Developing a method to assess the impact of incremental loss of floodplain in Scotland

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Executive summary

Incremental, piecemeal reduction of the functional fluvial floodplain is a threat to sustainable flood risk management in Scotland. From a flood risk management (FRM) perspective, removal of functional floodplain will often increase flood risk elsewhere, for example by increasing water levels upstream or downstream. Floodplain loss also results in ecological loss.

Despite Scottish Planning Policy seeking to safeguard functional floodplain, there are a number of reasons for loss, including historical planning permissions, householder and agricultural permitted developments and the cumulative effect of small scale developments.

Climate change is expected to have a significant impact on flood risk. As the frequency and magnitude of heavy rain events increase in the coming years, it is likely the frequency and magnitude of fluvial flooding will also increase.

Based on a literature review this report sets out a possible method for estimating floodplain loss and corresponding flood risk impacts.

Findings and proposed method

The review identified a range of methods suitable for use in Scotland, including existing SEPA models. The analysis suggests that the most appropriate approach to estimating incremental and piecemeal loss of fluvial floodplain over time is one which uses historical maps and aerial photography together with hydraulic modelling. This approach allows quantification of floodplain area and volume loss together with the effect upon flood risk.

We propose a method that uses:

- *information from historical maps, aerial photography* (per Gilvear and Winterbottom, 1992 and Acreman et al., 2003);
- *other datasets* (such as the locations of embankments per the SEPA Morphological Pressures Database); and
- *terrain information* (if available).

Together this can drive the SEPA national flood map models using different digital terrain data for different time periods (therefore representing change in the functional floodplain) and simulate floodplain loss over time.

A baseline (present day) model run would be obtained for a variety of flood events and this would be compared with the equivalent model runs for each time slice derived from the available information. The comparison would be made with respect to floodplain area, volume, conveyance and flood risk at receptor areas.

While the recommended approach could be applied to any size of catchment, it is possible that selecting a relatively small catchment supported with a reasonable historical dataset would show the largest

proportional changes in floodplain loss. This may be a good place to start as a pilot study before proceeding to larger scale catchments.

We suggest that the circa 25 km^2 Haystoun Burn, a tributary of the River Tweed, would be a good candidate for a pilot study as it has recent developments on the floodplain and an existing 1D/2D model.

Content

1 Study aims

1.1 The role of functional floodplain

Scottish Planning Policy[1] (SPP) defines the functional floodplain as "The areas of land where water flows in times of flood which should be safeguarded from further development because of their function as flood water storage areas. For planning purposes, the functional floodplain will generally have a greater than 0.5% (1:200) probability of flooding in any year"[2].

From a Flood Risk Management (FRM) perspective, the functional floodplain is extremely important because removal of that floodplain (e.g. by land raising or development) will often increase flood risk elsewhere (e.g. by increasing water levels upstream or downstream of the raised area). In addition, floodplains are one of the most biodiverse and productive ecosystems on Earth (Tockner and Stanford, 2002), and floodplain loss therefore also results in ecological loss.

SPP underpins safeguarding of the floodplain via land use planning and states (para 256) "Piecemeal reduction of the functional floodplain should be avoided given the cumulative effects of reducing storage capacity". However, the piecemeal loss of floodplain is not well recorded or quantified.

1.2 The impact of climate change on floodplain loss

Climate change is expected to have a significant impact on the water cycle and water-related functions. Rainfall has been increasing in Scotland over the past few decades, with a rise in heavy events. Across the UK severe flooding has been linked to an increase in extreme weather events as the climate changes (UKMO et al., 2011).

Observed climate trends and future projections[3] show an increase in extreme rainfall across the UK (e.g. European Environmental Agency, EEA, 2016; UK Climate Projections, UKCP18, Met Office 2018). In some cases increasing trends in river flow have been identified at some UK gauging stations (Harrigan et al., 2018; Hannaford and Marsh, 2008). Extreme weather events drive fluvial flooding (Centre for Ecology and Hydrology, CEH, 1999), thus as the frequency and magnitude of heavy rain events increase in the coming years it is likely the frequency and magnitude of fluvial flooding will also increase.

The floodplain and perceived flood risk of an area are defined and evaluated using annual probabilities (APs) of flooding. By increasing the frequency and magnitude of fluvial flooding the size of land covered by each AP will grow. By definition, this means the functional floodplain is likely to increase is size. Following on from this, areas that may have once been at low risk from flooding could, as a result of climate change, become higher risk.

1.3 Developing a method to assess floodplain loss

This study is a first step in identifying the potential impact that incremental and piecemeal functional floodplain loss could have on flood risk to downstream communities and local receptors. Previous studies in Scotland have assessed the effectiveness of the implementation of national planning policy in both planning for flood risk and climate change impacts[4]. The focus for this study is on the indirect impacts of functional floodplain loss, i.e. those away from the development site itself with the aim of answering the following questions:

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[1] https://www.gov.scot/publications/scottish-planning-policy/
[2] This is also known as the 0.5% Annual Probability, AP (200 year) flood.
[3] https://www.metoffice.gov.uk/research/collaboration/ukcp
[4] i.e. CXC's report on how Scottish local planning authorities assess flood risk https://www.climatexchange.org.uk/research/projects/assessing-the-consideration-of-flood-risk-by-scottish-local-planning-authorities/

a) What approaches/studies have been used in the UK and internationally to quantify floodplain loss over time?
b) How is floodplain defined in these studies and the value of the floodplain determined?
c) How applicable are these studies to Scotland?

The literature review spans both academic and grey literature, e.g. including journal articles and relevant guidance such as Environment Agency (EA) studies and site-specific Flood Risk Assessments UK and international papers and reports.

In analysing the applicability of the approaches to Scotland we considered whether the studies included *floodplain area* (the spatial extent of the floodplain), *volume* (the amount of water stored on the floodplain), the *impact of floodplain loss upon flood risk*, and *topographic* floodplain loss (particularly over time), see table 1 in section 3.2.

We have proposed a potential catchment for trialling the resulting proposed method, and compiled a list of data and hydraulic models relevant to this study and which could be used in further analysis of floodplain loss (Appendix D).

2 Reasons for floodplain loss

While Scottish Planning Policy seeks to safeguard the functional floodplain, floodplain loss has and can still occur for several reasons:

- Historical. Permission may have been granted under previous policy frameworks; developments can be built a number of years after planning permission is given.
- Catchment size. In Scotland, SEPA's (the Scottish Environment Protection Agency's) indicative fluvial (river) flood maps are only available for catchments with an area of 3 km^2 or greater. It is therefore possible that developments in smaller catchments are not assessed for flood risk and could still contribute to the loss of floodplain storage.
- Overriding need. Development in the floodplain may occur where flood risk and floodplain loss is balanced against other significant planning considerations. In other cases; for example, development of a Flood Protection Scheme (FPS, previously also referred to as Flood Prevention Scheme) where many properties will be protected from flooding, planning permission is granted (or in the case of a FPS is deemed to be granted under a direction issued by Scottish Ministers undersection 57(2B) of the Town and Country Planning (Scotland) Act 1997) even though there will be some loss of floodplain (e.g. through construction of walls and embankments).
- Scale of development. SEPA's document "SEPA standing advice for planning authorities and developers on development management consultations"[5] utilises standing advice for small scale extensions, domestic garages and garden sheds. While these developments may, on their own, have a very limited effect upon flood risk, cumulatively, they could have a much larger impact.
- Permitted development rights.
    - Householder Permitted development. Where the scale and nature of a development is minor and non-contentious then it may benefit from householder permitted development rights[6]. These are developments which are considered to have planning permission, provided they meet certain criteria and can include low walls, sheds, greenhouses, small ground floor extensions and hard surfaces.
    - Agricultural permitted development rights[7]. These are agricultural developments which can include barns or animal sheds, tracks, land raising, excavation and agricultural flood

[5] https://www.sepa.org.uk/media/136130/sepa-standing-advice-for-planning-authorities-and-developers-on-development-management-consultations.pdf
[6] Guidance on Householder Permitted Development Rights. Local Government and Communities Directive. Scottish Government. June 2016
[7] The Town and Country Planning (General Permitted Development) (Scotland) Order 1992

embankments. The scale of works allowable under agricultural permitted development rights (PDR) can be substantial, i.e. agricultural buildings constructed under PDR can have a footprint of up to 465 m^2. The development can also be constructed without the benefit of SuDS (Sustainable Drainage Systems) to reduce or attenuate peak flows. Individually, permitted development may only have a local effect upon floodplain storage loss, for example agricultural flood embankments have been shown to increase flood risk locally. Cumulatively, however, the effect could be much larger.

- Intensification of land use; for example, from open crops to polytunnels may not require planning permission but the resulting increase in impermeable area (from the polytunnel) could increase water run-off and potentially flood risk if within a floodplain.
- Road construction. Floodplain loss can occur due to road construction which is covered under the Roads (Scotland) Act 1984. This is not strictly land use planning, as it is covered by separate legislation. Roads can be raised across and/or along floodplains, guided by the Design Manual for Roads and Bridges (DMRB).

3 Assessing floodplain loss

3.1 Approaches for assessing flood plain loss

14 different approaches used in the UK and internationally to quantify floodplain loss and floodplain loss over time were identified in the literature. In these studies the floodplain is defined either *physically* (based upon geomorphological features such as river terraces) or *functionally* (based upon particular magnitudes of AP flood events), and the value is determined ecologically and/or with respect to the impact of floodplain loss upon flood risk.

The approaches can be summarised into three general types (of increasing complexity):

1. Empirical - based upon analysis of observed data only
2. Simplified conceptual - use a simple approach to estimate floodplain changes without any explicit simulation of channel hydraulics
3. Hydraulic modelling - based upon a river model which simulates channel hydraulics

3.1.1 Empirical methods

Empirical methods use observed data directly to allow the estimation of floodplain loss. Teng et al. (2017) noted that the accuracy of these methods depends of the quality of the data, i.e. spatial and temporal resolution, and emphasised that these are snapshots of the past.

Traditionally water levels and discharge data from gauging stations are the most relied upon data for historic and recent flood observation. However, the number of gauge stations providing water levels and discharge data typically diminishes over time with the closure of gauging stations and reduction of on-ground measurements (Teng et al., 2017). The situation in Scotland is more complicated as, from SEPA data, although gauging station numbers reduced circa 2010 and 2011, the network has expanded again in recent years. Overall there is a similar or larger number of stations operating than previously.

3.1.2 Simplified Conceptual methods

These methods use a simple approach to estimate floodplain changes without any explicit simulation of channel hydraulics. For example, these methods do not require any simulation of the physical processes of inundation with most being a variation on the “bathtub” method; the floodplain volume/area is derived by intersecting a series of planes at finite intervals with a high-resolution Digital Elevation or Terrain model (DEM or DTM, Teng et al. 2017). Floodplain loss can be considered either as the loss of floodplain volume/area or the loss of the hydrological functions of a floodplain.

3.1.3 Hydraulic Modelling

The most widely used method for quantifying functional floodplain area and volume loss is hydraulic modelling. This method determines the extent of inundations and flood depth for a range of annual flood probabilities resulting in an estimation of the floodplain(s) associated with those probabilities. For example, the national-scale flood maps of England and Scotland, published by the EA and SEPA respectively, were generated using hydraulic modelling.

3.2 Studies with applicability in Scotland

Elements of all of the methods used in the identified studies are applicable in some form to Scotland. However, with respect to estimating incremental and piecemeal loss of fluvial floodplain over time, the most appropriate approach appears to be one which uses historical maps and aerial photography together with hydraulic modelling such as the approach used by Acreman et al. (2003). Such an approach allows quantification of floodplain area and volume loss together with effect upon flood risk. The other approaches are either limited by data availability, geography (e.g. areas protected by FPS as considered in SEPA's existing "with" and "without" defences model runs), provide only a snapshot in time (e.g. WWNP, 2018), or do not account for topographic change on the floodplain (e.g. Entwhistle et al., 2009) and could therefore only be used locally rather than nationally.

Table 1 sets out the studies we incorporate elements from in the proposed methodology for assessing flood plain loss in Scotland. A table overview of all the approaches can be found in appendix A. Appendix B describes each study in relation to the research questions.

Table 1 Summary of approaches applicable to Scotland

Study (reference)	Method type	Method summary	Applicability in Scotland	Relevance in a national methodology
Gilvear and Winterbottom (1992)	Empirical	Analysed historical maps (the earliest being William Roy's Military Survey of Scotland 1747-55, also known as the Roy map), aerial photographs and documents on the Scottish River Tay	Depends on sufficient historical mapping and aerial photography being available. Although focussed more upon geomorphology than flood risk management, elements of these studies are very relevant.	The use of historical mapping and aerial photographs (where available) represents a good source of documenting changes on the floodplain through time.
WWNP (2018)	Simplified conceptual	Used open access, nationally available data to identify where watercourses are poorly connected to their floodplain across England. The value of the floodplain was determined relative to Natural Flood Management (NFM) opportunities to both	NFM measures are now considered as part of Scottish flood appraisal studies. SEPA have undertaken national NFM opportunity mapping and are currently identifying physical features (such as embankments).	Could be used to help identify areas where floodplain has been lost, but does not give an estimate of floodplain loss over time.

		allow reconnection of floodplains (for ecological benefits) and assist with flood risk management.		
Entwistle et al. (2019)	Simplified conceptual	Functional floodplain area was calculated at a single timestep. Land use cover information was used to estimate change in floodplain from 1990 onwards	This approach could be readily adopted in Scotland by using SEPA's flood outlines which are available for a variety of AP events. However, the approach does not consider topographic change in the floodplain, only land use.	SEPA flood maps can be used to identify the modern-day functional floodplain. Land use cover maps from 1990 onwards, which also cover Scotland, can be used to identify where the functional floodplain has been lost based on vegetation and land-use change. The approach does not consider topographic change, only land use and time period limited to 1990 on (from land cover information).
Acreman et al. (2003)	Hydraulic modelling	Hydrological and hydraulic modelling for alternative channel scenarios.	The hydrological modelling aspect of the approach could be simplified for widespread use.	Best used for comparison/validation of larger scale model studies, and limited to reach scale.
SEPA	Hydraulic Modelling	2D modelling at national scale to generate flood maps, including "with" and "without" defences runs in flood protection scheme (FPS) areas and sensitivity testing	The mapping is Scotland wide and covers a range of receptors. Without further analysis the maps will only provide estimates of flood volume loss at a single time period in FPS areas (based on "with" and "without" defences)	Existing "with" and "without" defences runs could give an immediate estimate of floodplain loss in FPS areas and the 2D models could be used for further modelling (e.g. topographic change over time) if sufficient data available.
Site specific FRAs	Hydraulic Modelling	Detailed 1D and 1D/2D hydraulic modelling at the reach scale, usually considering pre- and post-development (e.g. land raising for flood protection) scenarios	Many studies have been undertaken in Scotland and the underlying method is applicable. This approach is accepted technical practice for Flood Risk Assessment.	Limited to the river reach scale (i.e. generally several km long. May be best used for comparison/validation of larger scale model studies.

4 Proposed method

4.1 Criteria for including approach in proposed method

In devising an approach for Scotland we have focused on the following needs:

- relevance to both land use planning and operational flood risk management
- quantifying floodplain loss over time, including topographic changes
- availability of existing data sources (ranging from topographic information and hydrometry to model availability)
- applicability across different catchment scales
- nationally consistent

4.2 Summary of method for identifying and quantifying floodplain loss and impact

It is proposed that the SEPA flood mapping models could be used per the Acreman et al. (2003) approach by utilising information from historical maps, aerial photography (per Gilvear and Winterbottom, 1992 and Acreman et al., 2003), other datasets (such as the locations of embankments per the SEPA Morphological Pressures Database) and terrain information if available, to drive the SEPA models using different digital terrain data for different time periods (therefore representing change in the functional floodplain) and simulate floodplain loss over time. A baseline (present day) model run would be obtained for a variety of AP events and this compared with the equivalent model runs for each time slice derived from the available information. The comparison would be made with respect to floodplain area, volume, conveyance and flood risk at receptor areas. In this manner, incremental floodplain loss over time could be estimated.

Where possible the large scale SEPA models would be validated by comparison with reach scale models of the type used in Acreman et al. (2003) and site specific Flood Risk Assessments. Further details of the proposed method, together with suggestions for appropriate locations for trialling the method, are provided in Appendix B.

While there is potential to use the existing SEPA models to obtain an estimate of floodplain loss for a variety of AP values for a single point in time (e.g. using the “with” and “without” defences runs and/or expanding them with MPD and Section 19 data), this would not provide an estimate of incremental and piecemeal reduction in fluvial floodplain through time. Instead it is proposed that the SEPA models could be used per the Acreman et al. (2003) approach by utilising information from historical maps, aerial photography (per Gilvear and Winterbottom, 1992 and Acreman et al., 2003), other datasets (such as the locations of embankments per the SEPA MPD, Appendix C) and terrain information where available, to drive the SEPA models using different digital terrain data for different time periods (therefore representing change in the functional floodplain) and simulate floodplain loss over time. The SEPA models could be validated by comparison with reach scale models of the type used in Acreman et al. (2003) and the site specific FRAs.

The method is set out step by step in appendix C

4.3 Method advantages

- The method is applicable to all model scales and should allow estimation of floodplain area, volume loss and corresponding influence upon flood risk over time.
- It should be good at identifying floodplain loss as a result of built development as this is relatively easy to identify via the information available.
- It should allow the influence of agricultural embankments to be modelled through time if the information is there to allow this.
- It may allow for comparison with other studies e.g. the changes in flood risk estimated following floodplain loss could be compared with those estimated under climate change scenarios (e.g.

the existing SEPA Flood Map model runs include climate change outputs for the 3.33% AP, 30 year, and 0.5% AP, 200 year, defended runs).

4.4 Method disadvantages

- It assumes development is sequential (but large development may have occurred in a single time period of coverage).
- There are uncertainties associated with the availability and quality of information together with the manual interpretation of it and implementation within the DTM.
- Depending upon location, it may be limited by the available information e.g. agricultural embankments may pre-date the historical mapping, in which case it would not be possible to model through time, but instead resort to "with" and "without" embankment scenarios. In this method, it is worth noting that topographic surveys are an essential component to quantify floodplain storage loss. Documenting past floodplain changes might be limited by the availability of high-resolution topographic maps and/or aerial photography through time. Looking ahead, ongoing topographic data collection on a regular basis (e.g. via LiDAR) would be required in order to record future floodplain change.
- There are limitations in the use of the SEPA flood maps for this project due to the national scale at which they were created:
    - The models cannot determine when out of bank flow occurs, and have the underlying assumption that flow is out of bank at Qmed. This may not be the case in areas where there are embankments.
    - The models are also quasi steady state/infinite volume hydrographs.
    - The models are run in downstream to upstream order, so impacts from flood plain loss in an upstream model domain would not be seen in the downstream domain. This makes them unsuitable for looking at cumulative impacts across a large catchment.
- The method would be time consuming. It would require a large manual effort with respect to identifying catchment chronologies from the mapped information and developing a series of digital terrain data based upon that information.

4.5 Pilot study

While the recommended approach could be applied to any size of catchment, it is possible that selection of a relatively small catchments supported with a reasonable historical dataset would show the largest proportional changes in floodplain loss and this may be a good place to start as a pilot study before proceeding to larger scale catchments. For example, the circa 25 km^2 Haystoun Burn (a tributary of the River Tweed) has recent development on the floodplain and an existing 1D/2D model and would therefore be a good candidate for a pilot study.

In terms of which larger catchments could be piloted, of models which have been recently developed[8] (Appendix C), it is proposed that either the SEPA 1D/2D Flood Modeller/TUFLOW model of the lower Earn in Perth and Kinross, the upper River Don in Aberdeenshire or the Scottish Borders Council 1D/2D Flood Modeller/TUFLOW model of the River Tweed be used. This is because the models are for a relatively long reach of river (circa 24 km for the Earn from approximately Forteviot Bridge gauging station to downstream of Bridge of Earn, 39 km for the Don between approximately the Bridge of Alford and Haughton gauging stations and circa 20 km from Peebles to Walkerburn) with a relatively large catchment area (over 800 km^2) and should therefore be representative of a large rural catchment. Of the three catchments, the Earn may offer more potential for investigating potential functional floodplain loss. This is because the Earn model is fully 1D/2D (and therefore easy to implement changes such as removal of flood embankments in the 2D domain). The Tweed has many models available across the catchment but maybe

[8] There may be other models that SEPA has access to that cover large catchments/reaches and these should be reviewed by SEPA to complement the list of examples given.

require some modification as the lower reaches are 1D only, but has the wider benefit of a number of secondary tributary models (e.g. in addition to the Flood Modeller/TUFLOW Peebles model, there are also models of Galashiels, Broughton and the small Soonhope, Haystoun and Edderston Burn catchments) and there are FPS present in the catchment (e.g. at Galashiels).

Appendix A: Overview of studies identified in the literature review

Approaches/studies used in the UK and internationally to quantify floodplain loss over time			How the studies define floodplain and determine the value of the floodplain determined		How/whether the study quantified floodplain area and/or volume loss and associated impacts					Applicability in Scotland?	
Study (reference)	Method type	Method summary	Floodplain Defined by	Value of floodplain determined by	Floodplain Area Quantified?	Floodplain Volume Quantified?	Floodplain Loss Quantified?	Type of Floodplain Loss	Impact of Loss Upon Flood Risk Quantified?	Applicable to Scotland?	Could this method be carried forward to a national methodology?
Pinter et al. (2008)	Empirical	Analysis of observed gauging station data	Not defined but impacts estimated from water levels	Not determined	No	No	Indirectly from changes in water levels	Topographic	Yes	Yes, but did not explicitly define floodplain and requires large number of gauges and build dates of structures	No, insufficient data nationally.
Gilvear and Winterbottom (1992)	Empirical	Historical mapping & aerial photography	Physical (channel planform and embankments)	Ecology	Yes	No	Yes	Topographic	No	Yes, where sufficient historical mapping and aerial photography is available.	Yes, use of historical and mapping and aerial photography could be used.
Thomas et al. (2011)	Empirical	Landsat	Measured flood extents	Ecology	Yes	No	Yes	Topographic and ecological	No	Yes, but would be limited to areas of historical flood information.	No, insufficient historical flood map data nationally.
Dutta et al. (2016)	Empirical	Landsat	Measured flood extents	Not determined	Yes	Not from Landsat, but extent	Not quantified	Not quantified	No	Yes, but would be limited to	No, insufficient historical flood map data nationally.

						compared with model output which quantified volume				areas of historical flood information.	
Qi et al., (2013)	Empirical	Landsat and topographic maps	Measured flood extents	Not determined	Yes	Yes via superimposing flood outline on DEM	Not quantified	Not quantified	No	Yes, but would be limited to areas of historical flood information.	No, insufficient historical flood map data nationally.
WWF (2010)	Empirical	DTM, topographic maps and land used data	Physical (post-glacial terraces) and functional (1% AP) extent	Ecology	Yes	No	Yes	Topographic and ecological	No	Yes, but limited to FPS areas.	No, an immediate estimate for FPS areas could instead be obtained from SEPA's "with" and "without" defended model runs.
WWNP (2018)	Simplified conceptual	Flood maps and rivers	1% AP flood extent	Ecology and flood risk	Yes	Yes	Yes	Topographic and ecological	Yes	Yes, but would not allow estimation of floodplain loss over time.	Yes, potentially, but does not give an estimate of floodplain loss over time.
Entwistle et al. (2019)	Simplified conceptual	Flood maps, rivers and land cover information over time	1% AP flood extent	Land use	Yes	No	Yes	Land use	Yes	Yes, but does not consider topographic change in the floodplain, only land use.	Yes, but does not consider topographic change, only land use and time period limited to 1990 on (from land cover information).
Owens and Walling (2002)	Simplified conceptual	Sediment coring	Physical (landforms)	Land use	Yes	No	Yes	Land use	No	Yes, but does not consider topographic change other than for the physical floodplain,	No, not well suited to incremental floodplain loss.

										so may not pick up incremental floodplain loss	
Williams et al. (2009)	Simplified conceptual	Use of gauge data and LiDAR information for pre- and post-dam development	66.67% AP flood extent	Ecology	Yes	Yes	Yes	Ecological	No	Yes, but limited to similar cases.	No, best suited to localised studies.
Acreman et al. (2003)	Hydraulic modelling	Hydrological and hydraulic modelling for alternative channel scenarios	Modelled extent of historical events	Ecology and flood risk	Yes	Yes	Yes	Topographic	Yes	Yes (hydrological modelling aspect of the approach could be simplified for widespread use).	Yes, but as limited to reach scale may be best used for comparison/validation of larger scale model studies
Beevers et al. (2012)	Hydraulic modelling	Hydraulic modelling investigating the effect of road construction through time	Observed flood extents	Ecology	Yes	No	Yes	Topographic and ecological	Yes	Yes, but limited to areas where similar detailed information available	No, best suited to localised studies.
SEPA	Hydraulic Modelling	2D modelling at national scale to generate flood maps, including "with" and "without" defences runs in FPS areas and sensitivity testing	50% AP to 0.1% AP flood extents	Flood risk to receptors (through NRFA)	Yes	Yes	Yes in FPS areas only	Topographic in FPS areas	Yes	Yes, but without further analysis, will only provide estimates of flood volume loss at a single time period in FPS areas (based on "with" and "without" defences)	Yes, existing "with" and "without" defences runs could give an immediate estimate of floodplain loss in FPS areas and the 2D models could be used for further modelling (e.g. topographic change over time) if sufficient data available.

Site specific FRAs	Hydraulic Modelling	Detailed 1D and 1D/2D hydraulic modelling at the reach scale, usually considering pre- and post-development (e.g. land raising for flood protection) scenarios	0.5% AP flood extent	Flood risk	Yes	Yes	Yes	Topographic (and ecological in some cases)	Yes. (Usually through comparison of pre- and post-development water levels and volume and conveyance changes).	Yes, but generally limited to reach scale (of several km of river length)	Yes, but as limited to reach scale may be best used for comparison/validation of larger scale model studies

Appendix B: Review of approaches

I. Empirical method 1: Pinter et al. 2008

Pinter et al. (2008) found increases in flooding along the Mississippi River over the past 100-150 years by studying historical hydrograph data. To do this they constructed a hydrological database consisting of 26 rated gauge stations and 40 stage-only gauge stations along the Mississippi and Missouri Rivers, and a geospatial database of navigational structures with emplacement dates and physical characteristics. By analysing the trends in gauge data, the authors were able to quantify changes in flood levels and river heights in response to construction of wing dikes, bend-way weirs, meander cut-offs, navigational dams, bridges, and other river modifications through time. The study found the largest increases in river levels were associated with gauge locations that were upstream of wing dikes. For example, 14 km of downstream wing dikes constructed between 1892 and 1928 on the Upper Mississippi River were linked to an increase of 1.52 ± 0.08 m in stage for a flood flow of 4 times the mean daily flow. The authors noted that for each 1km length of wing dyke built, the river stage within 20 river miles would increase by 10.8 ± 0.6 cm. In contrast, the study found that gauges downstream of wing dikes saw a decrease in river levels, likely caused by simultaneous incision and conveyance loss. Likewise, levees were linked with both local increases and decreases in flood levels. Increases in flood levels due to levees were interpreted by Pinter et al. (2008) as loss of floodplain storage and loss of overbank flow conveyance. Whereas, decreases in flood levels that were linked to levee construction were interpreted as incision and flow confinement. Pinter et al. (2008) noted that the effects of other river structures were generally not as significant, but effects were still evident local to the structures.

How the study defined floodplain and determines the value of the floodplain

As their analysis was based upon gauged data only, Pinter et al. (2008) did not explicitly define the area or volume of the floodplain or its value. However, they were able to provide an indicative estimate of topographic floodplain loss through estimating change in water levels through time in comparison with nearby flood defence information.

Applicability in Scotland

In principle, this approach could be used in Scotland, particularly in areas where the dates of formal Flood Protection Schemes (FPS) are known. However, the network of river gauges in Scotland is nowhere near as extensive of that of the Mississippi and Missouri Rivers. This lack of base data would limit the applicability of the Pinter et al. (2008) approach in Scotland to areas with sufficient quantities of hydrometric data and records of the build dates of flood protection measures. Possible areas in Scotland include the Irvine or Tweed catchments where there are gauges upstream and downstream of the FPS and the build dates of the FPS are known.

II. Empirical method 2: Gilvear and Winterbottom (1992) and Gilvear et. al (1994)

Elements of this approach is included in the proposed method

Gilvear and Winterbottom (1992) analysed historical maps (the earliest being William Roy's Military Survey of Scotland 1747-55, also known as the Roy map), aerial photographs and documents on the Scottish River Tay system finding that flood embankments were built in the 19th and 20th centuries that modified unstable multichannel wandering river sections to confined narrow single channel reaches. In fact, the earliest known record of flood embankment construction on the River Tay is from a letter dated 23rd January 1733 (Gilvear et al., 1994). Gilvear et al. (1994) noted that historical flood embankment construction in Scotland has been largely piecemeal in nature because agricultural flood protection has historically been the right and responsibility of the riparian owner.

How the study defined floodplain and determines the value of the floodplain

In these studies, the area of the floodplain was defined physically (geomorphologically; using channel planform) and also through consideration of flood embankments. Floodplain volume was not defined. The value of the floodplain was largely determined environmentally, but some consideration of economic damages at Perth was also provided.

Applicability in Scotland

These studies were undertaken in Scotland. Although focussed more upon geomorphology than flood risk management, elements of these studies are very relevant. In particular, the use of historical mapping and aerial photographs (where available) represents a good source of documenting changes on the floodplain through time.

III. Empirical method 3: Thomas et al. 2011

Landsat (Multispectral Scanner (MSS) and Thematic Mapper (TM) imagery was used by Thomas et al. (2011) to map annual inundation of the Macquarie Marshes in Australia over 28 years (1979-2006). The floodplain was defined using these inundations maps and therefore they were delineating the functional floodplain. The authors used a five-stage process to investigate changes in inundation extent and patterns. First 28 Landsat MMS and TM imagery was selected for each year near spring (a total of 784 images) and then geometrically corrected to allow comparison. Binary inundation maps were derived integrating water and vegetation response for each image. Then to investigate changes in floodplain inundation three spatially explicit inundation indices were compiled. This enabled the authors to analyse long-term changes in inundation patterns of floodplain wetlands that did not correspond to changes in annual catchment or local rainfall.

How the study defined floodplain and determines the value of the floodplain

The area of the floodplain was defined according to observed annual inundation (floodplain volume was not defined) and the ecological value of the floodplain was implied but not explicitly stated.

Applicability in Scotland

This approach could potentially be used in Scotland but would be dependent upon a sufficiently large dataset (over both space and time) to be viable. Landsat TM data is available across Scotland from 1990 so the same method could be applied to gauged catchments in Scotland where gauge stations have been operating since 1990. This would be a time-consuming method to apply at the national scale, but it could be used at the catchment scale to verify hydraulic modelling results (see Dutta et al, 2016, below). However, as this approach is based upon historical data it would not directly allow consideration of design flood events (e.g. the 0.5% AP, 200 year event) unless the flood frequency of the historical event(s) has been calculated.

IV. Empirical method 4: Dutta et al. 2016

Similar to Thomas et al. (2013), Dutta et al. (2016) derived water flood maps from Landsat imagery and these were used to independently validate results from TVD (Teng-Vaze-Dutta) model simulated inundation.

Streamflow records were used to determine the dates when large flood events occurred. Landsat TM and Enhanced Thematic Mapper (ETM) data was for those time periods were then checked for image quality. Dutta et al. (2016) noted that Landsat images are only available at a frequency of 16 days, reducing the likelihood of acquiring an image during peak flooding.

How the study defined floodplain and determines the value of the floodplain

The area of the floodplain was defined according to observed imagery and the value of the floodplain was not explicitly stated.

Applicability in Scotland

Per Thomas et al. (2011), Landsat TM data is available across Scotland from 1990 so the same method could be applied to gauged catchments in Scotland where gauge stations have been operating since 1990. This would be a time-consuming method to apply at the national scale, but it could be used at the catchment scale to verify hydraulic modelling results.

It is also worth noting that the Dynamic Coast project[9] has used a combination of map and satellite images to display and quantify changes in the Scottish coastline over time, showing both erosion and accretion.

V. Empirical method 5: Qi et al. 2013

Qi et al., (2013) took a similar approach to Dutta et al. (2016) but took it a step further by using Landsat imagery and DEM to delineate changes in flood volumes for a local region around Poyang Lake, China. Boundaries of the observed inundation extent in the Landsat imagery were used to determine the inundation water surface level. This level was then superimposed upon the Digital Terrain Model (DTM) and the flood volume calculated.

How the study defined floodplain and determines the value of the floodplain

The area of the floodplain was defined according to observed imagery and the floodplain volume for that observed event calculated from applying the observed extent to a DEM. The value of the floodplain was not explicitly determined.

Applicability in Scotland

Per Thomas et al. (2011) and Dutta et al. (2016), this approach could be used in Scotland if sufficient data are available. In particular, if topographic data are available over time (e.g. representing topographic changes such as land raising or installation of embankments) then a series of DTMs could be constructed and flood extent, volumes, and hence loss over time be calculated. This would be dependent upon the availability of observed flood extent and topographic data and would not allow direct estimation of design events (e.g. the 0.5% AP, 200 year, flood) unless the flood frequency of that historical event has been established.

VI. Empirical method 6: WWF (2010)

Using Aster DTM data, land-use data, and a range of maps (including historical topographic maps, thematic maps, geomorphic and soil maps, and river vector data), floodplains along the Danube and main tributaries were delineated into the historic geomorphic floodplain and the current-day active floodplain (WWF, 2010). The historical extent (m2) of the floodplain was quantified using the topographic change associated with post-glacial terraces and natural floodplain delineation, e.g. in valley breakthroughs, as the boundary (WWF, 2010). While

[9] http://www.dynamiccoast.com/

the current active floodplain was defined as the area in between the 1% AP (100 year) flood defences. The study found that originally the Danube floodplains covered an area of 26,633 km^2, which has been reduced to an area of 8,561 km2 along the Danube. Similar techniques were employed to determine the extent of geomorphic floodplain for several large European rivers (EEA, 2016 and reference therein).

How the study defined floodplain and determines the value of the floodplain

The floodplain was defined both physically (geomorphologically; using identifiable landforms such as fluvial terraces) and functionally (as based on the 1% AP, 100 year, flood). Floodplain area and its loss were estimated, but volumes were not estimated. The ecological value of the floodplain was implied but not explicitly stated.

Applicability in Scotland

This approach could be applied to Scotland, but its direct application would be limited to FPS areas (as the approach used flood defences to help quantify floodplain loss; locations of FPS areas are shown on SEPA's Flood Map and details of FPS, including the standard of protection at the time of build are available on the Scottish Flood Defence Asset Database, SFDAD, provided by the Scottish Government and SEPA, Appendix C). In addition, the approach considers only floodplain area (and not volume) and comparison of the physical and functional floodplains may not yield floodplain loss information an appropriate scale over short time periods (relative to the time period required for physical, geomorphological change of the floodplain).

VII. Simplified Conceptual method 1: WWNP (2018)

Elements of this approach is included in the proposed method

The floodplain reconnection potential project (Working with Natural Processes, WWNP, 2018) quantified functional floodplain area (generally the 1% AP, 100 year event) at a single timestep. The authors used open access, nationally available data to identify where watercourses are poorly connected to their floodplain across England. The study used three datasets to constrain floodplain size and its reconnection potential:

1. Risk of Flooding from Rivers and Seas (EA Flood maps; note that the maps themselves were generated using large scale hydraulic models)
2. Detailed River Network (to be superseded by OS Water Network)
3. Constraints data (residential properties and key services)

How the study defined floodplain and determines the value of the floodplain

The floodplain area was defined using the 1% AP (100 year) event. The value of the floodplain was determined relative to Natural Flood Management (NFM) opportunities to both allow reconnection of floodplains (for ecological benefits) and assist with flood risk management.

Applicability in Scotland

The WWNP (2018) studies are applicable to Scotland and NFM measures are now considered as part of Scottish flood appraisal studies, being undertaken under the Local Flood Risk Management Plans required as part of the Flood Risk Management Scotland Act (2009). SEPA have undertaken national NFM opportunity mapping and are currently identifying physical features (such as embankments) under Section 19 of the Act. The WWNP (2018) approach could potentially be used to help identify areas where floodplain has been lost.

However, as the WWNP (2018) approach utilises national mapping from a single time interval, direct application of this approach without modification would not provide an estimate of floodplain loss across time.

VIII. Simplified Conceptual method 2: Entwhistle et al. (2019)

Elements of this approach is included in the proposed method

Functional floodplain area was calculated at a single timestep by Entwistle et al. (2019). This was an England-wide study with authors using the 1% AP (100 year) flood outline (EA flood zone 3) to establish floodplain regions. The floodplain regions were then segmented by rivers using the OS Open Rivers vector line dataset and a buffer search distance of 1 km either side of the river giving a floodplain area. The total area of functional floodplains in England was calculated to be over 6700 km2. Centre for Ecology and Hydrology (CEH) land use cover information was used to estimate change in floodplain from 1990 onwards (1990, 2000, 2007 and 2015 from the available land cover datasets).

How the study defined floodplain and determines the value of the floodplain

The floodplain area was defined using the 1% AP (100 year) event and floodplain volume was not calculated. The value of the floodplain was associated with land use.

Applicability in Scotland

This approach could be readily adopted in Scotland by using SEPA's flood outlines which are available for a variety of AP events. SEPA flood maps can be used to identify the modern-day functional floodplain then the CEH land use cover maps from 1990 onwards, which also cover Scotland, can be used to identify where the functional floodplain has been lost based on vegetation and land-use change. However, this approach assumes that the flood outline does not change through time and does not allow estimation of topographic change.

IX. Simplified Conceptual method 3: Owens and Walling (2002)

Sediment cores collected from river floodplains can provide information on temporal and spatial changes in sediment source and sedimentation rate (e.g. Owens and Walling 2002; Owens et al. 1999). The study by Owens and Walling (2002) in the Tweed catchment, Scotland, documented temporal changes in overbank sedimentation rates and sediment sources. The changes were linked more closely to changes in land-use and land management over the past 100 years. They noted correlations associated with the introduction of land drainage at the end of the 19th century, the rapid increase in afforestation since the 1940s and the post-war conversion of grassland to arable land.

How the study defined floodplain and determines the value of the floodplain

The floodplain was defined physically (by sediment coring) and floodplain volume was not calculated. The value of the floodplain was determined based upon land use change.

Applicability in Scotland

This approach was undertaken in Scotland and could be applied again. However, it does not quantify floodplain volume, topographic change (at timescales smaller than geomorphic change) or consider the functional floodplain (as defined using AP events).

X. Simplified Conceptual method 4: Williams et al. (2009)

Williams et al. (2009) quantified ecological functional floodplain area and quantified the loss for ecological functional floodplain volume in the Sacramento Valley due to a dam being built upstream. The authors used a similar approach to that of Entwistle et al. (2019) and WWNP (2018) by using AP extents to define the functional floodplain. The study then went further and calculated the loss in ecological functional floodplain volume using river gauge station data. In contrast to Entwistle et al. (2019) and WWNP (2018), Williams et al. (2009) defined the active (functional) floodplain by using the outline of the 66.67% AP (two out of three years) flood extent. The water surface pre- and post-dam construction was determined by interpolating the water surface slope between sets of recorded water levels at paired gauging stations 6-15 miles apart. By superimposing the water surface plane for different river stages on the detailed floodplain topography map (LiDAR) the volume of functional floodplain could be derived for pre- and post-dam construction. Comparing these volumes, the loss of ecological functional floodplain volume was determined.

How the study defined floodplain and determines the value of the floodplain

The floodplain was defined as the 66.67% AP (two out of three years) flood extent and both area and volume were considered. The value of the floodplain was determined ecologically.

Applicability in Scotland

By its nature, this study would be limited to loss of floodplain through dam construction and would therefore have limited applicability across Scotland.

XI. Hydraulic Modelling 1: Acreman et al. (2003)

Elements of this approach is included in the proposed method

Acreman et al. (2003) investigated the impacts current river alterations and hypothetical embankments would have on flood peaks along the River Cherwell, UK. The authors used a continuous hydrological model (CLASSIC) to generate flow inputs based upon observed rainfall to a hydraulic ISIS model (now known as Flood Modeller) for three scenarios; current floodplain and channel, restored channel, and current channel embanked. LiDAR (1m grid), historical maps, field surveys and air photos were used to determine the dimensions of current and pre-engineered channels in the catchment. Although the floodplain volume loss was not stated in this study, floodplain volume loss was implied by the impact of embankments on hydrograph flood peaks. The model results suggested that embanking the river (removing all floodplain volume) would raise the flood levels and increased peak flows downstream by 50-150%, essentially exporting the flood risk downstream from one set of floodplain residents to another.

How the study defined floodplain and determines the value of the floodplain

The floodplain was defined based upon the three scenarios used (current; restored and embanked). The value of the floodplain was determined ecologically and the impact of the different scenarios upon flood frequency was also considered, thus implying the corresponding impact upon flood risk.

Applicability in Scotland

This study approach could be applied in Scotland. However, the continuous simulation aspect of the modelling (used to produce the peak flows in this study) is reliant upon a greater quantity of data (e.g. a rain gauge network) compared to more traditional methods. The hydraulic modelling aspect of the study is readily applicable to Scotland.

XII.Hydraulic Modelling 2: Beevers et al. (2012)

Beevers et al. (2012) investigated the cumulative impacts road construction on flood water levels in the Cambodian Mekong floodplains over time. The hydraulic modelling showed that the building of successive sections of raised road without flow-through structures would result in a continual increase in the height of upstream floodwaters, and a more delayed and significantly reduced height of downstream floodwaters.

How the study defined floodplain and determines the value of the floodplain

The floodplain area was defined using observed water levels from 1999 and 2000. The value of the floodplain was determined ecologically.

Applicability in Scotland

This study approach could be applied in Scotland but, given the detailed structural information required, would be best suited to detailed study at the local scale.

XIII. Hydraulic Modelling 3: SEPA (2014)

Elements of this approach is included in the proposed method

SEPA has undertaken national 2D hydraulic river modelling in order to generate a set of national flood maps for catchments with catchment areas of 3 km2 and greater. SEPA have published these maps as required under the Flood Risk Management (Scotland) Act 2009. Flood maps of Scotland have been developed for likelihoods ranging from 0.1% AP (1000 years) to 20% AP (5 years) with climate change scenarios for the 0.5% AP (200 year return) and the 3.3% AP (30 years). In addition, SEPA have also identified potential NFM areas, and undertaken "with" and "without" flood defences runs (in areas with formal FPS) and have collected information on river morphological pressures (within the Morphological Pressures Database, MPD) including the location of large river embankments. SEPA are also currently gathering further information on artificial structures and natural features under Section 19 of the FRM Act. The flood maps have been used to help quantify the impacts of flooding on receptors at a national scale as part of the National Flood Risk Assessment (NFRA).

How the study defined floodplain and determines the value of the floodplain

Although flood maps are available for 0.1% AP (1000 years) to 20% AP (5 years) events, the functional floodplains are usually taken to be floodplain areas associated with the boundary of the 0.5% (200 years) Annual Probability (AP) or 0.1% AP (1000 years) depending upon where the proposed development type falls within Scottish Planning Policy's (SPP) Risk Framework, e.g. the 0.5% AP, 200 year event, applies to most residential developments, and the 0.1% AP (1000 year return) for most vulnerable areas such as schools and hospitals. The flood maps provide an indication of floodplain area and could potentially provide volume. The value of the floodplain has been determined relative to the impacts of flooding on receptors under the NFRA.

Applicability in Scotland

The SEPA mapping is Scotland wide and is therefore applicable. However, of the readily available information, only the "with" and "without" defences runs would provide an immediate source of floodplain loss information and these would be limited to areas with FPS in place. Investigation of other changes to floodplain loss (e.g. from topographic change outside of FPS areas) would likely require additional study but the 2D national models could provide a good starting point.

XIV. Hydraulic Modelling 4: Site Specific Flood Risk Assessments

Elements of this approach is included in the proposed method

Hydraulic modelling is commonly used to define river flood risk in site specific Flood Risk Assessments (FRAs) supporting planning applications. This is UK wide. In Scotland, typically, only FRAs where land raising has been proposed quote the volume of floodplain loss (for the 0.5% AP) this is because compensatory storage will be required as part of the development to ensure the total volume of the 0.5% AP floodplain does not change. Functional floodplain volume is often calculated by superimposing the modelled flood depth or flood surface for a given AP onto the high-resolution topographic map. In some FRAs topographic modifications have been made to the hydraulic model to emulate/remove land raising and embankments, and new flood maps for a range of APs are be generated giving functional floodplain area/volume loss. Commonly used hydraulic modelling software in Scottish FRAs include HEC-RAS and Flood Modeller (other examples include Integrated Catchment Models, ICM, and MIKE). An example list of FRA studies in Scotland is provided in Appendix D and data sources is provided in Appendix C.

How the study defined floodplain and determines the value of the floodplain

In Scotland the floodplain is usually defined using either the 0.5% AP (200 year) or 0.1% AP (1000 year) flood event. Both floodplain area and volume are ordinarily estimated and the value of the floodplain is determined with respect to ensuring that the site is protected from flooding while ensuring a neutral or better effect upon flood risk elsewhere.

Applicability in Scotland

Many studies have been undertaken in Scotland and the underlying method is applicable. The hydraulic models available are generally at the river reach scale (i.e. generally several km long) rather than the catchment scale and as such this approach may be best used for detailed studies and/or validating the outputs from larger scale models.

Appendix C: Detail of the proposed methodology

The details of this proposed methodology are as follows:

1. For a given catchment covered by the SEPA 2D models, the base run would be taken to be the existing model output. The base run should include the following AP events: 20%, 10%, 3.33%, 2%, 1%, 0.5% and 0.1% (corresponding to the 5, 10, 30, 50, 100, 200 and 1000 year events). By defining the functional floodplain in terms of a variety of AP events the impact of different scales of functional floodplain volume loss on flood risk can be interrogated.
2. For that base run, identify receptor areas (e.g. from NRFA) and calculate floodplain area volume, conveyance and risk. It may be necessary to make the simplifying assumption that the receptors form the baseline and do not change through time.
3. Develop a dataset to allow modelling of floodplain loss through time. For the selected catchment (see point 1 above), construct a sequence of development (taken to be all development depending upon data availability) based upon the following sources (note information from these might not be available for all locations and/or may be limited). Site-specific and national datasets should be investigated:
    a) Historical (and current) mapping. It might be possible to extend the period back to the mid-18th Century using the Roy map (e.g. per Gilvear and Winterbottom, 1992). Local maps may also be available.
    b) Aerial photography (per Gilvear and Winterbottom, 1992 and Acreman et al., 2003).
    c) Land use cover mapping (1990 to 2015; e.g. per Entwhistle et al, 2019).
    d) MasterMap (2001 to present).

    For historical maps and aerial photography building the dataset will likely to involve visual and manual checks. If floodplain loss is detected, the relevant maps or at the least topographic features and structures associated with floodplain loss would need to be digitised. In contrast Land use cover maps and master maps can be quickly compared, but they cannot explicitly show what or where the changes are that are causing the differences in land cover through time.

4. The output from the above would be a set of time slices of information depending upon the dates of that information. (E.g. 1890, 1920, 1950, etc).
    a) For each time slice, as far as possible based upon the available information, the topography interpreted by the model can be adjusted. The nature of the adjustment would be dependent upon the information and would range from manipulation of the DTM for that time slice (e.g. in the case of land raising), which could be time consuming, to changes which do not require edits to the DTM, but simply how the model interprets it (e.g. with and without agricultural embankments could potentially be run as the equivalent to "with" and "without" defences runs).
    b) For each time slice, run the SEPA models for a variety of AP values. (This being preferred to a single AP value, such as 0.5% AP, 200 years, as the effects upon floodplain loss may be different depending upon the AP value, e.g. agricultural flood embankments may have a larger influence with smaller AP values). For simplicity and to avoid masking changes in floodplain loss by changing hydrology estimates, the input hydrology from the base run could be retained. Alternatively, as this assumption may not be correct given climate change, trend analysis could be undertaken to adjust the hydrology estimates to the earlier time period.
    c) For each time slice, calculate floodplain area, volume and conveyance.
    d) Compare the results across the time slices and the base run in order to estimate floodplain loss over time. Also compare modelled flood hydrographs, floodplain areas, volumes and conveyance at selected receptor areas in order to estimate the influence of floodplain loss upon flood risk and flood hazard both locally and elsewhere in the catchment (e.g. further downstream).
5. Where possible, repeat steps 1 through 4 using a detailed hydraulic model for a river reach within the catchment and compare the overall results with those of the larger scale SEPA 2D models for that reach. If the results are similar then this would allow validation of the output of the large scale model. If the results are not similar then an investigation into the sources of the differences would need to be undertaken and the method adapted to account for those differences.

Appendix D: Data and model information

Table 3: Example list of available historical GIS data and models from councils. The information has been collated from direct correspondence.

	Available Historical GIS data	Models
Aberdeenshire		Don Model
Clackmannanshire	All historic flood information in an Access database	Current hydraulic models. FRA options appraisal report for Menstrie in late 2018. This involved updating a 1D HECRAS model to a 1D/2D model using "Flood Modeller" and a "TUFLOW" model. Tillicoultry model Alva Model
East Ayrshire	Known flood events held by SEPA	Irvine valley Flood Study which covers the entire length within EAC
East Dunbartonshire	Historical maps held by council GIS team	Flood models for some of the watercourse in our area: River Kelvin, Glazert Water and Allander Water
Orkney Islands	Some 2D records of extents of surface water flooding events in Kirkwall since 2010	Kirkwall basin (Section 16 model most recent; held by Scottish Water)
Perth & Kinross	Point shapefile of flood events since 1997. NB: does not cover the vast amount of unreported flood events	Recent hydraulic models
Scottish Borders		Peebles to Walkerburn (FM/TUFLOW) Broughton (FM/TUFLOW) Edderston Burn (HEC-RAS 2D) Soonhope Burn (FM/TUFLOW) Haystoun Burn (FM/TUFLOW) Chapmans Burn (InfoWorks) Galashiels (HEC-RAS) Hawick (FM) Selkirk (FM)
Stirling	Not many historical flood outlines but lots of photos from which outlines could be derived. List of flood events and impacts available.	Fintry HEC-RAS (2009) Stirling ISIS (currently being updated) Bridge of Allan (currently being updated) Aberfoyle ISIS (updated 2018) Callander ISIS (updated 2018) Callander small watercourses stage 1 inforworks CS 9.0 (2009) Upper Allan - Bridge of Allan to Blackford MIKE FLOOD (2013) Upper Forth and upper Teith – Craigforth to Aberfoyle and Craigforth to Callander respectively in ISIS (2011) Gargunnock (provided topo data to SEPA to re-run Gargunnock burn model) 2017

Appendix E: List of available datasets for modelling

No.	Dataset	Description	Supplier	Comment	Licence required?	Link (if available)
1	Historical mapping	Historical maps	National Library of Scotland	Identify historical floodplain and structures; some may pre-date even these maps (e.g. agricultural embankments)	N for viewing. Y to download	https://maps.nls.uk/geo/explore/side-by-side/#zoom=5&lat=56.0000&lon=-4.0000&layers=1&right=BingHyb https://maps.nls.uk/roy/
2	Historical mapping	Historical maps	Old Maps Online	Identify historical floodplain and structures	N for viewing. Y to download	https://www.oldmapsonline.org/
3	1970s mapping	1970s geo-tiffs	OS and National Library of Scotland	Geo-referenced	Y	-
4	Aerial photography	Historical and current aerial photography	Historic Environment Scotland (main); SEPA and LAs (may have flood specific photographs)	Identify change in land use through time.	N for viewing. Y to download	https://www.historicenvironment.scot/archives-and-research/archives-and-collections/ncap/
5	LiDAR	Current LiDAR data	Scottish Government	Base DTM for modelling. Phase 1 circa 2011/2012. Phase 2 circa 2013/2014.	Y but Openlicence	https://remotesensingdata.gov.scot/
6	LiDAR	Historical LiDAR data	SEPA	Identify historical floodplain; limited areas available.	Y	
7	MasterMap	Detailed topographic information	OS (but may be available via SEPA)	Identify built areas through time. Data available from 2001 to present	Y	https://www.ordnancesurvey.co.uk/business-and-government/help-and-support/products/os-MasterMap-schema-history.html
8	Land Cover map	Land cover over time	CEH (available for 1990, 2000, 2007, 2015); 25 m and 1 km resolution	Identify change in land use through time. Help define Manning's n on floodplain.	Y; but 1 km is free	https://www.ceh.ac.uk/services/information-products
9	Digitised Rivers Network	River centrelines	CEH (but may be available via SEPA)	Identify watercourses	Y	https://www.ceh.ac.uk/services/information-products

10	Water Network	River, stream, lake, canal vectors	OS	Identify watercourses	Y	https://www.ordnancesurvey.co.uk/business-and-government/products/os-mastermap-water-network.html
11	National flood maps	Indicative flood outlines	SEPA	Identify floodplain extent	Y	https://www.sepa.org.uk/environment/water/flooding/flood-maps/
12	Historical flood maps	Historical flood outlines	SEPA and LAs	Defines historical flood areas	Y	
13	Historical flood point data	Point locations of historical flooding	SEPA and LAs	Defines individual historical flood locations	Y	
14	Flood defence information	Locations and details of formal Flood Prevention Schemes	Scottish Government and SEPA	Locations and details of formal Flood Protection and Prevention Schemes	Y	https://www.scottishflooddefences.gov.uk/
15	Morphological pressures database	Locations of morphological pressures identified under the WFD	SEPA	May include floodplain modfications such as embankments	Y	
16	National flood models	Hydraulic models used to generate the fluvial flood maps	SEPA	Generally 2D only with limited exceptions	Y. A separate licence may also be required for the model type (e.g. 2D FM).	
17	Regional flood models	Hydraulic models used for flood appraisal studies	LAs	Detailed 1D and 1D/2D hydraulic models for river reaches considered for flood prevention schemes	Y	
18	Hydrometric data	River level, flow and rainfall data	SEPA and CEH	Used to estimate flood frequency	Y	https://nrfa.ceh.ac.uk/peak-flow-data

Appendix F: Additional Detail of Floodplain Losses Estimated in Example Scottish FRAs

Catchment	Catchment area (km^2)	Location	Modelled reach length (if known, km)	Type of floodplain reduction	Storage Displaced for 0.5% AP event (m^3)	Compensatory Storage used to offset displacement	Change in Water Level/Flood Risk Upstream	Change in Water Level/Flood Risk Downstream	Source
River Dee & River Don	2083 & 1310	Aberdeenshire, Aberdeen Western Peripheral Route	N/A	Embankment	~100,000	Y; Some compensatory storage provided	60 cm increase at B road (0.5% AP scenario)	13 cm (0.5% AP scenario)	Planning portal
River Dee	2083	Aberdeenshire, Site Adjacent to Broomhill Roundabout, Kintore	N/A	Land Raising	~10,500	N; Partly done under permitted development rights	Impact not assessed	Impact not assessed	Planning portal
River Dee	2007	Aberdeenshire, Caravan site at Maryculter	N/A	Embankments	~108,000	N	Impact not assessed	Impact not assessed	Planning portal
River Clyde	1936	Glasgow, Oatlands/Shawfield	N/A	Land raising	~15,500	Y; residential development – only 75% compensatory storage possible	0.02 cm	0.02 cm	Planning portal
River Clyde	1100	South Lanarkshire, Crossford	N/A	Land raising	1400	N; Agricultural permitted development	20 -30 cm	Impact not assessed	Planning portal
River Clyde	1100	South Lanarkshire, High Netherfauldhouse Farm	N/A	Land raising	Not known	N	Impact not assessed	Impact not assessed	Planning portal
River Forth	1036	Stirling, Fisherman's Walk	N/A	Land raising	Not known	No record	Not known	Not known	Planning portal
River Earn	860	Oudenarde, Bridge of Earn, Perth and Kinross	N/A	Land raising	35,000	Not estimated	Not known	Not known	Planning portal
River Earn	860	Bridge of Earn, Clayton Park	N/A	Land Raising	Not known	N; Proposed but not provided	Impact not assessed	Impact not assessed	Planning portal
River Don	793	Haughton gauging station, Aberdeenshire	37	Permitted development (assumed): agricultural embankment	Not estimated	N	Descriptions of increased flooding provided when embankments removed from modelling.		Planning portal

Catchment	Catchment area (km^2)	Location	Modelled reach length (if known, km)	Type of floodplain reduction	Storage Displaced for 0.5% AP event (m^3)	Compensatory Storage used to offset displacement	Change in Water Level/Flood Risk Upstream	Change in Water Level/Flood Risk Downstream	Source
River Findhorn & River Lossie	782 & 217	Moray, Elgin and Forres	N/A	Flood walls	Not known	N; Flood Protection Scheme	-	-	Planning portal
River North Esk	765	St Cyrus, traveller site	N/A	Land raising	Not known	N	Not known	Not known	Planning portal
River Tweed	753	Cardrona Village, Cardrona Way	N/A	Land raising	Not known	N	Impact not assessed	Impact not assessed	Planning portal
River Tweed	753	Peebles, Crossburn	N/A	Land rasing	Not known	N; Not feasible to provide compensatory storage in the vicinity	Not known	Not known	Planning portal
River Isla	649	Perth and Kinross, Meigle	N/A	Land raising	Not known	N	Not known	Not known	Planning portal
River Spey	534	Highland Council, A9 dualling at Kingussie Spey Crossing	N/A	Embankment	Not known	N; Not feasible to provide compensatory storage in the vicinity	-	-	Planning portal
River South Esk	487	Brechin FPS	N/A	Flood walls	Not known	N; Flood Protection Scheme			Planning portal
River Leven	378	Cameronbridge, Fife	2.3	Land raising	3,063	Y	0 cm	0 cm	Planning portal
River Teviot	323	Hawick, Sainsbury's	N/A	Land raising	Not known	N	Flood depth at supermarket raised by ~30-50 cm		Planning portal
Gala Water	207	Galashiels, Scottish Borders	5	Railway embankment	Not quantified	N	0.08 to 0.25	-	Planning portal
Jed Water	102	Jedforest, Scottish Borders	1.8	Land raising	208	Y	0.01 to 0.02	-	Planning portal
River Braan	96	Perth and Kinross, Dalreoch	N/A	Embankments & land raising	Not known	N	-	-	Planning portal
River Eden	31	Cashmill, Dunshalt	N/A	Land raising	Not known	N	-	-	Planning portal
Caddon Water	29	Clovenfords	N/A	Land raising	Not known	N; already raised	-	-	Planning portal

Catchment	Catchment area (km^2)	Location	Modelled reach length (if known, km)	Type of floodplain reduction	Storage Displaced for 0.5% AP event (m^3)	Compensatory Storage used to offset displacement	Change in Water Level/Flood Risk Upstream	Change in Water Level/Flood Risk Downstream	Source
Burn of Linkwood	26	Moray, Site R2 Waulkmill	N/A	Land raising	Not known	N; Housing development	-	-	Planning portal
Allan Water	12	Blackford, Perth & Kinross	1.3	Permitted development (assumed): agricultural embankment	2,500	N; Existing embankment	0.05 - 0.14 cm	0 cm	Planning portal
Clynelish Burn	5	Clynelish, Highland	1.4	Flood walls	525	Y	-0.01 cm	-0.01 cm	Planning portal
Clynelish Burn	5	Clynelish, Highland	1.4	Flood walls & removal of bridges	525	Y	-	Av = 10 cm Max = 24 cm	Planning portal
Tower, Culloden and Smithton Burns	1.5	Smithton and Culloden, Highland	0.12	Building on floodplain	Not quantified	N; Flood Protection Scheme	Impact not assessed	Impact not assessed	Planning portal

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