would result in the water levels in this area being reduced, whereas in reality this is not likely to occur.</p> <p>- Check of dwt_13_21 shows water ponding to the south at Tamfourhill. The OS mapping indicates some kind of culvert under the watercourse, but it is not clear where this exits, therefore it is not possible to include a cut through. Therefore the ponding is illustrative of a worst case, culvert blockage. Even with a culvert included the topography in the vicinity, plus the volume of water, would cause local ponding as shown in the outputs.</p>
Date	13 December 2012

C.2 Fluvial Flood Estimate Review

Key

Action required	Potential to have a significant impact on study outcomes.
Action maybe required	Potential to affect study outcomes. Amendments may be required. Otherwise further explanation is required in the report.
No Action required	Negligible impact on the study outcomes.

1. Project Details

Project Name	
Report(s) being reviewed	
Date and version of report	
Author and Company	
Reviewer	
Date of review	
Review Status	

2. Concept Review

Item	Check	Comments
Is there evidence that a concept review was undertaken at the start of the project?	<input type="checkbox"/>	
Did the preliminary methodology get sign off from SEPA and an internal principle hydrologist? Reviewers? Date?	<input type="checkbox"/>	
Does the report adequately define the hydrology methodology, and provide details of updates required throughout the life cycle of the project?	<input type="checkbox"/>	
Does the report capture the key catchment processes and flood mechanisms?	<input type="checkbox"/>	
What is the chosen methodology, FEH RR, FEH Statistical, Hybrid, REFH2, Other.	<input type="checkbox"/>	

3. Review of Data

Item	Check	Comments
Has a report of the available data been undertaken and is outlined in sufficient detail in the report?	<input type="checkbox"/>	
Does the review include both flow and level stations? Current and closed stations?	<input type="checkbox"/>	
Have stations outside the Hi-Flows-UK dataset been considered?	<input type="checkbox"/>	

Has the flood peak data in Hi-Flows been reviewed against the SEPA raw data, and extended to present day where necessary?	<input type="checkbox"/>	
Has the data been assigned a quality rating or has an opinion of the robustness of the data been provided?	<input type="checkbox"/>	
Where necessary, have rating reviews been undertaken? What was the outcome? Where rating reviews deviate from SEPA rating curves, have the differences been explained, and has the new rating curve been approved by SEPA?	<input type="checkbox"/>	
Does the review include rain gauge data?	<input type="checkbox"/>	
Has the rain gauge data review looked at data from sources outside SEPA? i.e Met Office?	<input type="checkbox"/>	
Has RADAR data been considered for calibration events, and compared against SEPA/Met Office observed data.	<input type="checkbox"/>	
Is the review supported by plots, i.e hydrographs/hyetographs or time series?	<input type="checkbox"/>	

4. Calibration Events

Item	Check	Comments
Have calibration events been selected? How many? Dates? Has the quality of the data from all sources over the period of the calibration events been reviewed?	<input type="checkbox"/>	
Is flow/level and rain gauge data available for the chosen events, and has a quality rating been applied to the data?	<input type="checkbox"/>	
Has RADAR data been considered for calibration events? If so has this been compared against SEPA/Met Office observed data.	<input type="checkbox"/>	
Has MORECS data been obtained, reviewed and used to calibrate antecedent conditions?	<input type="checkbox"/>	

5. Boundaries & Reconciliation Points.

Item	Check	Comments
Is there evidence that a catchment schematisation exercise has been undertaken?	<input type="checkbox"/>	
Have all major and minor inflow locations been represented and detailed in the report, and is the schematisation appropriate?	<input type="checkbox"/>	
Have flow estimation points for the purpose of flow reconciliation been outlined in the report?	<input type="checkbox"/>	
Do the locations of the flow estimation points provide a robust hydrological assessment, i.e are located at the locations of interest (e.g. confluences, areas of known flood risk, gauging stations, model boundaries)	<input type="checkbox"/>	
Where tributaries have not been represented as a discrete boundary inflow, has this been detailed and adequately explained?	<input type="checkbox"/>	
Have lateral inflows been included, if so, have they been	<input type="checkbox"/>	

adequately explained and justified?		
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6. Catchment Descriptors

Item	Check	Comments
Has a review of the catchment been undertaken, and the presence of significant land use or catchment factors been described?	<input type="checkbox"/>	
Have catchment descriptors been extracted for flood estimation, and, if so are they clearly presented?	<input type="checkbox"/>	
Is yes, have the parameters been sense checked, and details provided of any changes? – Area, Urbext etc	<input type="checkbox"/>	
Where changes have been made, have these been properly documented and justified?	<input type="checkbox"/>	

7. Estimation of QMED

Item	Check	Comments
How has QMED been derived? i.e using observed data – AMAX/POT or by Catchment Descriptors. Has the method been justified?	<input type="checkbox"/>	
Has a climatic variation adjustment been applied?	<input type="checkbox"/>	
Have confidence intervals been presented?	<input type="checkbox"/>	
Has the revised QMED equation (CEH, 2008) been used where QMED is estimated from catchment descriptors?	<input type="checkbox"/>	
Does the calculation record state whether URBEXT ₁₉₉₀ or URBEXT₂₀₀₀ has been used?	<input type="checkbox"/>	
Have donor sites been used?	<input type="checkbox"/>	
Is there an adequate audit trail, documenting how donor sites have been chosen? i.e. have similarity of catchment descriptors been documented, quality of gauge, as well as distance from catchment centroids.	<input type="checkbox"/>	
Has the revised method of data transfer (CEH, 2008) been used in the selection of donor sites and calculation of adjustment factors for QMED?	<input type="checkbox"/>	
Is the assessment considered robust?	<input type="checkbox"/>	

8. FEH Statistical Method – Estimation of Growth Curves

Item	Check	Comments
What methodology has been applied? i.e Single Site, Pooling Group, Enhanced Single Site for pooling groups at rural gauges?	<input type="checkbox"/>	
Is the chosen methodology adequately justified in the context of catchment dynamics, data available?	<input type="checkbox"/>	
If pooling group has been used, have multiple pooling groups been used for the different catchments, or a single for the entire catchment?	<input type="checkbox"/>	

Has the composition of the pooling group(s) been recorded?	<input type="checkbox"/>	
Has an audit trail of decision making for pooling groups been presented? Reasons for exclusion explained?	<input type="checkbox"/>	
What distribution has been applied? GL, GEV, Pearsons Type 3?	<input type="checkbox"/>	

9. Rainfall-runoff approaches

Item	Check	Comments
What technique has been used? Hybrid, i.e FEH Statistical with FEH RR, or REFH2. Has the chosen approach been justified with reference to key catchment characteristics?	<input type="checkbox"/>	
If the FEH RR method has been used, have the parameters Tp(0) and SPR been adjusted using donor catchments if available?	<input type="checkbox"/>	
If a flood event or lag analysis has been carried out for estimating Tp(0) or SPR, is a list of the events and description of the results provided?	<input type="checkbox"/>	
Has the derived FEH RR critical duration been reviewed? And compared against observed data if available?	<input type="checkbox"/>	
If ReFH2 has been applied at or near a flow gauging station, have model parameters been estimated from flow and rainfall data?	<input type="checkbox"/>	
If ReFH2 parameters have been estimated from observed data, is a list of the events and description of the results provided?	<input type="checkbox"/>	
If REFH2 has been used is it documented whether the alpha factor has been applied? SEPA guidance recommends that the factor should not be invoked for Scottish catchments.	<input type="checkbox"/>	
Does the calculation record state what storm durations were used for the rainfall-runoff calculations?	<input type="checkbox"/>	
Are different critical storm durations appropriate for different parts of the catchment, and have they been applied?		
Does the report consider the hydrograph shape and volumes? i.e Archer Approach.	<input type="checkbox"/>	

10. Small Catchment methods – IOH 124, ADAS

Item	Check	Comments
Has a non FEH method for small catchment hydrology been applied?	<input type="checkbox"/>	
If, yes, which method has been used? And has the application of the method been justified with reference to catchment characteristics?	<input type="checkbox"/>	

11. Results

Item	Check	Comments
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Have derived QMED values been compared to gauged records upstream/downstream to ensure consistency with observed data?	<input type="checkbox"/>	
Have design flows been considered at a catchment scale, and do flows increase downstream, if not are the reasons adequately explained, i.e flood plain storage?	<input type="checkbox"/>	
Have design growth curves for the range of return periods assessed been presented and plotted for multiple methodologies in order to validate the chosen approach?	<input type="checkbox"/>	
Have design flows been checked against observed flood peaks and the theoretical return period sense checked?	<input type="checkbox"/>	
If there are any other studies in the catchment, has the report presented these and discussed similarities/differences?	<input type="checkbox"/>	
Are confidence limits presented for the chosen design flows?	<input type="checkbox"/>	
Have limitations of the approach been outlined and recommendations presented for future improvements?	<input type="checkbox"/>	
Is the final approach clearly defined, and the final design flows clearly outlined in tabular and graphical format against where possible observed AMAX data?	<input type="checkbox"/>	
Does the report clearly outline how the principle flows are input into the hydrodynamic model and how intervening catchments are to be included?	<input type="checkbox"/>	

12. Conclusion

Item	Check	Comments
Is the hydrology methodology clearly defined, such that it can be reproduced in the future?	<input type="checkbox"/>	
Is the methodology appropriate and proportionate to the study in question?	<input type="checkbox"/>	
Has all the available data been used in order to inform the approach?	<input type="checkbox"/>	
Has the approach been developed in conjunction with SEPA staff and got company sign off?	<input type="checkbox"/>	
In your professional opinion is the chosen approach acceptable for the study in question?	<input type="checkbox"/>	
Any additional comments/changes required, over and above comments already included in the review?	<input type="checkbox"/>	

D Report Template

A report template will be provided here at a later date.

E Model Deliverables

E.1 General

Model file paths should be kept below 50 characters where possible, whilst ensuring meaning or logical structure is not lost.

A logical and descriptive naming structure for models and scenarios should be adopted. File and scenario names should include the following information where appropriate.

- River reach identifier e.g. Tay. For long rivers abbreviate the name.
- Version
- Return period
- Storm duration
- Scenario identifiers – D for defended, ND for undefended, S_N for sensitivity to roughness, S_Q for sensitivity to flow. Climate change scenarios to be labelled with the scenario run e.g. 2080H.

Eg. Tay_V1_10yrs_10hrs_D.ied

E.2 InfoWorks(CS and ICM)

A compact transportable database (.iwc) and migration file (.cs2icm) should be for Infoworks CS models. For ICM models a transportable database (.icmt) should be supplied. These transportable databases should include all the information which was used to run the model. This will include, but may not be limited to, the following information:

- The model network (s)
- Inflow files
- Rainfall files
- Trade/waste flows
- Initial conditions
- Level boundaries
- Run files
- Ground model
- Results files (unless prohibitively large)

A description should be provided to accompany any scenarios used in ICM modelling.

E.3 MIKE Flood

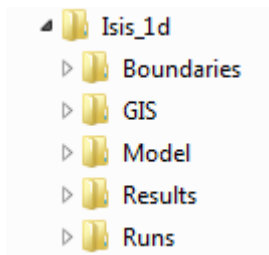
Please contact SEPA for details.

E.4 HECRAS

File Type	File extensions to contain	Description
Model	.prj	Project file. Contains title of project, unit system, list of files associated with project and list of default variables.
	.p01	Plan files. Each plan will represent a different specific

		set of geometric and flow data.
	.g01	Geometric data. Geo-referenced cross sections and information on structures.
	.f01	Steady flow data (if used). This will contain inflow locations, values and reach boundary conditions.
	.u01	Unsteady flow data (if used). This will contain inflow locations, hydrographs and reach boundary conditions.
	.q01	Quasi-steady flow data (if used). This will contain inflow locations, hydrographs and reach boundary conditions.
Results	.log	Log file for the project.
	.b01	Boundary condition file used in unsteady flow simulations.
	.bco	Unsteady flow log output file.
	.ic.001	Initial condition file used for each unsteady flow plan.
Runs	.r01	Model run file for steady state simulations.
	.x01	Model run file for unsteady state simulations.
	.o01	Output file for each plan.

E.5 FloodModeller¹⁴ 1D

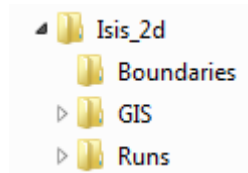


File Type	File extensions to contain	Description
Boundaries	.ied	Hydrological boundary conditions or operating rules for structures. .ied files should be used running multiple design events through the same model rather than importing boundary conditions to the .dat file.
Model	.dat	Model data file. There should be a single .dat file for each different model geometry used.
	.gxy	Georeferenced model schematic.
	.ixy	Diagrammatic model schematic. Not compulsory, largely superseded by .gxy file.
	.iic or .zzs	Initial condition files. These may not exist as it is good practice to include initial conditions in the .dat file unless multiple initial conditions are being run with the same geometry. The .ied files state if a separate initial conditions file has been used. These must be supplied if used.
Results	.zzs	Model results file for steady state simulations
	.zzn	Model results files for unsteady simulations. Note that both the .zzn and .zsl are required in order to open the files.
	.zsl	
	.zzd	Diagnostics file. Containing error messages and

¹⁴ Formerly ISIS.

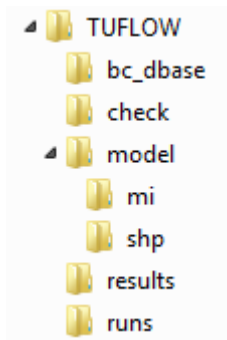
		warnings.
	.zxx	Supplementary results file. Must be included for FloodModeller 1D-2D or FloodModeller-Tuflow simulations.
Runs	.ief	Model run parameter file, one per scenario for design runs.
GIS	GIS format.	For models containing non georeferenced cross sections, spills extracted from a DTM, or reservoir units shapefiles showing the extent and location of these should be supplied. These are not necessary for running the model but are necessary for flood mapping and auditing purposes. Any GIS files used in model construction must be supplied.

E.6 FloodModeller 2D



Folder/File	File extensions	Description
Runs	.xml	Model run files. There should be one of these per scenario run.
GIS	.shp .asc etc.	There should be a GIS folder containing all model GIS inputs. The exact files required will be specified in the .xml file. The same GIS folder and files should be referenced by multiple scenarios
Boundaries	.ied	Hydrological boundary conditions if these are not contained in the .xml file.
Results and check files	.asc, .dat, .sup, .2Dm	The results folder name matches the .xml file name and is created in the Run directory. Check files have the extension .chk*.asc and should be provided for all runs to enable checking. Model results are in .dat, .sup and .2Dm format. There is one .dat file for each output and one .sup and .2Dm file for each model run. All 3 components of the results files are required.

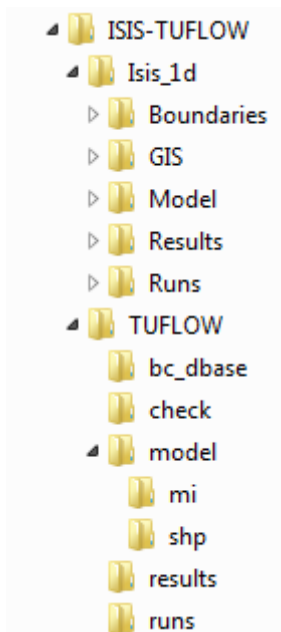
E.7 TUFLOW



Folder	File extensions	Description
bc_dbase	.csv, .xls	Boundary condition data.
check		Model check files.
model	.tbc	Boundary conditions control file
	.tgc	Geometry control file.
	.tmf	Sets model roughness.
mi		mi or shp. Model GIS files. All files must be included.
results		Model results and log files.
runs	.tcf, .ecf	Simulation run files

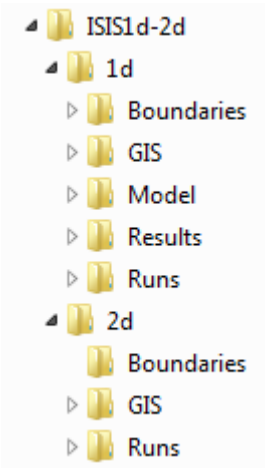
E.8 FloodModeller-TUFLOW

Files are to be included as in the ISIS1D and TUFLOW descriptions above.



E.9 FloodModeller 1D-2D

Files are to be included as in the ISIS1D and ISIS2D descriptions above.



For all coupled ISIS-TUFLOW models the volume output options should be selected in the additional output tabs. The 1D volume output and save interval should be the same as the volume output interval in the 2D model.

F Model Node Naming Structure

For models which require names to be entered for model cross sections the industry standard [XX][CHAINAGE][CHAR] node naming strategy should be adopted where:

XX is the river identifier. This is usually some abbreviation of the river name e.g. Tay or F for the River Tay or River Forth. Use a separate identifier for each tributary in the model.

CHAINAGE is the chainage. The chainage should be 0 at the d/s end of a river, or at a confluence. Chainage should be measured along the centerline of the river from the tidal limit.

CHAR is an optional additional descriptor that can contain letter or numbers. This is usually used for structures such as bridges e.g. BrUp – upstream bridge node, Wr1Dn – downstream node of weir one. Try to be consistent within a model, but there are no hard and fast rules as some software restricts node name length, typical names are given in Table 15-1, and an example of node naming around a bridge in an ISIS 1D model is given in Figure 15-1.

Tributary inflows should be named after the tributary e.g. Pow for the Pow Burn or Devon for the River Devon.

Table 15-1: Typical abbreviations added to Isis node labels.

Typical Abbreviation	Structure/Item
Wr,W	Weir
Sp,S	Spill
Br,B	Bridge
Cu,C	Culvert
Up,U,u	Upstream
Dn,D,d	Downstream

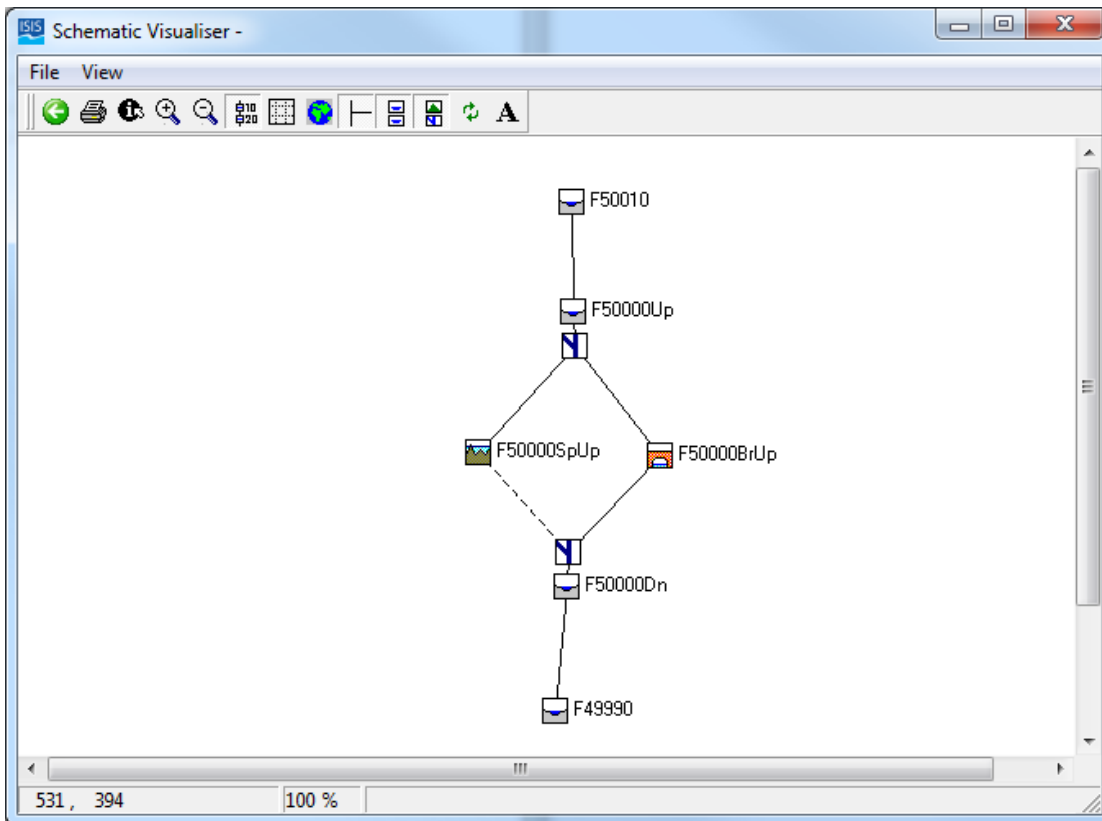


Figure 15-1: Example ISIS node labels around a bridge with a spill at chainage 50000 m.

G Glossary

Term	Description
AMAX Series	A series of the largest event in any given year
Annual exceedance probability	The probability that an event of the same or greater magnitude will occur in any one year. This is the reciprocal of the return period.
Antecedent Conditions	The wetness of a catchment prior to a flood event.
Area of benefit	An area which has benefited from a flood defence and is now at a reduced risk of flooding relative to the scheme's standard of protection.
Average Recurrence Interval	The average period between events of a same or greater magnitude.
Backwater Effect	The effect on water level upstream of a structure or constriction in flow where the depth is raised above the normal depth for the flow. The backwater length is the distance upstream of the constriction or structure before normal depth is re-established.
Catchment	All the land drained by a river and its tributaries.
Calibration	The process of adjusting model parameters to make a model fit with measured conditions (e.g. measured flows). This process should be followed by validation using a different set of data to that used in the calibration.
Conceptual model	Conceptual models are simple qualitative descriptions of a system as a chain of concepts or processes, which are used to help understand how the system works.
Confidence interval	An estimated range of values which is likely to include the value of an unknown parameter (e.g. the 0.5% AEP design flow). The width of the confidence interval indicates how certain the value of the unknown parameter is.
Design event	A flood event of a given annual exceedance probability against which the suitability of any proposed development and mitigation measures are assessed.
Embankment	An artificial raising of the natural bank height of a water body.
Flood Risk Assessment (FRA)	Flood Risk Assessments are detailed studies of an area where flood risk may be present. These are often used to inform planning decisions, develop flood schemes and they also contributed to the National Flood Risk Assessment. They detail site specific flood risk.
Flood Risk Management (Scotland) Act 2009	Legislation which transposes the EC Floods Directive into Scots Law and aims to reduce the adverse consequences of flooding on communities, the environment, cultural heritage and economic activity.
Flood Risk Management Plan	A term used in the FRM Act. Flood Risk Management Plans set out the actions that will be taken to reduce flood risk in a Local Plan District. They comprise Flood Risk Management Strategies, developed by SEPA, and Local

	Flood Risk Management Plans produced by lead local authorities.
Flood Risk Management Strategy	Sets out a long-term vision for the overall reduction of flood risk. They will contain a summary of flood risk in each Local Plan District, together with information on catchment characteristics and a summary of objectives and measures for Potentially Vulnerable Areas.
Floodplain	Area of land that borders a watercourse, an estuary or the sea, over which water flows in time of flood, or would flow but for the presence of flood defences and other structures where they exist.
Fluvial flooding	Flooding from a river or other watercourse.
Froude Number	A dimensionless parameter which represents the ratio between inertial and gravity forces in a fluid.
Reconciliation Points	Locations within a hydraulic model where the peak flow is constrained to match a hydrological estimate. These are typically located at gauging stations or at key receptors such as flood defences.
Hazard	A hazard is a source of potential damage or harm. In terms of the FRM Act, hazard refers to the characteristics (extent, depth, velocity) of a flood.
Hazard rating	A function of depth, velocity and a debris factor used to assess the risk to people from flooding.
Software (model code)	Generic software program , which can be used for different study areas without modifying the source code
Local Flood Risk Management Plans	Local Flood Risk Management Plans, produced by lead local authorities, will take forward the objectives and actions set out in Flood Risk Management Strategies. They will provide detail on the funding, timeline of delivery, arrangements and co-ordination of actions at the local level during each 6 year planning cycle.
Modeller	Person who applies of a software to a particular study area, including input data and parameter values 1. the developer of a model 2. someone working with a model
Modelling	Making a model or working with a model
Model	Site application of a software to a particular study area, including input data and parameter values; Note: 'model' is often referred to as a computer program (a model program) with corresponding input. However, the word 'model' may also refer to some notes on paper, a mathematical model, a diagram or a figure
Natural flood management	A set of flood management techniques that aim to work with natural processes (or nature) to manage flood risk.
Pluvial flooding	Flooding that results from rainfall runoff flowing or ponding over the ground before it enters a natural (e.g. watercourse) or artificial (e.g. sewer) drainage system or when it cannot enter a drainage system (e.g. because the system is already full to capacity or the drainage inlets have a limited capacity).
Peak Over Threshold Series (POT)	All events over a given threshold
Potentially Vulnerable	Areas based on interconfluence catchments that contain

Areas	significant flood risks, sufficient to justify further assessment and appraisal of flood management actions. The NFRA has identified 243 of these for Scotland.
Responsible Authority	Designated in the FRM Act as Local Authorities, Scottish Water and from 21 December 2013 the National Park Authorities and Forestry Commission Scotland. Responsible authorities, along with SEPA and Scottish Ministers, have specific duties in relation to their flood risk related functions.

Return Period	The average interval between years containing an event of the same or greater magnitude.
Risk	A measure of the combination of the likelihood of flooding occurring and the associated impacts on people, the economy and the environment. For a hazard to become a risk there have to be receptors.
Sensitivity Analysis	Sensitivity testing involves varying an element of the modelling and assessing how this alters the model results. This helps develop an understanding of the confidence in the model and its outputs.
Standard of Protection	The lowest probability flood event that a defence will withstand to a high degree of confidence throughout its design life, This allows for uncertainty in the assessment and physical processes such as settlement. This is not the same as the threshold of flooding.
Steady–state model	A hydraulic model in which the flow at any point in the model is constant with time. This type of model cannot estimate the effects of storage on flood levels or downstream flows
Still Water Level	In coastal studies, the water level due to a combination of astronomical tide and surge. Still water levels and waves are often treated separately, however waves may increase still water levels at the coast due to a process called wave setup.
Sub critical flow	Flow for which the Froude number is less than 1.
Supercritical flow	Flow for which the Froude number is greater than 1.
Threshold of Flooding/Overtopping	The most probable flood event at which a defence will be overtopped. This is not the same as the standard of protection.
Upstream/Downstream boundary	The limits of the model assessment upstream and downstream of the site of interest
Velocity	The speed and direction that the water travels.
Verification	The process of checking a numerical solution generated by the software against one or more analytical solutions or other numerical solutions to determine its accuracy. Verification ensures that the computer programme accurately solves the equations that constitute the mathematical model. The software can be verified.
Validation	The process of demonstrating that a given site-specific model is capable of making accurate predictions for periods outside a calibration period. A model is said to be validated if its accuracy and predictive capability in the validation period have been proven to be within acceptable limits or errors.
Water Year	Hydrological analysis in the UK is typically based on water years. UK water years are defined as 1 st October to 30 th September. The 2015 water year starts on 1 st October 2015.

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