

**BALLATER FLOOD PROTECTION SCHEME
GEOMORPHIC PROCESS MODEL AND REVIEW OF MORPHOLOGICAL IMPACTS**

FINAL REPORT

**Prepared for
RPS
and
Aberdeenshire Council**

**Prepared by
cbec eco-engineering UK Ltd**

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NON-TECHNICAL SUMMARY

Aberdeenshire Council commissioned the Ballater Flood Protection Scheme, aiming to protect vital infrastructure around Ballater and the surrounding area from future flooding from the River Dee, as well as reducing future risk through the implementation of sustainable flood protection measures.

This study involved a survey of the River Dee and local tributaries, to collect information on the physical structure of the rivers and pressures which could be affecting this (such as straightening, embankments, weirs, etc.). This information was then linked to potential flood risk, and was considered in terms of the impact that current and proposed flood protection measures may have, and the impact to such measures during future flood events.

Key Findings

- The section of River Dee bordering Ballater Golf Course scored the highest of all sections of river surveyed, in terms of potential for future change.
- The channel in the vicinity of the Red Brae and surrounding area, is dominated by erosional processes.
- Significant embankments along the left bank of the River Dee around Ballater Golf Course, disconnect the river from its natural floodplain. During flood events, the confined flow puts significant strain on the river banks (and the associated embankments) in this area. These structures can eventually breach, resulting in significant flooding to the Golf Course and, in very large flood events, Ballater itself (as occurred during Storm Frank).
- The left bank floodplain immediately upstream of the River Gairn confluence, offers a potential opportunity for the installation of set-back embankments, to retain water within this area during flood events, as a form of Natural Flood Management.

Recommendations

- It is strongly advised that sediment transport (i.e. morphodynamic) modelling is undertaken along the section of the River Dee upstream of the Red Brae, extending downstream towards the meander bend by the sewage works. Reasons for this include:
 - To allow for a sufficiently detailed assessment of the impacts of erosion and deposition in the Red Brae to River Muick area;
 - There is some uncertainty as to the dominant processes in the section of channel immediately downstream of Ballater Bridge. Further detailed monitoring will aid determination of this;
 - The Flood Protection Scheme design should consider potential future evolution of the River Dee. Given the complex nature of the river adjacent to Ballater Golf Course (and downstream of Ballater), morphodynamic modelling the most suitable and accurate method of predicting how the river will react during future flood events.
- Allowing the river to utilise old channels in the left bank floodplain (adjacent to the Golf Course) and adjacent right bank floodplain area during periods of high flow, it will likely reduce strain on the left bank immediately upstream of this area. The design of these channels/ areas should be carefully considered, so as not to increase risk of flooding within the local vicinity, or downstream by Ballater Bridge.
- Investigation into the potential use of the left bank floodplain (upstream of the River Gairn) during flood events, should be undertaken, to assess the feasibility and benefit of this option. This would complement the proposed Flood Protection Scheme measures.

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GLOSSARY OF TERMS

Term	Definition
Aggradation	The process by which (typically) deposition of sediment increases channel elevation in a river system.
Alluvial	Relating to fluvial deposits of gravel, sand, silt and clay.
Channel form	The size and shape of a river or stream channel.
Culvert	A conduit used for the conveyance of a watercourse or surface drainage water under a roadway, railroad, canal or other impediment.
Deposition	The act of a water body depositing sediment.
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.
Floodplain connectivity	The hydrological link between a floodplain and a river or stream.
Fluvial processes	Interactions between the flowing water within a river or stream channel and the physical forms associated with the channels. Processes of erosion, transportation and deposition produce the characteristic landforms in river channels.
Geomorphic/ geomorphology/ morphological	In relation to land forms (specifically rivers in the context of this report) and the processes that shape them.
Inundation	Flooding resulting from channel capacity being exceeded.
Lower gradient units	Features found in streams with gentle gradients (e.g. pools and riffles).
Reach	A general term for a length of stream or river.
Realignment	An instance where a river course has been altered (straightened or re-meandered).
Reference condition / state	Used in river restoration to define how a particular river would look and behave if un-impacted. This is the ultimate target for restoration and can be used as a benchmark against which restoration measures are assessed.
Riparian	Relating to the banks of a burn or river.
Roughness	A measure of how rough the bed of a river or stream is.
Shear stress	The force per unit bed area, in a direction parallel to the bed, exerted by the flow. This is measured as an absolute value.
Sinuosity	The curving nature of a river course. Determined as; actual channel length divided by straight line distance.
Shields stress	A dimensionless number relating to the fluid force on the particle to the weight of the particle. It basically provides an index of the likelihood of a given size of particle moving at a given location in the river under a given flood event.
Storage	The act of retaining sediment or water for any given period of time.

1. INTRODUCTION

The River Dee drains ~2,200 km² of north-east Scotland, flowing in an approximately west to east direction, rising in the Cairngorm mountains and covering ~140 km to enter the North Sea at Aberdeen. The main tributaries of the river include the Feugh, Muick, Clunie, Gairn, Lui, Tanar and Culter system. The Dee is a predominantly rural catchment, with the main land uses comprising agriculture (transitioning from rough grazing in the upper catchment to predominantly intensive agriculture in the lowland areas), and commercial forestry. Significant urban areas within the catchment include the towns of Braemar, Ballater, Banchory and Peterculter, before the river enters the city of Aberdeen and its conurbation on approach to the North Sea.

The Dee has a history of flooding at several locations along its length. Potentially Vulnerable Areas (PAVs) have been designated on the Dee main stem at Ballater, Banchory and Aberdeen, as well as on several tributaries. This report relates directly to the Ballater area (PVA 06/22).

On 30th December 2015, the River Dee experienced the most significant flood event since the Muckle Spate of 1829. The event, termed 'Storm Frank', caused flood devastation within southern and eastern areas of Ballater village. Infrastructure within the surrounding area was also impacted, with a number of bridges (including Polhillock bridge and Cambus O'May bridge) damaged, farms impacted, and important landmarks (e.g. the nearby Abergeldie Castle) left under threat. Extensive erosion of banks and river terraces in the vicinity of Ballater village (including that at Red Brae, west of Ballater golf course) contributed significant volumes of sediment to the Dee mainstem.

Aberdeenshire Council have now commissioned the Ballater Flood Protection Scheme to feed into the Local Flood Risk Management Plan, itself part of the wider Flood Risk Management Strategy developed by SEPA. The Scheme aims to protect vital infrastructure around Ballater and the surrounding area from future flooding from the River Dee, as well as reducing future risk through the implementation of sustainable flood protection measures.

cbec was approached to undertake a geomorphological survey of the water bodies within the study area, with the aim of assessing channel morphology and current physical processes within the system, linking these to potential flood risk and considering the impact that proposed flood protection measures may have. Our approach is described in further detail in the following section.

1.1 AIMS OF THE GEOMORPHIC PROCESS MODEL

The main aim of this stage in the project was to develop a model of contemporary system processes ('Geomorphic Process Model', GPM) of the sections of River Dee mainstem (and associated tributaries) of interest, with which a qualitative assessment of the likely physical response of the site to various combinations of project options could be undertaken. This would subsequently allow for the determination of the likely trajectory of post-implementation evolution (i.e. both in terms of physical condition and implications for instream/ riparian habitats).

This conceptual model describes the current and 'reference condition' (i.e. the physical state under un-impacted conditions of the channel – floodplain system, for both the main-stem River Dee and tributaries of interest). The characterisation of the physical condition of the channel/ floodplain through the study extents is fundamentally based on patterns of sediment erosion, transport and storage. The model allows a geomorphic interpretation of the key processes throughout the study area that control channel/ floodplain morphology, key habitats, hydrological function/ flood process, the character of the associated riparian zone. Comparison of the low impact state with current channel

conditions allows for the understanding of the inherent dynamic character of the study areas and the degree to which they have been altered by human activities.

This work has been structured on extensive existing data sets developed for the Dee mainstem, and augmented with significant additional field-derived data. Included in all analyses is an assessment of uncertainty in relation to current conditions, reference conditions and the proposed restoration options.

1.2 CATCHMENT-BASED APPROACH

Whilst a fully catchment-based approach was not possible within the scope of the project, where possible, aspects of this approach were adopted. This involved information at larger scales directing more detailed and site-specific analyses at higher resolutions (i.e., a 'hierarchical spatially-nested' approach). The benefit of this approach was twofold; (1) it provided an efficient framework to generally assess conditions across the wider system, and (2) it defined key representative sites where higher resolution assessments were undertaken to determine critical processes driving fluvial processes of the river at a specific location.

2. CHANNEL MORPHOLOGY

This section describes the geomorphic regime of the study area and the methodologies used to determine this. These assessments were based, where possible, on existing data (current and historical maps, aerial photographs) but extensive field-based geomorphic surveys (the 'fluvial audit' stage) were also necessary.

A modified version of the 'Fluvial Audit' methodology as described in Sear et al. (1995) was adopted to characterise the physical/geomorphic character of this section of the Dee system. The methodology used has been developed by Dr. Moir over the last 15+ years for the application to upland river systems and used in peer-reviewed, published scientific literature (Moir et al. 2004, Moir and Pasternack 2008) and a number of project reports. In addition, assessment of aerial imagery, published reports and historical map-based information provided data that assisted in describing the dynamic channel behaviour of the system.

The fluvial audit assessment continuously characterised physical conditions along a ~12 km section of the main-stem River Dee, from OS NGR NO 32682 96518 (upstream) to NO 41064 98167, (approximately 3.8 km downstream of Ballater). In addition, sections of four tributaries were surveyed to their confluences with the Dee; Girnock Burn from NO 32580 95745, River Gairn from NO 34541 98325, River Muick from NO 35525 94155 and Tullich Burn from NO 38736 97494. The survey extents are shown in Figure 2.1.

2.1 BASIC PHYSICAL CONTROLS ON CHANNEL MORPHOLOGY

To understand the morphological character of the Dee system, it is important to highlight that physical characteristics of river systems are organised in a nested hierarchy. This means physical processes operating at larger scales influence those at successively finer resolutions (Frissell et al., 1986), ultimately controlling the micro-scale distribution of hydraulic and sediment transport processes. The micro- (e.g., depths, velocities and substrate size distribution), meso- (individual morphological units, e.g., pools, riffles, runs etc) and reach (larger scale channel morphology types, characterised by different assemblages of morphological units) scales are therefore all equally critical elements within this hierarchy, with different geomorphic and ecological processes being relevant at each resolution. The classification approach adopted in this project concentrated on the reach and morphological unit (meso) scales. The reconnaissance nature of the methodology precludes characterisation at the micro-scale that would require some degree of quantitative measurement and significantly increase survey time. Reach type is typically characterized at a relative scale of 10-100 channel widths in length with morphological units in the range 1-5 channel widths.

The morphological character of the channel at a given location (i.e., reach type) is defined in terms of the relative balance between sediment supply and transport capacity. In the case of Scottish mid-catchment gravel-bed streams such as the section included in this project, morphological character is often associated with a relative decrease in valley confinement, a widening of the rivers' functional floodplain and localised variations in sediment transport capacity, associated with changes in underlying geology. Reach types typically can exhibit varied morphological characters, ranging from localised areas of high slope and confined valleys dominated by low erodibility of boundary materials to areas of very dynamic morphology, where both sediment supply and deposition rates are high.

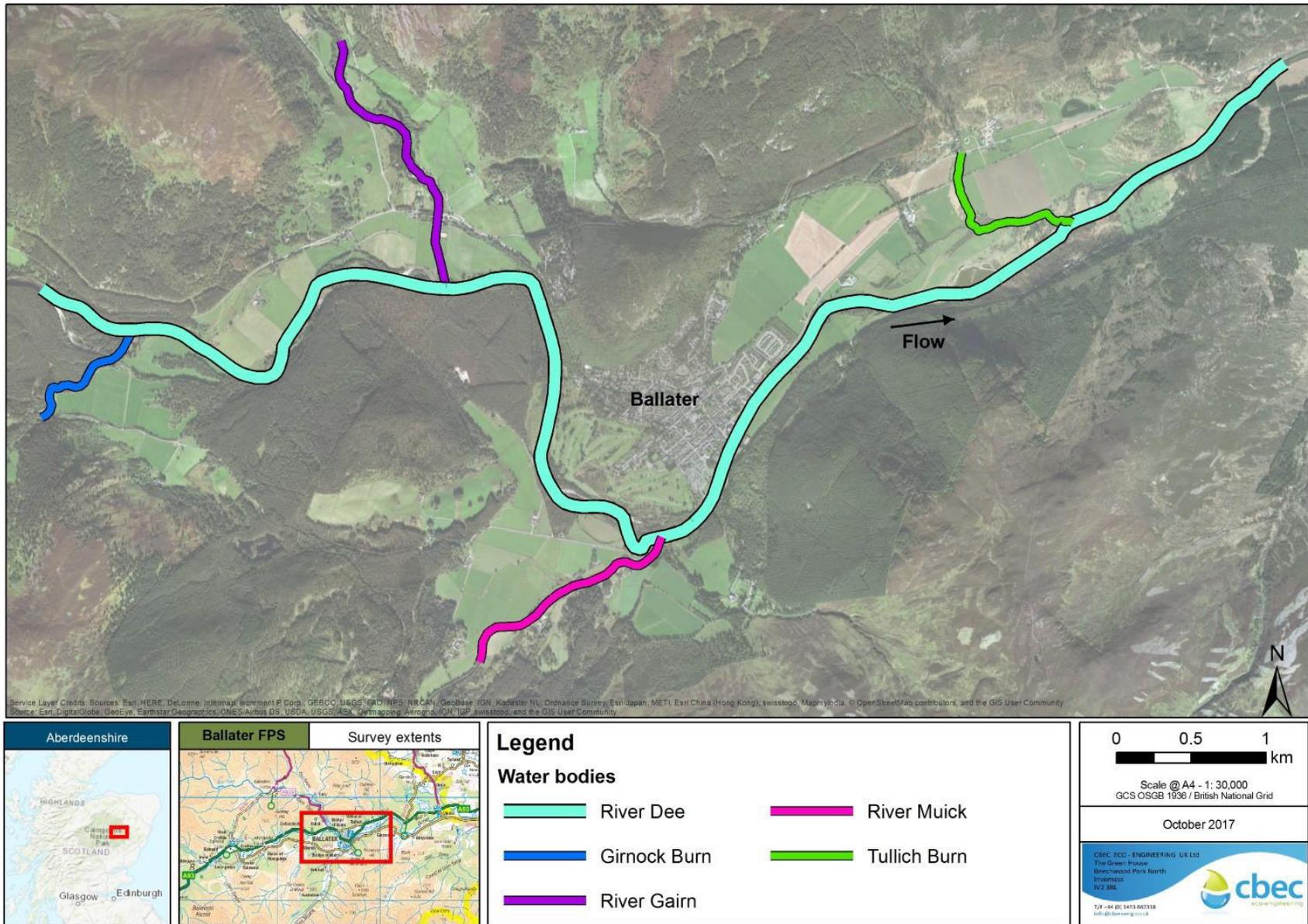


Figure 2.1 Surveyed extents of River Dee mainstem and main tributaries.

At the next spatial scale down, characteristic morphological units are associated with each reach type over a longitudinal scale of many (>10) channel widths (Montgomery and Buffington, 1997); indeed, the assemblage of morphological units to some extent defines reach type. Despite being explicitly linked through the concept of hierarchical organization, reach type and morphological unit scale data provide different information. Reach type indexes the general spatial distribution of 'geomorphic regime' of a river system (i.e., the approximate ratio of sediment supply to transport capacity) while morphological unit data provides higher resolution qualitative insight as to meso-scale hydraulic, sedimentary and instream habitat conditions.

Set within these central concepts, the spatial distribution of channel morphology classifications (at the reach and morphological unit scales) and factors that influence the sediment supply and transport capacity regimes were recorded for both the main-stem Dee and all four tributaries included in the study area. All spatial information was obtained from a hand-held Global Positioning System (GPS) with typical accuracy $\pm 5\text{m}$ and recorded using a bespoke app developed specifically for the purpose of undertaking fluvial audits.

2.2 REACH TYPE CLASSIFICATION

A qualitative, expert judgment classification approach developed from established procedures (Montgomery and Buffington, 1997; Brierley and Fryirs, 2000) was implemented in this project. As discussed above, this system is based on the physical character of the channel, particularly the presence and type of bedforms. Classification is not carried out based on a single point observation. Rather, channel condition is observed over at least 10 channel widths so that the classification is commensurate with the spatial resolution defined for reach type.

2.3 MORPHOLOGICAL UNIT CLASSIFICATION

While valid for the types of system included within the study area, the morphological unit classification has been developed with single-thread, low to moderate energy channels in mind and represents an idealised continuum of increasing flow depth, decreasing flow velocity through the sequence of riffle-run-glide-pool. Note that in more complex morphologies (particularly ones exhibiting dynamic geomorphic processes producing multiple thread channels), many more unit types with characteristic depth-velocity-substrate signatures could be defined.

The following are descriptions of the morphological unit types typically associated with this section of the Dee system. Note that these unit descriptions are indexed to low flow conditions; the meso-scale character of the channel (particularly relative hydraulic characteristics) will change with increasing discharge.

Riffle: relatively fast and shallow flow with high water surface slope and rough water surface texture. Such units may be associated with the downstream face of a transverse (alternate) bar feature.

Run: exhibits a moderate flow velocity, low to moderate depth and moderate water surface slope. Such units typically exhibit a moderate to high roughness of water surface texture and tend not to be associated with transverse bar features that riffles may be.

Glide: low velocity but insufficient depth to be classified a pool. Tend to have relatively large longitudinal extent, and exhibit tranquil water surface.

Pool: a region of relatively deep and slow flow with low water surface slope.

2.4 CLASSIFICATION OF CONTROLS ON PROCESS REGIME

In addition to the reach and meso-scale morphological classification, factors that influence the process regime of the channel (i.e., those potentially influencing the delivery and movement of sediment to the channel) are also recorded. These data were subsequently linked to the morphological data to provide some insight as to the dominant controls on spatial patterns of physical channel condition. These factors are recorded as linear (e.g., bank erosion, tree cover, bank protection) or point data (e.g., tributary input, large woody debris, weir). The upstream and downstream limits of linear features are recorded. Where relevant, the river bank that the data is associated with is also recorded. Data is collected in the following three categories:

2.4.1. Sediment input/ storage:

- a. Bank erosion (including poaching by livestock). This is categorized as moderate or severe depending on the condition of the bank and other indicators as to sediment input rate (e.g., previously bank-side fences within channel, collapsing bank-side trees, condition of adjacent channel bed).
- b. Tributaries. These are characterized as low, moderate or large relative sediment input depending on the character of main-stem channel at the confluence (e.g., presence of confluence bar) and the characteristics of tributary sub-basin (e.g., drainage area relative to the main-stem channel, relief, rainfall).
- c. Depositional sedimentary features. The longitudinal extent, type (e.g., point, lateral, transverse, medial) and 'dynamic condition' of bar features is recorded. 'Dynamic condition' is a subjective definition depending on the appearance of the bar (e.g., vegetated or not, sorting, abrasion marks on clasts etc).

2.4.2. Vegetation:

- a. Bank-side tree cover. Recorded when tree cover is sufficiently close to the active channel to influence fluvial process (e.g., local hydraulics, bank stability).
- b. Large Wood Material (LWM). The degree to which the feature spans the active channel (and, therefore, impacts fluvial processes) can be recorded.

2.4.3. River engineering:

- a. Bank protection. The extent, type (e.g., gabions, boulder, wall etc) and state of repair of bank protection is recorded and then categorized in terms of likely impact to fluvial processes as low, moderate or high.
- b. Bridges. The number of bridge piers impacting fluvial process (i.e., piers within the active channel) and the clearance from the channel bed to the bridge span (indicating the likelihood of impedance of flood flows) are recorded.
- c. Embankments. The extent and state of repair of embankments is recorded and then categorized in terms of likely impact to fluvial processes as low, moderate or high
- d. Channel realignment and re-sectioning. The extent, indicators of damage, percentage of recovery towards reference conditions and likely impact to fluvial processes have been recorded.
- e. Weirs. The height and state of repair of weir structures are recorded.
- f. Croys/ groynes/ boulder placement. The height, state of repair and extent into the active channel of croys/ groynes are recorded.

2.5 SUMMARY OF ASSESSMENT RESULTS

The study area within the main-stem River Dee exhibits a varying morphology incorporating ‘transport-limited’ reaches (with frequent presence of depositional features and inactive historic channels) as well as ‘supply-limited’ reaches, where transport capacity exceeds sediment supply (usually in association with localised increases in valley slope and confinement and lower erodibility of boundary materials). Importantly, significant morphological adjustment (leading to generally increased physical heterogeneity) has resulted from the extreme ‘Storm Frank’ flood event in Dec 2015 that largely exceed thresholds for sediment transport and induced extensive lateral channel migration (i.e. through bank erosion).

Channel morphology reflects the relative balance between the supply of sediment to the channel and the ability of the channel to transport that imposed load (the transport capacity). In response to general patterns in valley slope, transport capacity tends to systematically decrease in a downstream direction in rivers, although with important localised variations in this general trend. Sediment supply is typically more spatially and temporally variable, with many factors (e.g., glacial legacy influencing the distributions of sediment types, vegetation, valley slope characteristics, localised extreme weather events, etc) influencing the rate and size of material delivered to a watercourse. The integration of these systematic and stochastic controlling processes tends to produce a general downstream trend in channel morphology (reach type) but with significant local variation about this general pattern (i.e. the ‘river dis-continuum’ theory). Given their importance to understanding geomorphic processes and flood risk at Ballater, the spatial variation of these patterns throughout the River Dee study area (both main-stem and associated tributaries) will be summarised in this section.

The focus area for this study is centred around the town of Ballater for the main-stem River Dee, with four additional tributaries (Girnock Burn, River Gairn, River Muick and Tullich Burn) included within the scope of the fluvial audit. For brevity, the results of the fluvial audit are reported within three broad sections within the main-stem River Dee:

- Upstream of Ballater golf course (**Section 2.5.1**);
- Ballater between the golf course and Ballater Bridge (**Section 2.5.2**); and
- Downstream of Ballater Bridge (**Section 2.5.3**).

In addition, the results of the survey for the 4 different tributaries are reported independently below in (**Sections 2.5.4- 2.5.7**).

These sections are illustrated in **Figure 2.2**, with survey data provided in **Figure 2.3** and **Figure 2.4**.

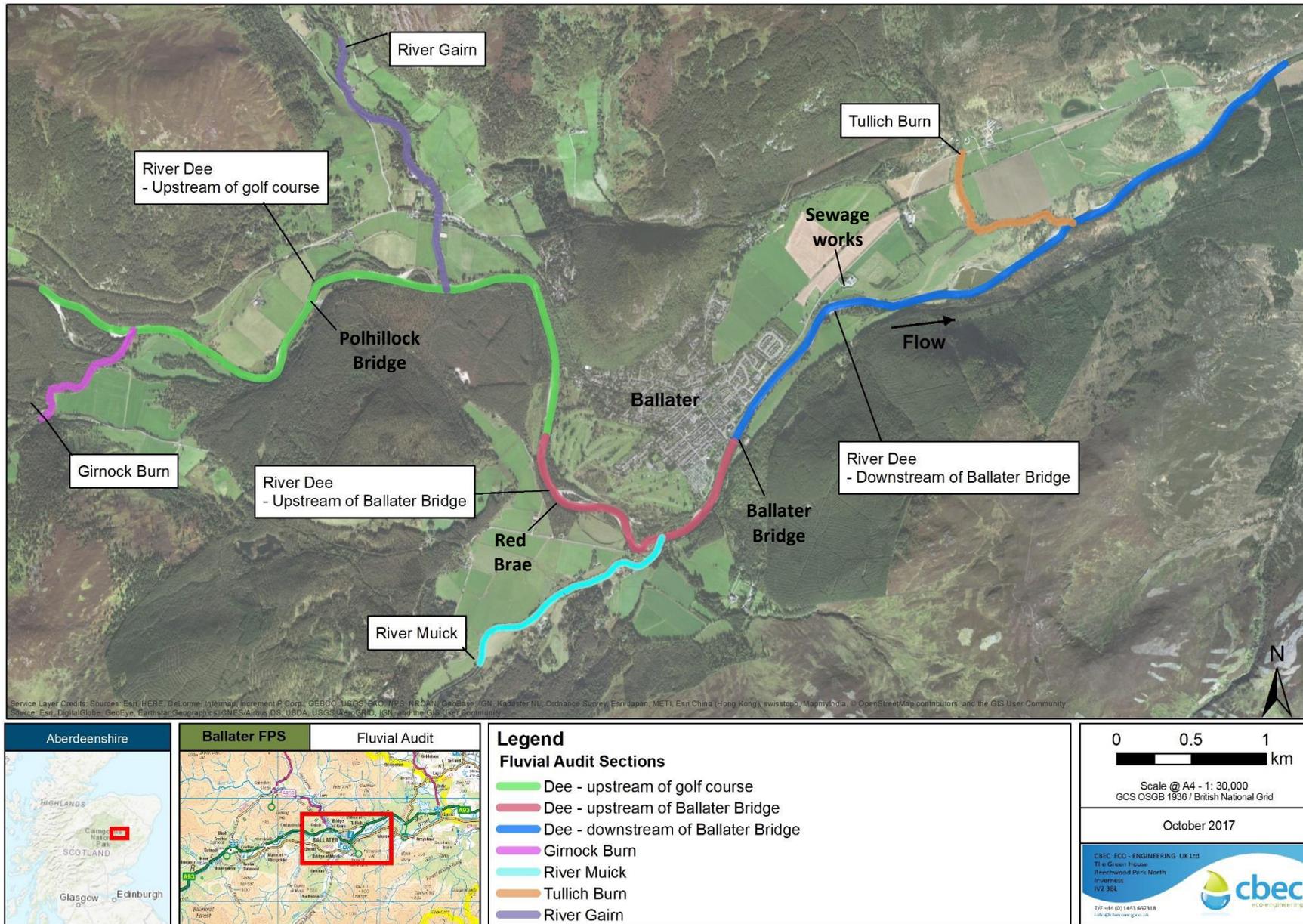


Figure 2.2 Fluvial Audit summary sections and key features.

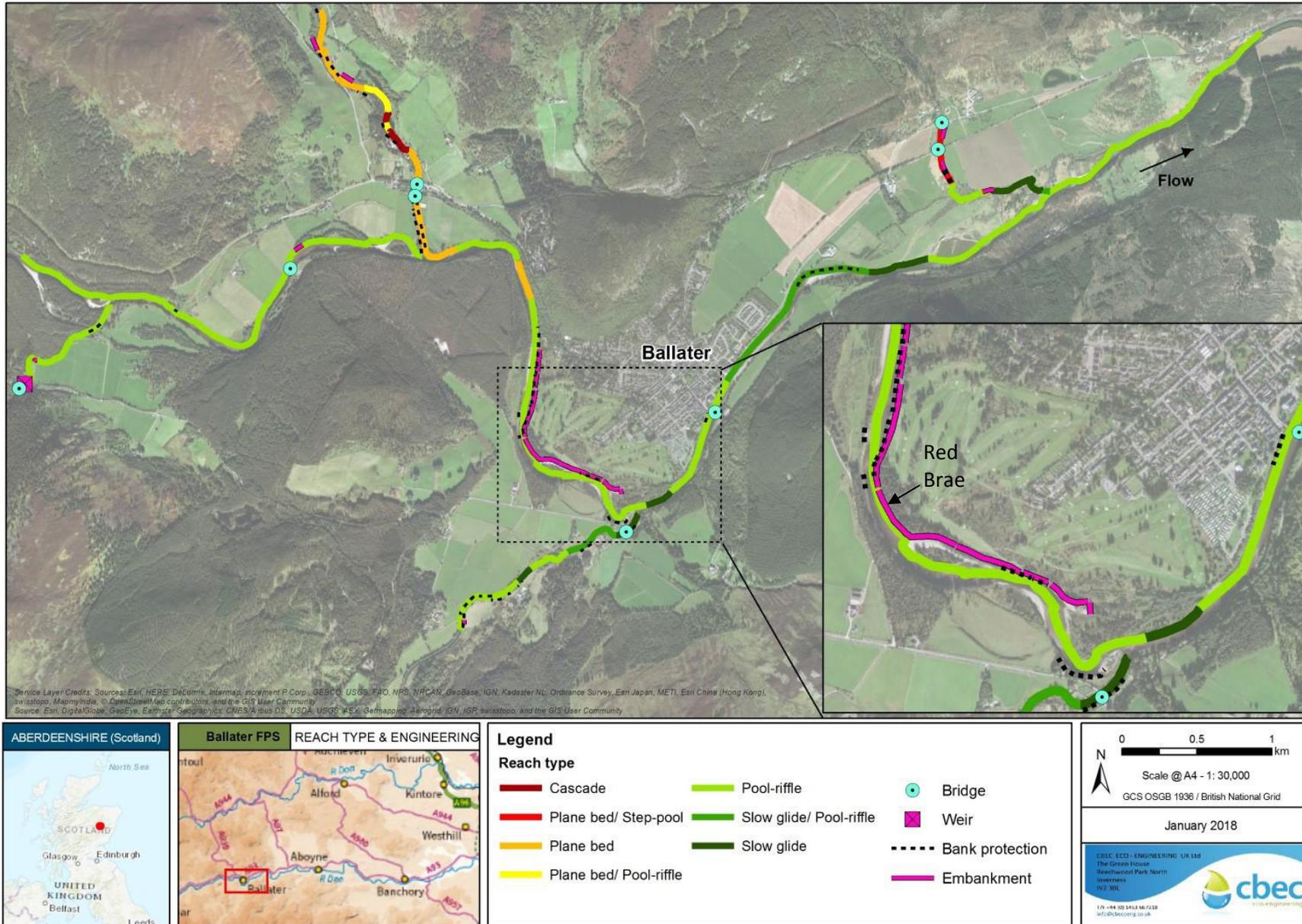
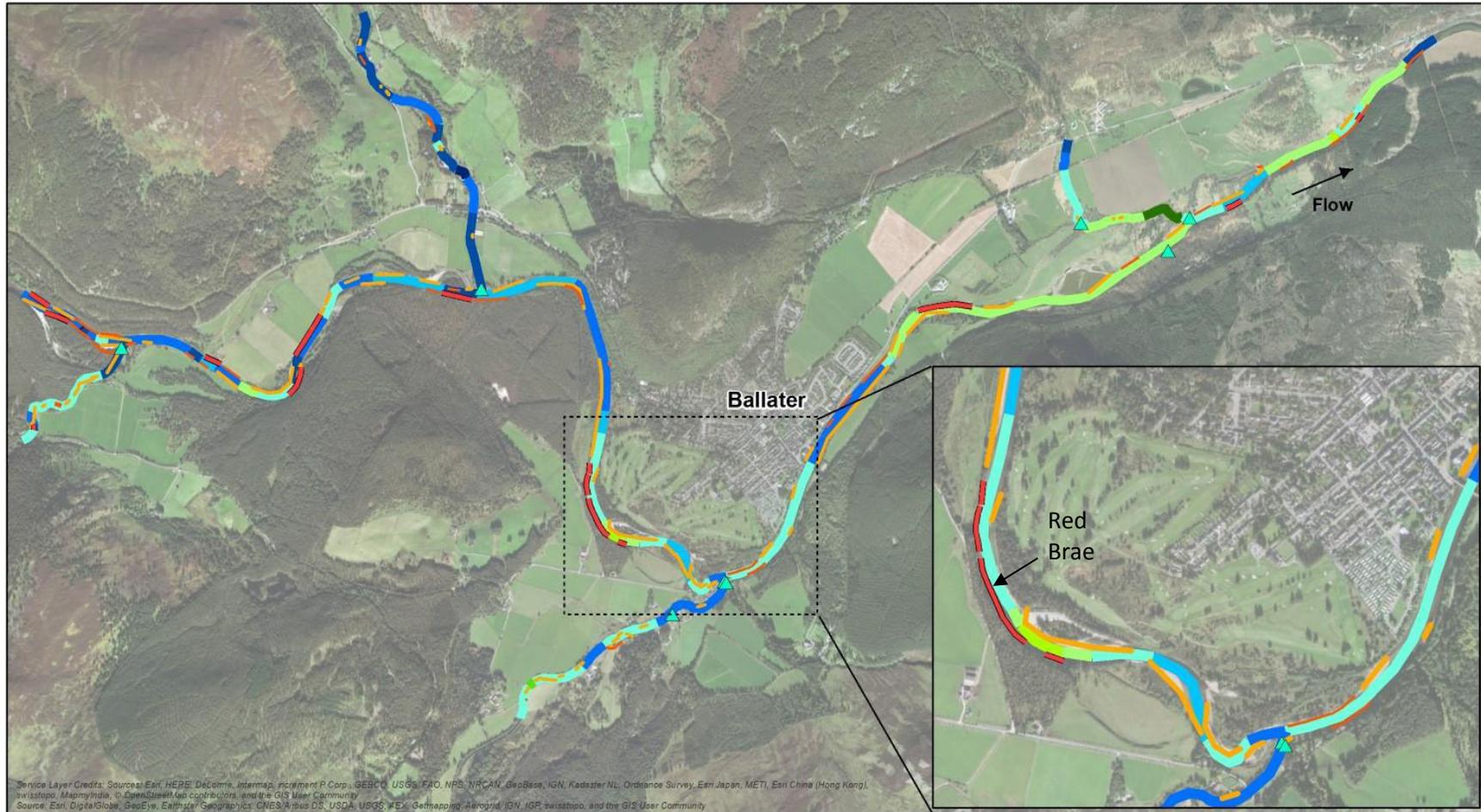
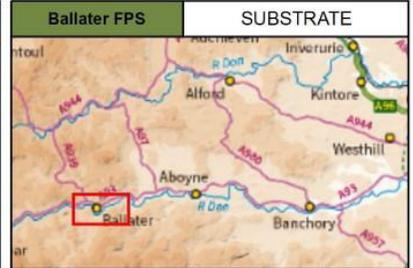


Figure 2.3 Reach type and engineering pressures



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 Source: Esri, DigitalGlobe, GeoEye, Earthstar/Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, IGF, Swisstopo, and the GIS User Community



SUBSTRATE	
	Cobble/gravel
	Gravel/cobble
	Gravel
	Sand/cobble
	Silt
	Bedrock
	Boulder/cobble
	Cobble/boulder
	Cobble
	Tributary
	Alluvial barform
Bank erosion	
	Severe
	moderate

0 0.5 1 km
 Scale @ A4 - 1:30,000
 GCS OSGB 1936 / British National Grid
 January 2018
 cbec
 ECO-ENGINEERING UK LTD
 The Green House
 Beechwood Park, North
 Inverurie
 IV2 3JL
 01463 843300
 info@cbec.org.uk

Figure 2.4 Sediment dynamics

2.5.1. Main-stem River Dee (upstream of Ballater golf course)

This section of the Dee is generally set within relatively erodible superficial geology (dominated by wide alluvial deposits and laterally constricted by river terraces and glacio-fluvial deposits), resulting in a relatively low threshold for geomorphic change.

At the upstream limit of this section (in the vicinity of the confluence with the Girnock Burn), historic evidence of a relatively short wandering section was recorded. Analysis of the available time-series of historic maps (starting with OS One Inch-1897) has highlighted a tendency towards decrease in planform sinuosity during the pre-Storm Frank period, with evidence of stabilisation of bars/ mid-channel islands, and a progressive shift towards a morphology dominated by a single-thread channel flowing in proximity to the northern bank (likely associated with recovery from geomorphic instability generated during the Muckle Spate event). However, the magnitude of the Storm Frank event exceeded local thresholds for geomorphic change, resulting in both severe erosion of the boundary materials (bed and banks) in the main channel and partial reactivation of historic channels, leading to localised severe aggradation. This has produced both a reconfiguration of channel geometry and a significant increase in availability of unstable erodible sediment following the Storm Frank event. Importantly, these changes are likely to have resulted in a localised decrease in threshold for geomorphic change, with the potential to lead to significant future adjustment of channel geometry and mobilisation of sediments during subsequent smaller flood events.

Similar processes were recorded through other reaches within this section of the main-stem River Dee. This was particularly evident in the reach neighbouring Polhillock Bridge, where severe erosion of river terraces and alluvial deposits was recorded. A proportion of the material eroded upstream of Polhillock Bridge was deposited immediately downstream, where lateral confinement and stream power decrease, leading to formation of large depositional features (i.e. alluvial bars), aggradation of historic channels and subsequent concentration of energy and erosional capacity on the banks of the main-stem River Dee. As a result, significant erosion of river terraces has been recorded immediately downstream of the aggrading section (in proximity of the confluence with the River Gairn).

While subsequent patterns of channel adjustment and sediment transport through this section will be largely dictated by the relationship between the rates of vegetation colonisation/ depositional feature stabilisation and the frequency/ magnitude of future flood events, the observed changes in channel geometry and availability of transportable material are likely to have produced a temporary adjustment (lowering) of thresholds for geomorphic change. When coupled with the forecasted evolution in rainfall patterns for this area of Scotland (with an increase in frequency and magnitude of heavy rainfall events), a period of geomorphic instability and rapid adjustment of channel form can reasonably be expected for this section of the main-stem River Dee.

Considering this increase in the supply of materials with the potential for mobilisation during flood events and the predicted lowering of thresholds for geomorphic change, it is considered that this area of the main-stem River Dee has the capacity to supply significant volumes of sediment to downstream reaches during subsequent flood events. In addition, a localised increase in valley confinement coupled with a decrease in sinuosity was recorded in the reach immediately downstream (i.e. between the confluence with the River Gairn and Ballater golf course). It is, therefore, considered that 'efficient' sediment transport through the lower section of this area of the River Dee is likely to result in a potential for increase in supply of sediment to the reach immediately upstream of Ballater.

Photos for this reach are provided in **Figure 2.5**.



Figure 2.5 Survey photos from mainstem River Dee (upstream of Ballater Golf Course). Top left: significant deposition at upstream extent of reach, bottom left: severe erosion on right bank upstream of Polhilllock Bridge, top right: extensive erosion along left bank upstream of Polhilllock Bridge, bottom right: section of naturally confined river corridor downstream of River Gairn confluence).

2.5.2. Main-stem River Dee (between golf course and Ballater Bridge)

The historical evolution of channel form of the River Dee (between 1866 – 1972) is assessed in detail in an extensive review of the geomorphological character of the system (Cheltenham and Gloucester College, 2000). The study indicates that this particular section of the Dee has seen significant erosion in the Red Brae locality throughout this period. It also identified this specific area as being a major source of potential future input to the Dee system. SEPA's 2017 review corroborates this, and estimates that the bank has eroded/ retreated by up to 20 m in a five year period between 2011 and 2016, with Storm Frank being responsible for a significant proportion of this.

Extensive engineering pressures in the form of 'grey' bank protection and embankments were recorded in this area during the fluvial audit (a total of 743 m of bank protection and 1,093 m of embankments were recorded for a section of 2,193 m in the main-stem River Dee).

Within a hydrological regime lacking extreme flood events of similar magnitude to the Muckle Spate or Storm Frank (such as the period between 1829 and 2015), the joint effects of increasing engineering bank stabilisation works and stabilising historic depositional features would have likely resulted in a tendency towards an increase in transport capacity through this section of the mainstem Dee, potentially leading towards a limitation in the extent and residence time of sediment deposits (i.e. as alluvial barforms). Consequently, thresholds for geomorphic change under smaller flood events would tend to rise as a result of reduced sediment supply (associated with installation of extensive bank protection and stabilisation of historic depositional features), further contributing towards a relative decrease in morphological dynamism.

However, the regime described above has important implications for the understanding of the short to medium term effects in the Ballater area of an event of the magnitude of Storm Frank. While thresholds for geomorphic change have broadly been raised throughout this area over the last 150 years, it is considered likely that an extreme event (such as Storm Frank) would exceed these by surpassing the design specifications of engineering works that limit bank erosion and by producing shear stress levels beyond that required for the mobilisation of historic fluvial deposits. Under this scenario, an extreme flood event would be expected to lead to widespread mobilisation and reworking of sediments through bed and bank erosion.

Quantitative assessments of erosion and deposition patterns through this area (Addy, 2017; SEPA, 2017) have verified this principle by comparing detailed pre- and post-Storm Frank topographical data. In summary, both analysis have concluded that the Storm Frank event has produced an overall net erosion through this section of the main-stem Dee, consistent with the predicted response to an extreme event under the conceptual geomorphic regime described above.

Importantly, Storm Frank has significantly disturbed depositional features that had, for the century preceding this event, been characterised by progressive stabilisation. As a result, it is anticipated that thresholds for geomorphic change will have experienced a temporary lowering, following the disturbance associated with the Storm Frank event. Field observations from cbec's fluvial audit and SEPA's geomorphology team corroborate this hypothesis, with areas of severe bank erosion and localised deposition being observed without flows of bankfull or higher having occurred over the period between Storm Frank (December 2015) and the date of the fluvial audit (October 2017).

Considering the objectives of this project, it is deemed important to further explore the implications of this change in geomorphic regime. **Section 3** will, therefore, aim to provide a semi-quantitative assessment of the relative intensity of sediment supply, deposition and transport processes. In addition, **Section 4** will integrate these findings with the flood protection measures being proposed at Ballater to assess potential implications to geomorphic regime and flood risk.

Photos for this reach are provided in **Figure 2.6** and **Figure 2.7**.



Figure 2.6 Survey photos from mainstem River Dee (between Ballater Golf Course and Ballater Bridge). Top left: rip rap bank protection on left bank (view upstream), bottom left: significant river terrace erosion at Red Brae (right bank), top right: Additional view of eroded right bank, bottom right: boulder rip rap in left bank.



Figure 2.7 Survey photos from mainstem River Dee (between Ballater Golf Course and Ballater Bridge) continued. Top left: repaired embankment breach on left bank by golf course, bottom left: paleochannel within left bank, top right: River Muick confluence (view from left bank), bottom right: view upstream from Ballater Bridge.

2.5.3. Main-stem River Dee (downstream of Ballater Bridge)

Downstream of Ballater Bridge, geomorphic change as a result of Storm Frank appears to be generally less extensive and of lower net magnitude compared to sections upstream. Whilst alluvial bars exist throughout the section between the Bridge and the sewage works, analysis of historical maps suggests that such features have been present since at least the mid-19th century. The DEM of difference produced for SEPA's 2017 study also supports this, although it is acknowledged that some assumptions were made as to channel bed elevation for the purposes of that analysis. Therefore the error associated with the in-channel data will be greater than the inherent error associated with LiDAR.

During very large flood events such as Storm Frank, changes to floodplain geometry/ roughness tend to be the governing control over patterns of erosion and deposition. In one localised section of this reach (the meander bend by the sewage works located immediately downstream of Ballater), the left bank failed during the storm, causing a significant amount of water to enter the floodplain. In this section of channel, an increase in the channel's erosional capacity is evident. This is manifested in high shear stress at the location where channel geometry constrains flow towards the left bank

This appears to be the only area within this section of the study site to experience notable change during the flood; the failure of the left bank was coupled with an increase in size of the adjacent point bar on the right bank (Matheson, pers. comm). Severe erosion on this left bank was recorded during the survey, alongside extensive hard bank protection (some of which appeared damaged). The point bar, consisting largely of imbricated coarse cobble and boulder material, shows little sign of colonisation by vegetation, suggesting at least partial inundation and turnover of sediment across the feature since Storm Frank.

The geomorphic response of this reach to the storm is considered consistent with its general character (i.e. characterised by relatively high shields stress during flood events). Whilst it is anticipated that the episodic extreme events (such as Storm Frank) are likely to result in some significant channel adjustments, bedforms resulting from these rare events are likely to remain quasi-stable during lower magnitude flood events. However, this merits further investigation specifically through the use of morphodynamic modelling to monitor bedform change.

Further downstream (in proximity to the confluence with the Tullich Burn), the main-stem River Dee exhibited evidence of dynamic geomorphic adjustment. Similarly to the processes observed upstream in the vicinity of the Girnock Burn confluence, the Storm Frank event has resulted in significant aggradation of secondary channels, the formation of large depositional bar features and locally increased erosion of river terraces. Whilst these geomorphic responses are considered consistent with the expected response for the reach type recorded at this location, it will likely be important for this section to be included within any future hydraulic model, to assess the contribution of this stretch of channel to flood risk within Ballater.

Photos for this reach are provided in **Figure 2.8**.



Figure 2.8 Survey photos from mainstem River Dee (downstream from Ballater Bridge). Top left: view downstream from Ballater bridge, bottom left: deposition (right bank) and bank protection by sewage works (left bank), top right: view downstream showing single thread channel, bottom right: significant hillslope coupling (right bank)

2.5.4. Girnock Burn

The Girnock Burn is an important monitoring site for salmonid production, with adult and smolt fish traps situated at Littlemill, 0.75 km upstream from the confluence with the mainstem Dee. A large modern weir with multiple sluice gates is situated at the site.

The surveyed extent of the burn is a moderate/ high gradient reach with localised sinuosity and a predominantly pool-riffle reach typology. A series of cobble and gravel bars were evident throughout the surveyed extent of the burn, on alternating banks, allowing for the development of short, consecutive riffle/ run/ pool and glide morphological unit types. The non-stabilised nature of these depositional features can be explained by the dynamic nature of the burn throughout much of this section (partly related to the extra roughness provided by the riparian vegetation. Additionally, deposition within the downstream extent of the water body (on approach to the Dee confluence), is likely to occur due to backwater effect from the main river during flood events. Minor evidence of bank erosion within the Girnock Burn reaches can be attributed to the continuous mature vegetation along the lower extents of the burn, acting to stabilise both banks.

2.5.5. River Gairn

The River Gairn is one of the larger tributaries of within the Dee catchment, with a catchment area of 143.6 km² (Cheltenham & Gloucester College, 2000). The river flows within a narrow corridor of alluvium throughout its lower catchment, the valley widening on approach to the Dee confluence. Immediately upstream of the B972, the current planform exhibits slight sinuosity, transitioning to a straighter alignment downstream of the main road. Roy Military Highlands mapping (1747-52), although indicative at best, suggests that the downstream extent of the River Gairn (south of the current B972), was historically more dynamic than it is currently, with the channel split in one section by a large medial bar feature. Today, whilst a lateral bar is present within this area, the planform is less complex, most likely a result of confinement due to the use of surrounding land for agriculture.

The surveyed extent of the burn was dominated by plane bed reach typology, with shorter, intermittent cascade sections. Related to this, run and glide unit morphology was prevalent through much of the reach, consisting of predominantly cobble and/ or boulder substrate. Higher gradient, localised sections of exposed bedrock also exist upstream of the B972, increasing transport capacity of coarse sediment.

Similar to the Girnock Burn, bank erosion was minimal throughout the surveyed River Gairn extent due to the presence and diversity of riparian vegetation.

2.5.6. River Muick

The River Muick is another major tributary of the Dee with a catchment area of 110.3 km² (Cheltenham & Gloucester College, 2000), confluencing to the south of Ballater, adjacent to Ballater Golf Course. Sections of the Muick flow through Birkhall Estate, limiting access during the surveys to a ~1.6 km section at the downstream limit of the water body.

The rivers course runs through an alluvial floodplain, narrowing through its central section and transitioning to an alluvial fan around the confluence as the gradient decreases. Pool-riffle and transitional pool-riffle/ slow glide reach typologies dominated the 1.6 km, with regular lateral and medial cobble bar features recorded.

The river flows through predominantly pastoral agricultural land, and is bordered by mature trees along the majority of its banks within this section, limiting supply of alluvial sediments downstream to the main-stem River Dee.

2.5.7. Tullich Burn

The Tullich Burn enters the Dee downstream of Ballater, and is one of the smaller of the four tributaries surveyed. Downstream of the A93, the burn runs south towards the Dee. Here, it is bordered by agricultural land (with cattle grazing at the time of survey) and is aligned with embankments along a considerable stretch on the left bank for ~350 m downstream of the road bridge. Historical mapping dating from 1843 – 1882¹ shows the alignment to be much the same as the current day course, however, at the downstream end of the burn, the same mapping shows a more complex/ diverse system as well as a series of well-defined paleochannels associated with the main-stem River Dee.

Roy mapping, again whilst indicative only, suggests that the Tullich Burn ran slightly east of its present course within the surveyed reach, entering the Dee in approximately the same location as it does today. Some historical realignment along sections of the water body may have been undertaken, confining the channel to its current day course in order to maximise agricultural productivity of the surrounding floodplain.

The burn is dominated by run and glide units within the upstream section, before transitioning to a more complex morphology of alternating pools, runs and riffles prior to the left bend meander. Run dominated reach with coarse cobble and boulder substrate, transitioning to finer cobble and gravels as gradient reduces towards the downstream extent of the burn on approach to the confluence.

Superficial geology for much of the Tullich Burn catchment consists predominantly of glacial till, as evident by the coarse nature of substrate noted immediately downstream of the A93 road crossing. Substrate becomes increasingly alluvial on approach to the Dee confluence, with finer gravels evident in the bed and within the channel banks.

Input of flow and sediment from the Tullich Burn appears minimal relative to the size and capacity of the Dee mainstem. Located at the downstream extent of the study area to the east of Ballater, the burn does not appear to contribute to flood risk within the town itself.

¹ Available from the National Library of Scotland online at:
<http://maps.nls.uk/geo/explore/#zoom=14&lat=57.0629&lon=-3.0056&layers=6&b=1> (Accessed 20/11/17)

3. DEVELOPMENT OF CONCEPTUAL PROCESS-IMPACTS MODEL

The development of a conceptual process-impacts model provides a semi-quantitative analysis of the Dee system surrounding Ballater, allowing a more in-depth analysis of the characteristics of the system highlighted in **Section 2.5**. The aim of the conceptual model is to develop a process-based understanding of the behaviour of the mainstem Dee and associated tributaries in this area, before establishing the potential impacts of the proposed Flood Scheme measures.

Conceptual model development comprised of

a number of elements. Initial division of the system into a series of geomorphically defined reaches (**Section 3.1**) provided the basis for further analysis. The physical character of the system was assessed through analysis of specific stream power in relation to the sediment budget (determined from indices of sediment input and sediment storage, derived from fluvial audit data and aerial imagery) (**Sections 3.2-3.3**). This allowed the continuous description of the 'geomorphic process regime' (the relative balance of the supply of sediment to the system and the capacity of the river to transport that supply) and prediction of likely rates of morphological adjustment (including lateral migration and avulsion of the channel) (**Section 3.4**). The dominant geomorphic process and degree of channel dynamic behaviour are summarised in **Section 3.5**. The physical process model allowed identification of the likely sensitivity of a given reach to engineering or other pressures.

3.1 IDENTIFICATION OF GEOMORPHIC SUB-REACHES

Definition of channel sub-reaches based on geomorphic variables was important in order to achieve the aim of understanding physical process in relevant sections of the Dee system and thereby identifying the pressures impacting on this. The river and associated tributaries were divided into sub-reaches at significant geomorphic boundaries, examples of which included tributary confluences, changes in valley slope or changes in the degree of lateral constriction/ valley width. These boundaries indicate points at which there is likely to be a change in geomorphic process and the sub-reaches generated therefore represent logical sections within which to undertake subsequent geomorphic analysis and identification of system pressures.

Sub-reach boundaries were identified using all available, relevant information, including the fluvial audit data, maps and aerial photographs. Sub-reaches were between 48 m and 2594 m in length, with a mean length of 570 m; 31 sub-reaches were identified in total (**Figure 3.1**). The number and lengths of sub-reaches were determined to be at a spatial scale that allowed appropriate interpretation and resolution of geomorphic variables for the objectives of the project, while being manageable in terms of the data analysis process.

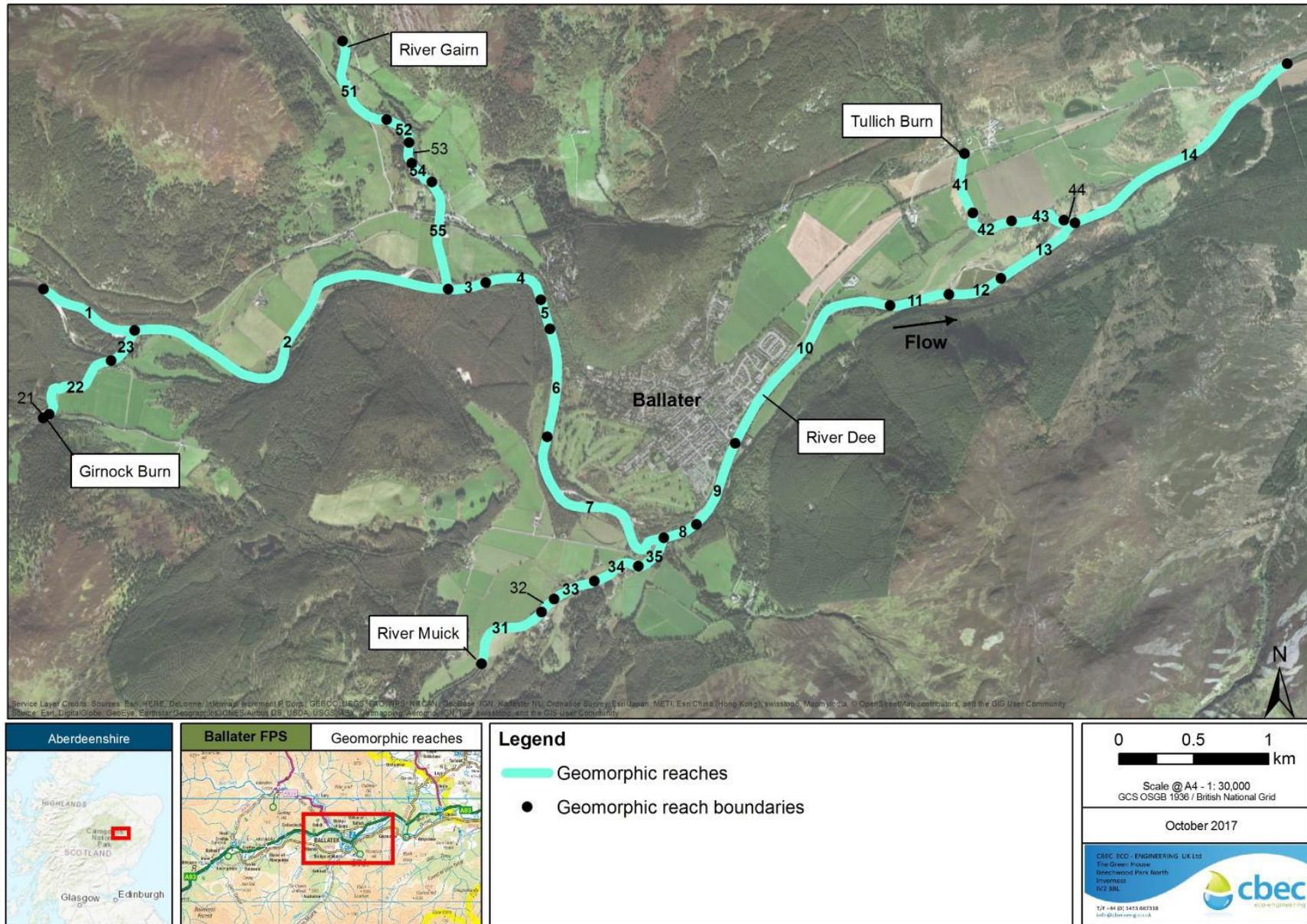


Figure 3.1 Delineated geomorphic sub-reaches.

3.2 SPECIFIC STREAM POWER ASSESSMENT

Specific stream power (SSP) is the unit rate at which energy is applied to the bed of a river and is closely related to processes of dynamic channel behaviour (including lateral migration and avulsion of the channel) and sediment transport regime. It is defined as:

$$\omega = \frac{\rho \cdot g \cdot S \cdot Q_{bf}}{w}$$

where ρ is the density of water, g is gravitational acceleration, S is slope (typically indexed to channel bed or water surface slope), Q_{bf} is bankfull discharge (typically indexed to the 2-year return interval flow) and w is bankfull channel width. Analysis of specific stream power provides a quantitative measure of the geomorphic energy regime of the identified sub-reaches which, together with sediment input and storage, is an important element of the physical process model.

Calculation of specific stream power at a given location relies on information on channel slope, bankfull channel width and bankfull discharge. Bankfull discharge was taken from SEPA's existing stream power dataset, available at 50 m centres along each water body. This data was checked, and for any point with an obvious discrepancy or no attached information, a value was calculated based on the mean of the points immediately upstream and downstream of that point. Slope was calculated based on elevations taken from 2016 LiDAR data for most sub-reaches. Where recent LiDAR was not available (i.e. the upper surveyed extents of tributaries), previous 2011 LiDAR was used instead. Bankfull width was taken from SEPAs stream power layer, with any missing width values measured directly from available aerial imagery².

The specific stream power values calculated for each sub-reach are shown in map format in **Figure 3.2** and plotted as specific stream power vs. distance downstream in **Figure 3.3**.

Specific stream power shows moderate variations through the study area. On the mainstem Dee, the highest sub-reach specific stream power, 593.6 Wm^{-2} , was found downstream of the River Gairn confluence. This high stream power was a result of the increase in discharge coming from the River Gairn, together with an increase in channel slope and significant increase in confinement as the channel enters an area dominated by bedrock channel boundaries. A stream power of this magnitude is typically found in steep, high energy rivers with confined channels, cobble/gravel bed material and high sediment transport capacity (Nanson and Croke, 1992).

With the exception of sub-reach 11, specific stream power values of between 192.0 and 405.8 Wm^{-2} were calculated for all remaining sub-reaches of the surveyed extent of the River Dee. These values of specific stream power are characteristic of medium-high energy, gravel bed channels (Nanson and Croke, 1992). Whilst difficult to ascertain with confidence over the limited extents of the study area, specific stream power on the mainstem Dee showed a generally decreasing trend with distance downstream, relating to general trends in valley slope. In sub-reach 11, a specific stream power value of 19.6 Wm^{-2} is observed, this typically falling within a range associated with low-medium energy,

² it is acknowledged that there are likely to be some inaccuracies associated with the values extracted from the dataset (as would be expected with this type of spatially derived data). A number of spot checks were performed at random, with error margins at those locations found to be <5 m. This was assumed to be within acceptable levels of error, particularly as the determination of bankfull channel width can be subjective.

laterally migrating, meandering rivers (sand-bed at lower specific stream powers, gravel-bed at higher values) (Nanson and Croke, 1992). This is a result of a combination of increasing channel width with distance downstream and minor slope (dominant morphological units within this sub-reach are pool and glide).

The four tributaries included within the study display varying patterns of specific stream power. Sub-reach 54 on the River Gairn displayed the highest value of specific stream power recorded during the surveys, of 1019 Wm^{-2} . This reflects a confined, high gradient sub-reach dominated by bedrock, with a bedrock 'chute' through which flow is further constricted. Downstream, a reduction in specific stream power is observed due to a widening of the river corridor (sub-reach 55).

On both the Girnock and Tullich Burns, specific stream power generally reduces with distance downstream. As both burns approach their confluence with the Dee, specific stream power reduces significantly (both record values of $<100 \text{ Wm}^{-2}$ for the majority of their downstream extents, most likely attributable to backwater effect (as was observed during the fluvial audit).

These variations in specific stream power are useful indicators for areas of the catchment that are likely to exhibit dynamic channel behaviour, with information on sediment input and storage further explaining spatial variation in channel morphology and predicting areas sensitive to geomorphic change.

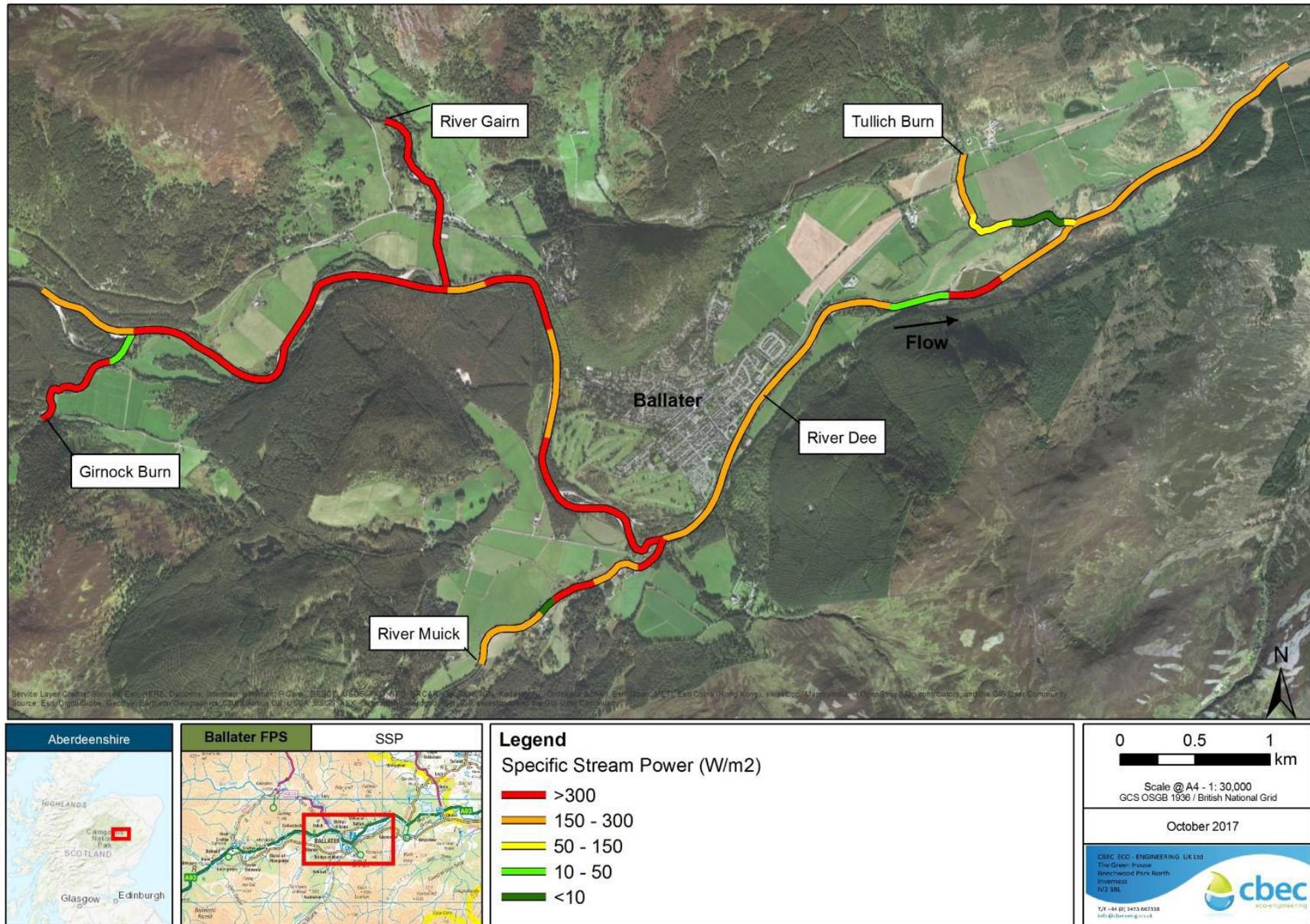


Figure 3.2 Specific Stream Power (SSP) by sub-reach.

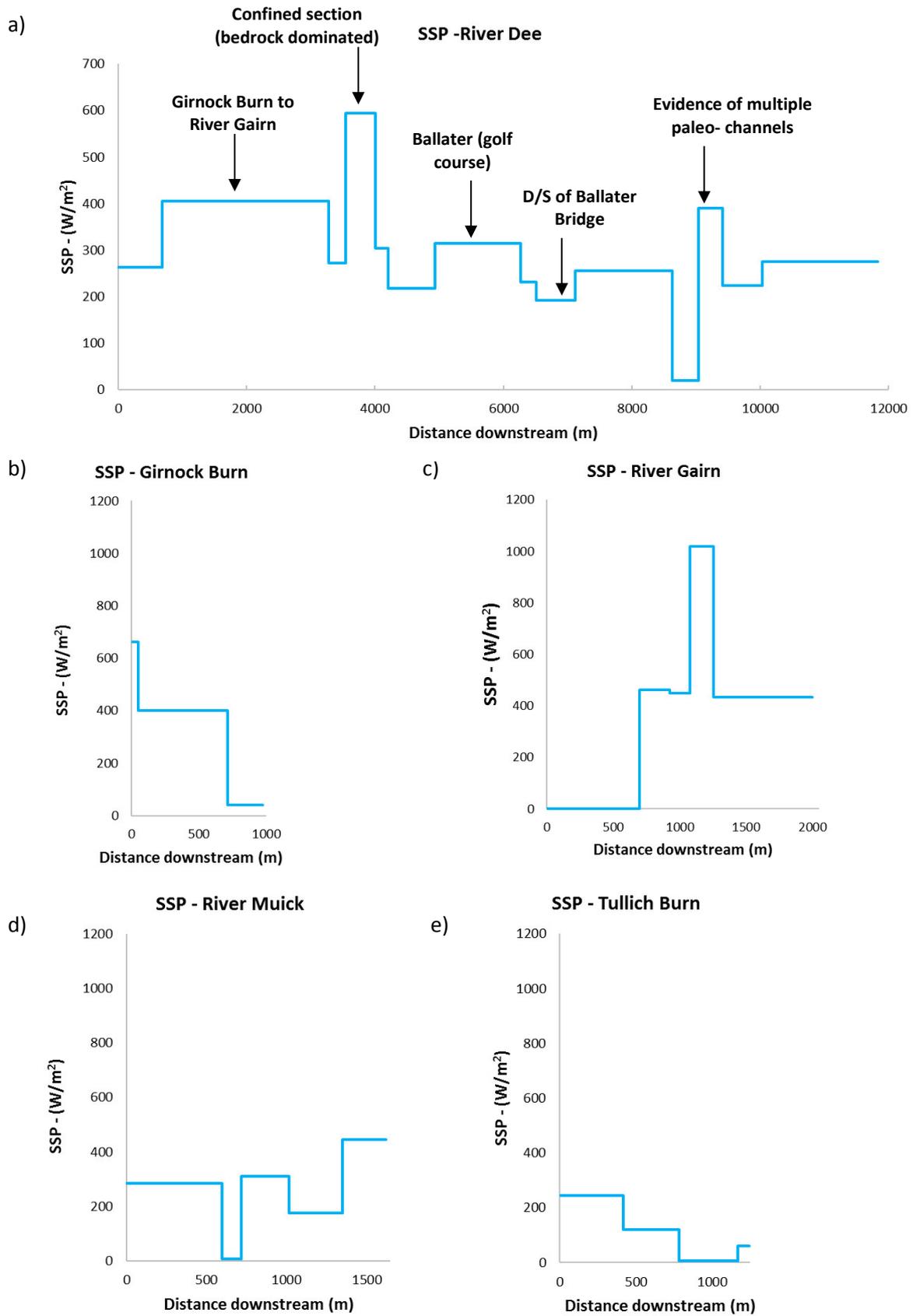


Figure 3.3 Downstream variation in specific stream power for a) River Dee, b) Girnock Burn, c) River Gairn, d) River Muick and e) Tullich Burn. (Note: Dee plot is shown on smaller index scale than tributaries)

b) Sediment input index

The volumetric rate of sediment input to a sub-reach, and the dominant size of this sediment, is important in determining how the energy of the flow (i.e. as indexed by specific stream power) is translated into geomorphic 'work' (i.e. dynamic channel behaviour) and the channel morphology that results. Sources of sediment input include bank/ terrace erosion and tributaries.

Absolute volumes of sediment input could not be determined with sufficient accuracy, given the scope and timeframe of the project. Therefore, relative levels of sediment input from bank erosion were estimated from the fluvial audit data, using a non-dimensional method of assessment. This allowed reaches to be compared with each other in terms of the level of sediment input. Incidences of bank/ terrace erosion were given a weighting based on the recorded severity of the erosion and the height of the bank (with scores for instances of severe bank erosion using a 1.5 multiplier). The weighting was then multiplied by the length of the feature. The Sediment Input index was then calculated by adding all the scores for individual erosional features and dividing these by the length of geomorphic sub-reach.

Given the minor amount of tributaries recorded as inputting moderate or major input, tributaries were only combined with erosion indices for the Dee mainstem. Values for each of the four main tributaries (Girnock Burn, River Gairn, River Muick and Tullich Burn) were calculated based on the average sub-reach sediment input index score. These scores were then added to the sediment input index to provide a quantitative means for measuring sediment input.

The sediment input index calculated for each sub-reach is shown in map format in **Figure 3.4** and plotted as Sediment input index vs. distance downstream in **Figure 3.5**.

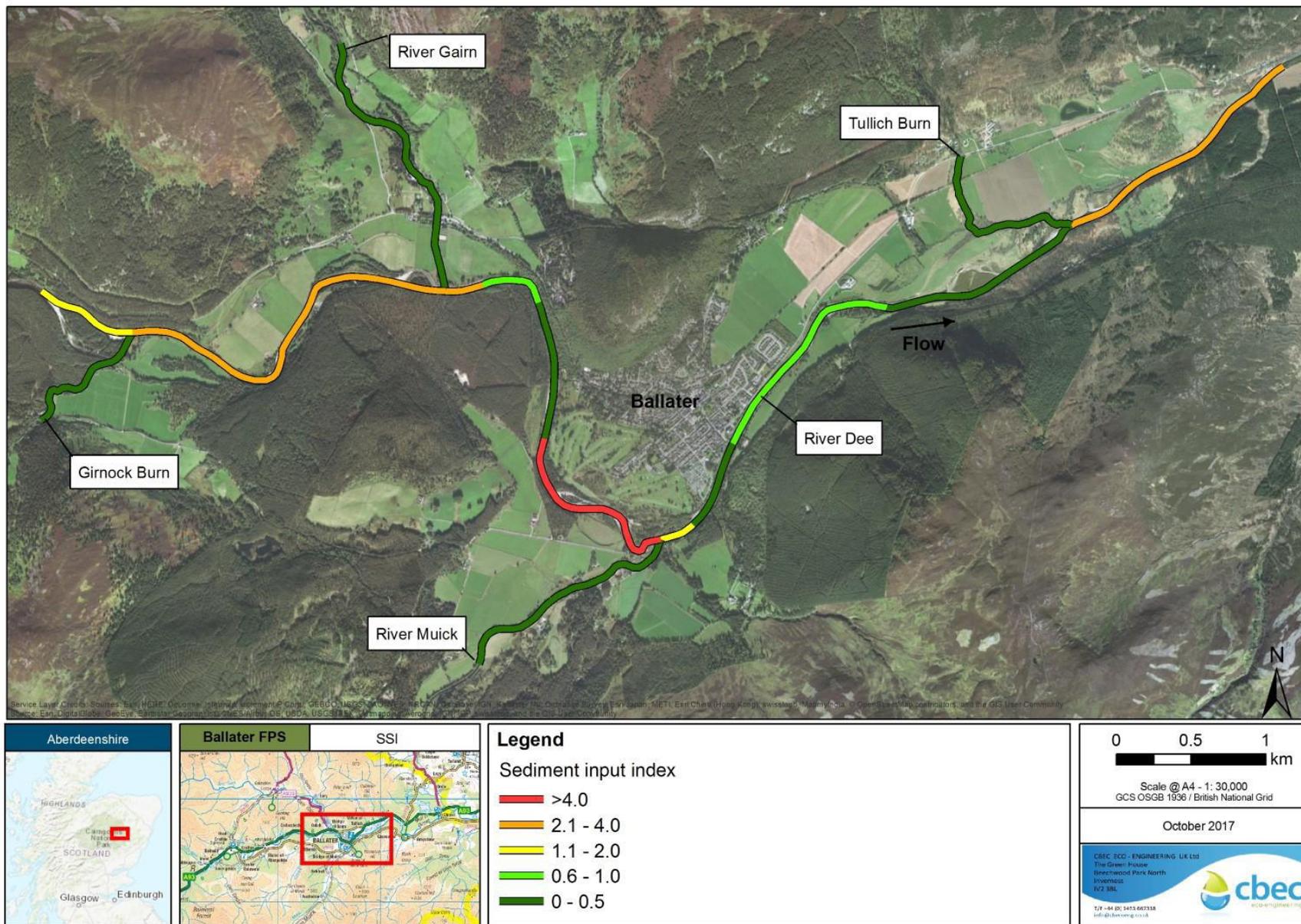


Figure 3.4 Sediment input index by sub-reach.

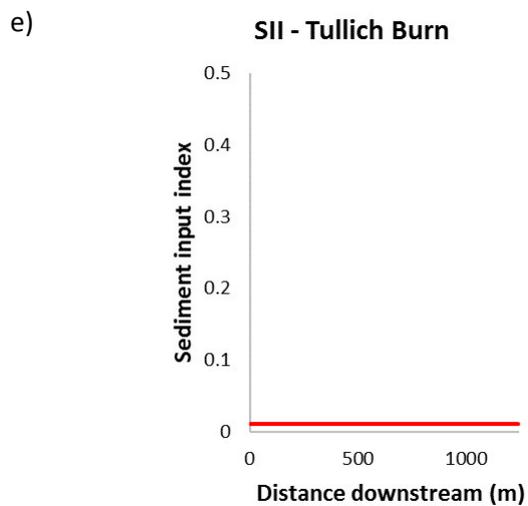
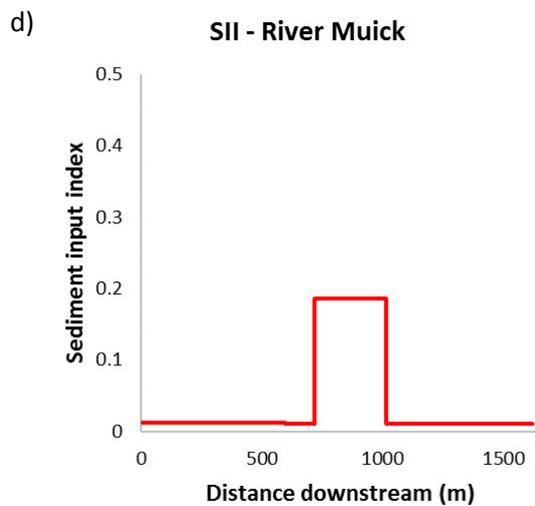
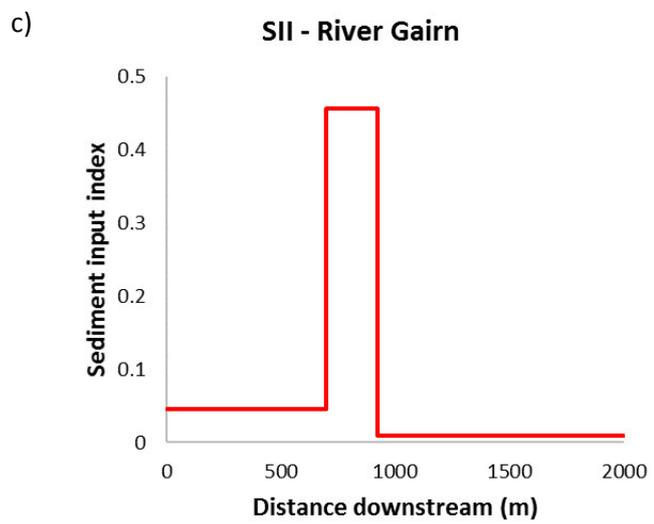
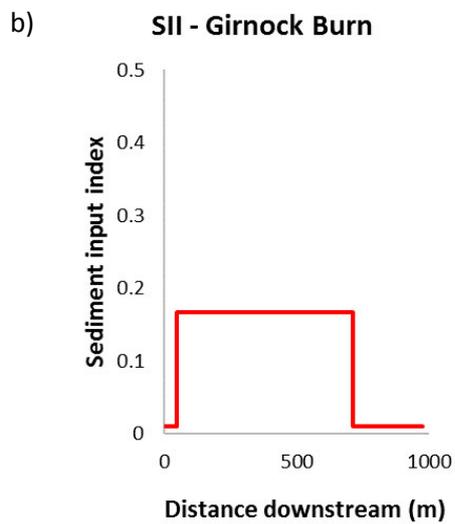
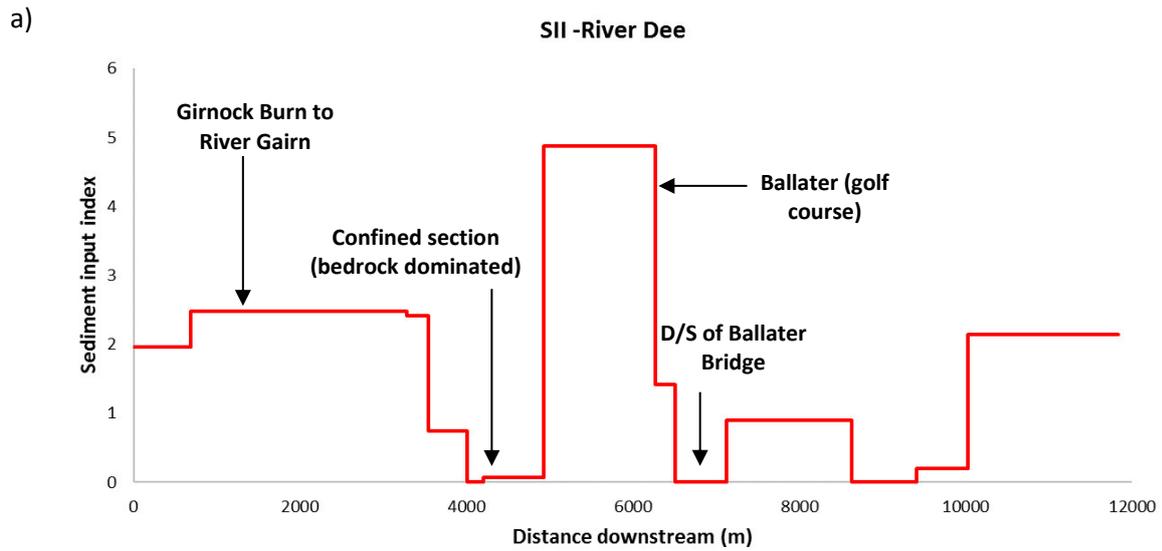


Figure 3.5 Downstream variation in sediment supply for a) River Dee, b) Girnock Burn, c) River Gairn, d) River Muick and e) Tullich Burn. (Note: Dee plot is shown on larger index scale than tributaries)

3.3 SEDIMENT STORAGE INDEX

For the purposes of this assessment, the term 'storage' refers to localised deposition that results in transient storage of alluvial material, that is transported through the system in flood events, replaced by new material from upstream. In this way the depositional features are stable; they are made up of different individual clasts between floods but their form remains relatively consistent (if the channel is in some form of dynamic equilibrium and not systematically aggrading/ eroding).

Data relating to depositional sedimentary features were collected during the fluvial audit. Using GIS, a total area of deposition was then summed for each geomorphic sub-reach³. The total was then divided by sub-reach length to give an index of sediment storage (in m^2m^{-1}). The sediment storage index calculated for each sub-reach is shown in map format in **Figure 3.6**, while sediment storage index vs. distance downstream is shown in **Figure 3.7**.

Key areas of deposition within the study area are sub-reach 1 (the upstream extent of the mainstem Dee), sub-reaches 6 and 7 (adjacent to Ballater golf course), and sub-reach 10 (immediately downstream of the Royal Bridge in Ballater). Each of these mainstem sub-reaches consist of significant alluvial bar features (a combination of lateral, transverse and point).

Compared to the depositional areas on the River Dee, the associated tributaries each recorded minor levels of sediment storage. That said, small gravel and/ or cobble bar features were evident in certain stretches of the Girnock Burn, River Muick and Tullich Burn. The River Gairn deposited sediment was coarser in nature and, whilst some flood deposition (specifically cobble and boulder-sized material) was evident during the field surveys, there was generally only minor evidence of well-formed alluvial bar features (owing to the gradient of the channel throughout).

³ It should be noted that this analysis does not provide an absolute volume of sediment storage, but an area, which is taken to be representative of the level of sediment storage.

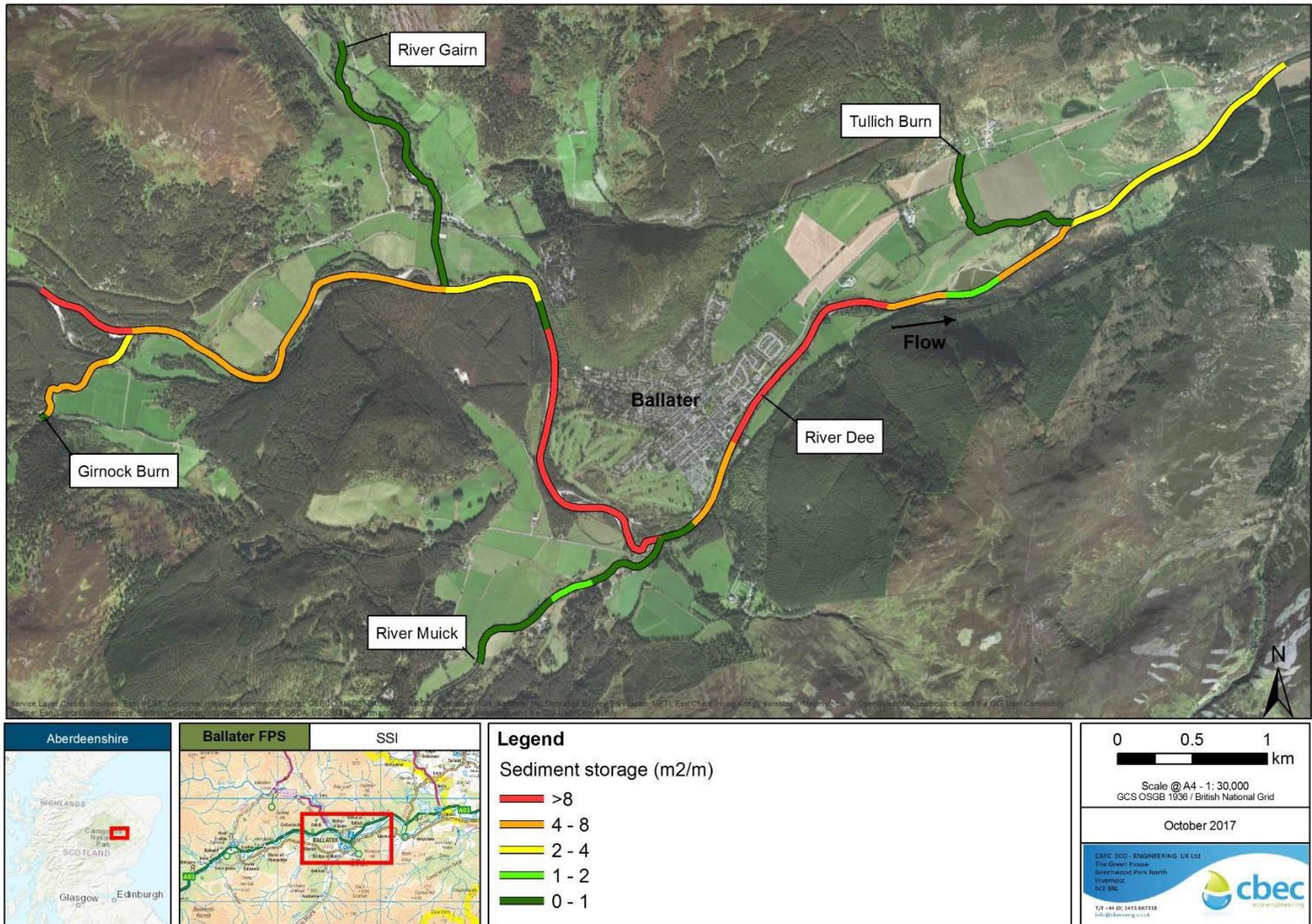


Figure 3.6 Sediment storage index by sub-reach.

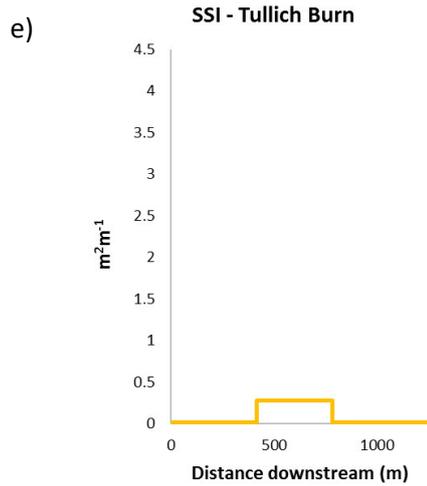
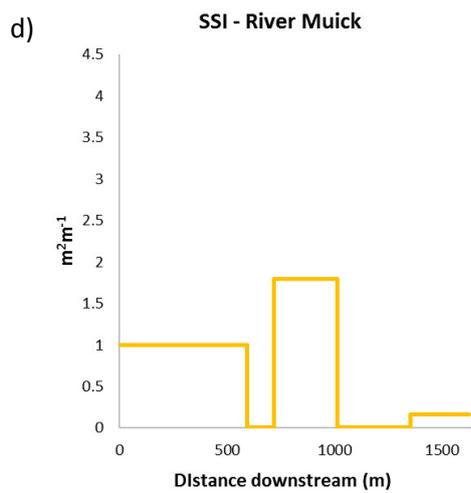
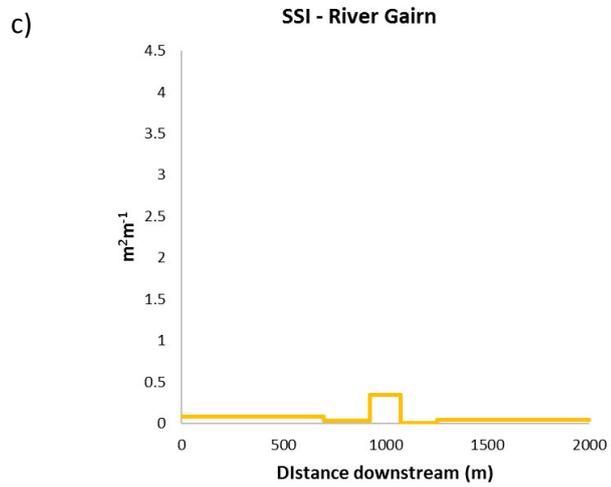
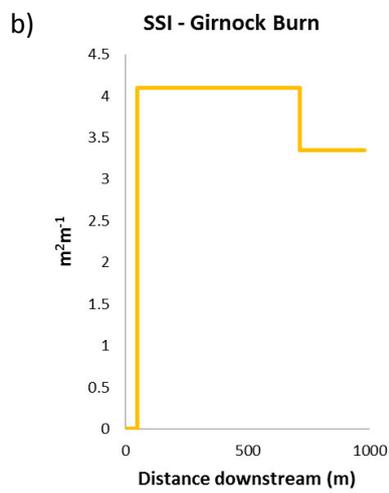
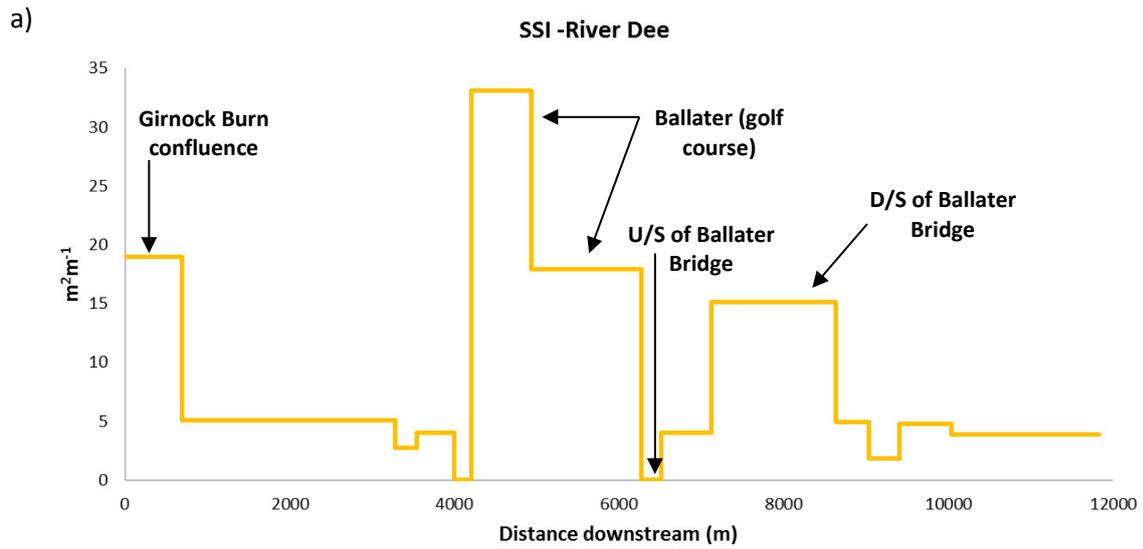


Figure 3.7 Downstream variation in sediment storage for a) River Dee, b) Girnock Burn, c) River Gairn, d) River Muick and e) Tullich Burn. (Note: Dee plot is shown on larger index scale than tributaries).

3.4 GEOMORPHIC PROCESS REGIME

The relationships between sediment input, sediment storage and specific stream power (SSP) define the dominant geomorphic process in a given sub-reach, whether the reach is a zone of net sediment supply, transfer or storage, and, by association, its likely rate of morphological adjustment. The downstream variation in sediment storage was explored in relation to sediment input and specific stream power, using the combined plots (**Figure 3.8**), to gain an understanding of the geomorphic process regime throughout the system. The plots show varying relationships between the three variables, reflecting the changing balance between sediment input, transport and storage with distance downstream.

Within the upper study sub-reaches of the Dee mainstem, storage and supply are dominant processes, scoring a high geomorphic process intensity. As evident in the field, sub-reach 1 is a dynamic reach, with the river forming multiple channels threaded through a large area of deposition immediately upstream and adjacent to the Girnock Burn confluence. The widening of the river corridor in this reach, coupled with a moderate specific stream power, allows sediment to be deposited in the descending limb of flood hydrographs. Storage is a key process here; minor evidence of stabilisation of these features means that these deposits are likely to represent temporary stores that are reworked and moved downstream during extreme flood events.

Downstream of the confluence (sub-reach 2), the river re-forms a single thread channel, with increased transport capacity reducing the rate of deposition and encouraging erosional processes. As a result, bank/ river terrace erosion throughout this reach is extensive and in places, particularly severe (i.e. on alternating banks upstream of Polhillock Bridge).

Further downstream in sub-reaches 6 and 7 (adjacent to Ballater Golf Course), the river alternates between high levels of sediment storage with minimal input (sub-reach 6), to significant input and storage (sub-reach 7). This is particularly severe along the Red Brae bank, where scour is leading to the failure of an extensive length of high alluvial river terrace. Deposition is also extensive throughout this sub-reach, explained by a combination of upstream/ within reach supply and increased channel sinuosity and resulting alternation of thalweg. A high specific stream power value of 314 Wm^{-2} within this reach, as shown in **Figure 3.8 c**), indicates that this sediment is likely to be subject to reworking during floods, making this section of the channel highly dynamic.

High levels of sediment input from sub-reach 7, coupled with the reduction in sinuosity and stabilisation of banks through sub-reaches 8 and 9, allow for efficient transfer of material. Downstream of Ballater bridge (sub-reach 10), storage has been calculated as the dominant process. Again, it is important to note that this refers to temporary deposition, and that this is likely to be transported downstream during flood events, often being replaced by new material supplied from upstream. In this reach, this is manifested as extensive cobble-dominated lateral and point bars. Increased bar deposition further downstream in this reach has the potential to encourage lateral hydraulic process and, thereby, channel migration through active meandering. Evidence of such behaviour was evident within the downstream extents of this reach during the fluvial audit. Here, hard bank protection lined the left bank $\sim 1.1 \text{ km}$ downstream of the bridge, with an aim of mitigating against the recent bank failure, and preventing lateral migration into the left bank floodplain adjacent to the sewage works (OS NGR NO 37981 96631).

Towards the end of the River Dee mainstem surveyed extent (sub-reach 14), an increase in sediment input (mainly from increased bank erosion, as well as minor input from the Tullich Burn, coincides with a relatively high specific stream power, and a subsequent decrease in sediment storage (**Figure 3.8**).

Within each of the surveyed tributaries, sediment storage and sediment input remain at comparatively low levels, reflecting the relatively high transport capacity resulting from increased specific stream power in this steep and confined section.

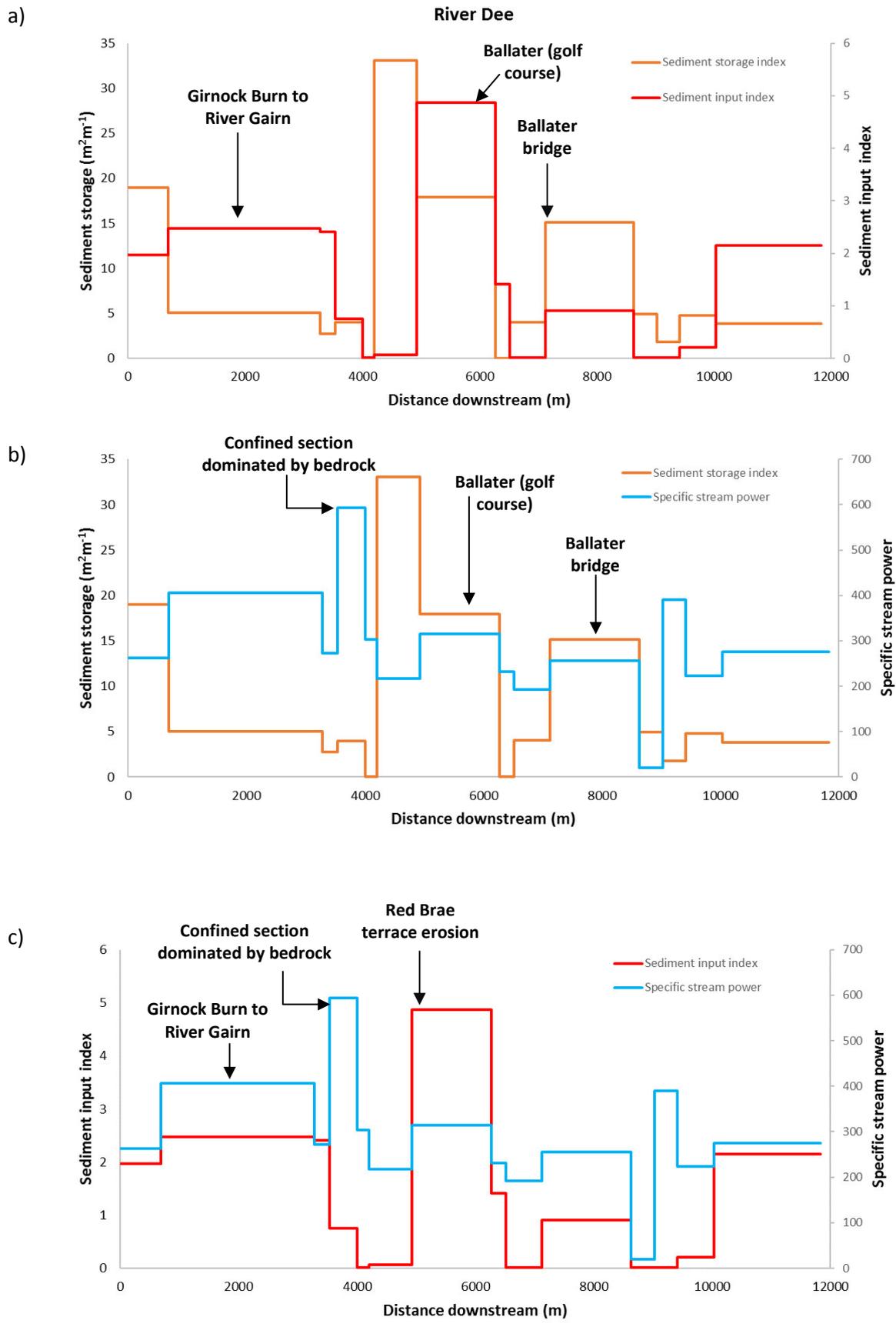


Figure 3.8 River Dee spatial patterns of a) sediment storage and sediment input b) sediment storage and specific stream power, and c) sediment input and specific stream power.

3.5 GPM SUMMARY

The product of specific stream power, sediment input index and sediment storage index (i.e. $SSP \times SSI$) was calculated for each sub-reach, to provide a measure of 'geomorphic process intensity'⁴.

Geomorphic behaviour was simplified to three processes: sediment transport, sediment supply and sediment storage, with the intensity of each process taken to be represented by specific stream power, sediment input index and sediment storage index, respectively. The dominant geomorphic process in each sub-reach was derived from the relative magnitudes of these three values. The values within each index were normalised (to make them comparable with each other) by dividing by the mean index value across all sub-reaches. In each sub-reach, the index with the highest normalised value was then taken to indicate the dominant process.

The dominant geomorphic process and the geomorphic process intensity together provide a semi-quantitative description of the nature of geomorphic behaviour across the River Dee system. This is depicted in map form in **Figure 3.9**, which indicates zones of sediment supply, transfer and storage, together with the degree of channel dynamic behaviour or stability (i.e. geomorphic process intensity).

The upper extents of the surveyed Dee mainstem around the Girnock Burn tributary are storage dominated, transitioning to supply dominated moving downstream and on approach to Polhillock bridge. From the River Gairn confluence, this shifts to transport dominated morphologies as the channel narrows as a result of natural confinement. Within the central Dee sections, extensive cobble/gravel bar features exist. However, sediment supply dominates physical processes at this location (**Figure 3.9**), owing to the erodible nature of the alluvial river terrace deposits dominating the superficial geology. Further downstream, the river banks become more stable due to well established/mature vegetation riparian cover. As the river flows under Ballater bridge, storage once again appears dominant, with large lateral and transverse bar features prevalent in the active corridor. This continues past the sewage works on the left bank, before stabilising. Towards the end of the surveyed mainstem (downstream of the Tullich Burn confluence), an increase in sediment supply and stream power leads to corresponding reduction in sediment storage. As expected, the four main tributaries surveyed are dominated by sediment transport processes, which, with relatively low geomorphic process intensity scores, suggests that these lower reaches are moderately stable.

Geomorphic process intensity, or dynamic behaviour, provides an indication of the likely sensitivity of the system to change (e.g. during a large-scale flood event), as well as the sensitivity of the system to modifications. Engineering or land use modifications on dynamic reaches are likely to have a greater impact on geomorphology than those on less dynamic, more stable sub-reaches, because of the greater propensity of the channel to react in the more dynamic reaches. The level of dynamic behaviour of each sub-reach is, therefore, an important factor in determining its restoration priority, in conjunction with the degree of engineering and land use pressures, as described below. In addition, understanding of the dominant process in a reach is important for assessing the likely impacts of engineering and land use pressures, as well as determining the geomorphic response to restoration interventions and allowing suitable restoration options to be developed.

⁴ A previous study by cbec on the River Till (River Till River Restoration Strategy, 2012) found GPI to relate well to the degree of historic channel movement, having a log-linear relationship with an R-squared value of 0.89 (where an R-squared value of 1 would indicate a perfect relationship), and was therefore considered to be a good indication of channel dynamic behaviour.

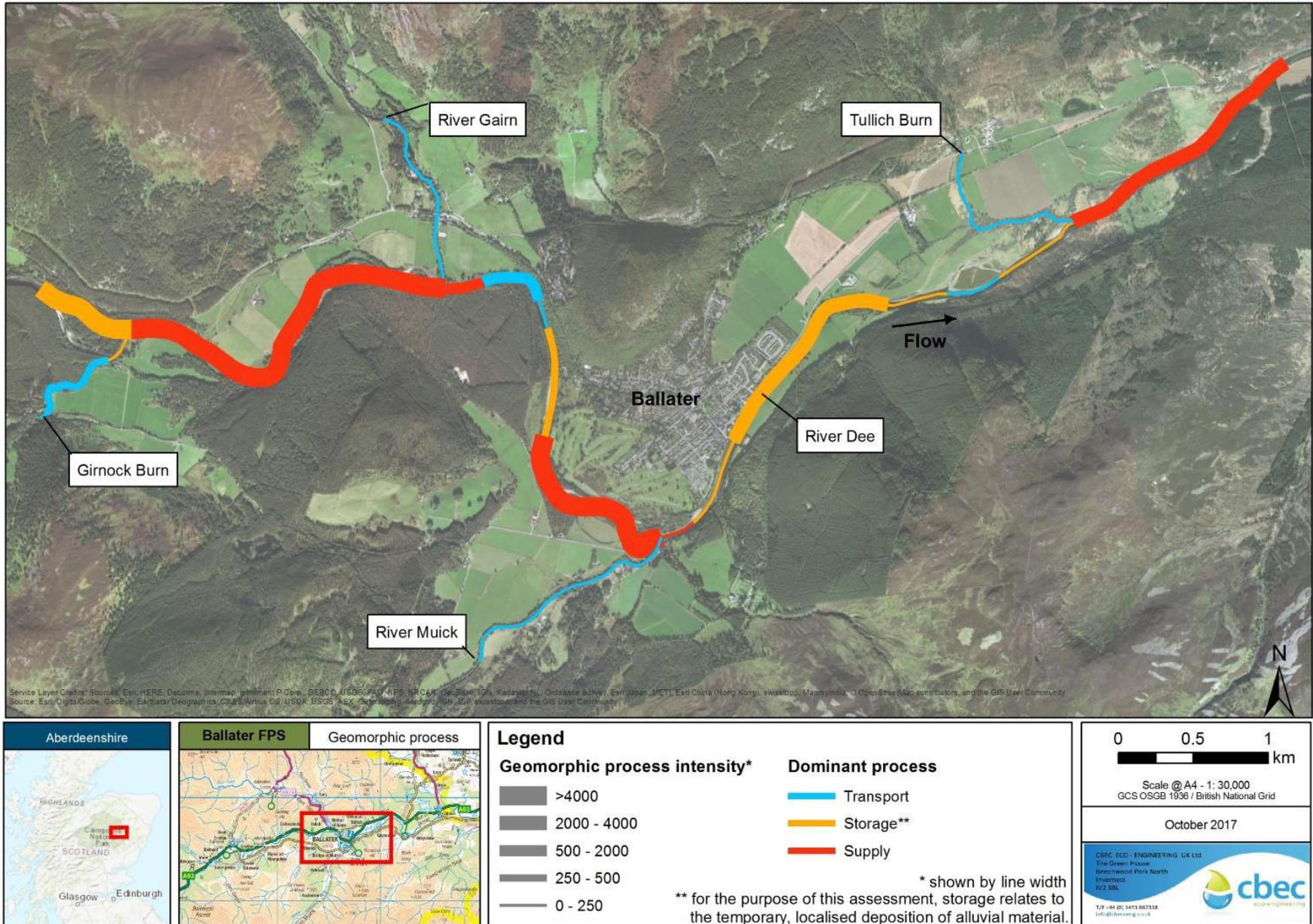


Figure 3.9 Geomorphic process regime

4. ASSESSMENT OF POTENTIAL IMPACTS TO/ FROM PROPOSED FLOOD PROTECTION MEASURES

Outputs from the geomorphic process model, partnered with the results of the fluvial audit and desk-based assessments, have highlighted a number of characteristics of the main-stem River Dee's geomorphic regime that are considered relevant to the development of flood protection options at Ballater.

Namely:

- Storm Frank is likely to have temporarily lowered thresholds for geomorphic change in a number of key locations in the River Dee upstream of Ballater Bridge (Girnock Burn confluence, River Gairn confluence and vicinity of Ballater golf course);
- Availability of sediment to be transported downstream has significantly increased in association with destabilisation of banks and historic depositional features. In addition, the presence of recent, unstable deposits associated with Storm Frank's sediment 'pulse' is further contributing to this temporary increase in sediment available for transport at relatively low flood events;
- Reaches upstream of Ballater are deemed to possess sufficient stream power to efficiently transport coarse sediment during flood events to the reaches immediately adjacent to Ballater;
- Analysis undertaken for this report and separate assessment undertaken by SEPA (2017) suggests that the Red Brae and surrounding area remains net erosional. However, future monitoring/ modelling is recommended as a more quantitative means of understanding the implications of the continued erosion and associated deposition within this area;
- Lowering of thresholds for geomorphic change is likely to result in frequent adjustment of channel form in the vicinity of the River Muick confluence, even at relatively small flood events. Importantly, this section of the River Dee has the highest score in Geomorphic Process Intensity (GPI) calculations within the study area, further supporting the hypothesis that significant geomorphic adjustment can be expected under the current configuration of the Dee's geomorphic regime;
- The Geomorphic Process Model has identified the reach immediately downstream of Ballater Bridge as 'storage dominant'. However, the lack of stabilising/ stabilised bars here coupled with the fact that stream power does not directly account for roughness, suggests that this straight stretch of the river is likely to be relatively efficient (for a given slope) compared to other more sinuous sections. Given that there is some uncertainty here, there is value in further higher resolution assessment with morphodynamic modelling.

As a result of the understanding of geomorphic regime brought about by the above assessments, the following scenarios for geomorphic evolution of channel form are considered sufficiently probable to merit inclusion in the development of flood protection measures at Ballater:

- The increase in availability of transportable sediment upstream of Ballater, coupled with the capacity for efficient sediment transport has the potential to deliver new sediment pulses to the section between Ballater golf course and the confluence with the River Muick, influencing the rates of geomorphic adjustment during subsequent flood events;
- The geomorphic instability observed for the reach in the vicinity of the confluence with the River Muick is likely to temporarily increase rates of supply to downstream reaches. As stated above, there is some doubt over the dominant process within the stretch downstream of

Ballater Bridge. Therefore it is advised that morphodynamic modelling be undertaken, incorporating this reach with sufficient resolution to resolve the influence of such depositional features.

4.1.1. Additional recommendations

While the set-bank embankments and flood wall extensions being proposed are considered unlikely to significantly effect the geomorphic processes regulating the evolution of channel form in the vicinity of Ballater, their effectiveness is deemed to be highly dependent on how well they align with the expected evolution of the main-stem River Dee channel (particularly considering the significant disturbance brought about by the Storm Frank event).

With that objective in mind, the following proposals are advanced for discussion with project partners and potential inclusion in the final version of the flood protection measures:

- Given the observed and predicted future geomorphic instability in the vicinity of Ballater, developing hydraulic models to assess flood risk based solely on the current channel configuration is deemed to possess limited value. Given the high rates of erosion and deposition experienced between the vicinity of Ballater golf course and the confluence with the River Muick (as well as the potential for the future delivery of sediment pulses from upstream reaches), current channel geometry is likely to vary significantly following moderate and large flood events. Therefore, a morphodynamic modelling approach incorporating a mobile bed is recommended as the most accurate methodology available to assess the evolution of channel form and more accurately predict how this will likely influence the frequency and patterns of flooding at Ballater.
- The 90° embankment present in the left bank upstream of the confluence with the River Muick, is deemed to potentially result in an increase in water levels in the vicinity of Ballater golf course. While connectivity with the floodplain is currently limited at this location by the presence of the embankment, both cbec and SEPA have recorded instances of recent erosion of fluvial deposits along the left bank where the channel appears to tend towards reoccupying paleo-channels present in this section of floodplain. There is also potential opportunity to utilise a section of the opposite bank, in an area of former channel alignment. It is recommended that the option to formalise existing paleo-channels and investigate the right bank floodplain at this location is included for discussion during the development of the flood protection scheme (**Figure 4.1**). In broad terms, these high flow channels/ areas should be designed to inundate below bankfull flow and have sufficient capacity to mitigate flood risk immediately upstream of this area. However, the design of these channels should be carefully assessed using morphodynamic modelling tools to ensure their geometry minimises the risk of aggradation following flood events. Additionally, it is important to ensure that no significant increase in risk is posed to local infrastructure, or downstream areas such as Ballater bridge, through the increased flow capacity.

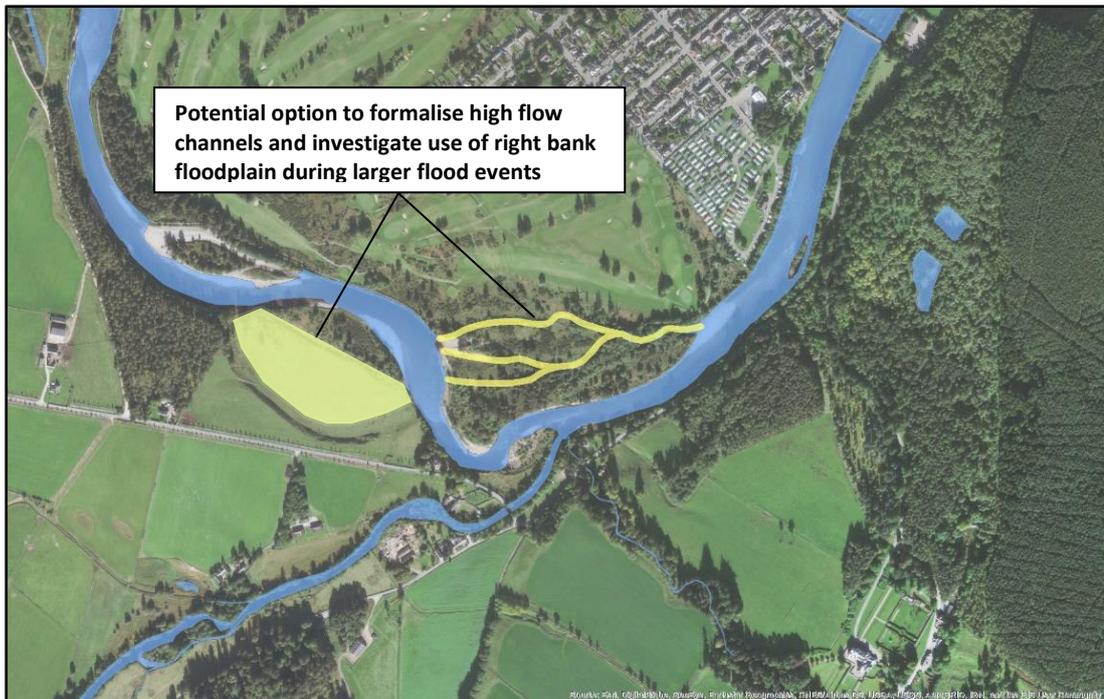


Figure 4.1 Indicative location of potential high flow/ partially reactivated paleo-channels

- An additional option to complement the proposed flood protection measures has been identified in the vicinity of the River Gairn confluence. Given the relatively high contribution of this waterbody to the hydrology of the Dee system (the River Gairn contributes with 22.24% to the total catchment area at the point of confluence), there may be a benefit to investigating options for desynchronising flood peaks by reconnecting sections of the floodplain (Figure 4.2). During the fluvial audit, a wide area of floodplain with no residential or commercial properties along the left bank has been identified. Promoting a hydrological study of duration and timing of flood peaks in both the Gairn and the Dee and utilising hydraulic modelling tools to investigate flood patterns, may highlight a potential option to install set-back embankments that retain flood water within this area. However, the feasibility and potential benefits of this measure can only be accurately assessed with further, detailed investigations.

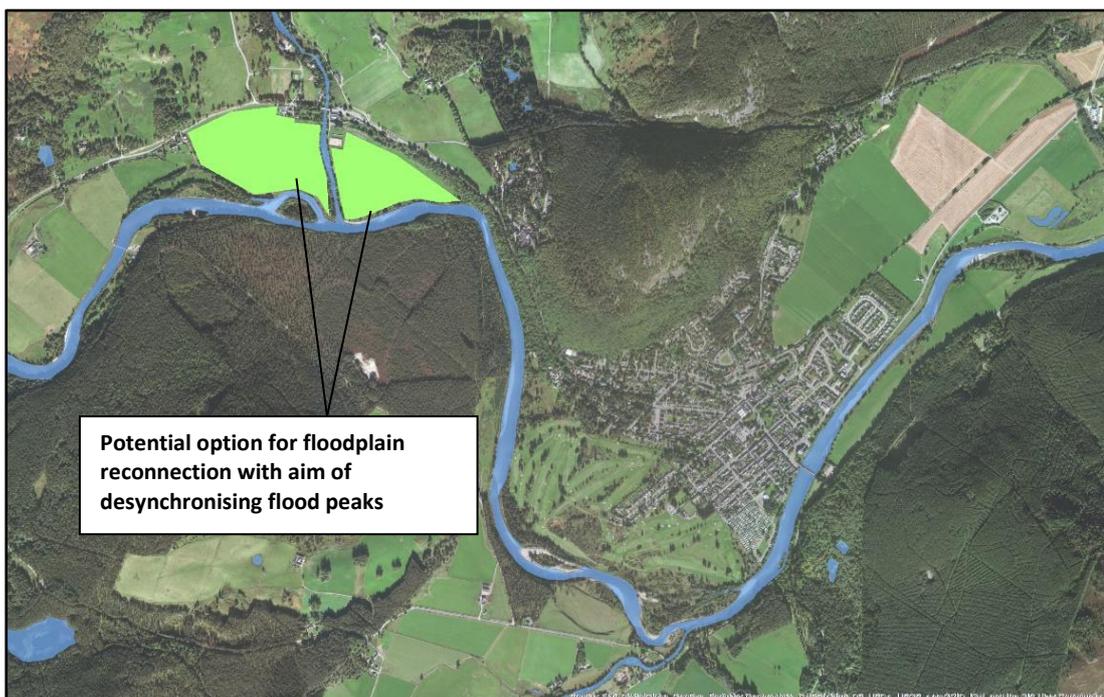


Figure 4.2 Indicative location of potential floodplain reconnection

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