SEPA
Scottish Environment Protection Agency
Buidheann Dìon Àrainneachd na h-Alba

Gravel Deposits and Flood Risk to Agricultural Land

SEPA would like to acknowledge the assistance of Andrew Bauer of NFUS, Mr & Mrs Anderson, John Christie, Roddy Kennedy, Robbie Laird, Jamie Williamson and Davie Winton in the preparation of this report.

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Executive Summary

Using three different sites across Scotland, SEPA has investigated the link between sediment deposits in the river channels and flood risk to adjacent agricultural land. The three sites were located on the River Feshie at the confluence with the River Spey, the River Tay near Ballinluig and the River Dee at Ballater.

Flooding of adjacent land occurs when the main river channel fills with water and spills out over the banks. There are a number of things which can have an effect on where and when this happens. The size of the channel is obviously important but things like channel slope, channel shape and what is happening upstream and downstream can all have an important role.

It is often assumed that removing areas of sediment (gravel and cobbles) which are exposed in rivers during normal flows will make the channel bigger and therefore less likely to spill out onto adjacent land. This is not always the case. For example, an area of exposed sediment may be located in a section of the river which is bigger than sections upstream or downstream. In this case it is the smaller sections upstream and downstream which determine where and when water spills out.

Artificial constraints on the river, such as bridges and embankments, can force the water level up more quickly during flood events than if they were not present and the water was able to spread out. This can cause backing up of flow at the constraint which may cause water to spill out upstream earlier than if the constraint was not present.

Rivers transport sediment as well as water. Sediment only moves during high flows. Some areas of exposed sediment will reduce in size during a flood event and then re-establish as the event recedes. It is often the wider sections of channel where sediment is deposited as a flood recedes because this is where the flow slows down first.

The movement of sediment through part of a river (also called a reach) can be defined in three ways:

- Erosional – where the amount of sediment leaving the reach is more than that coming into it
- Balanced – where the amount of sediment leaving the reach is about the same as that coming into it

- Depositional - where the amount of sediment leaving the reach is less than that coming into it

Discrete and sometimes very large areas of exposed sediment can occur in all three types.

In erosional reaches sediment deposits will almost always be found in the wider sections of channel. Removing the sediment deposits is therefore unlikely to reduce flood risk to adjacent land.

In balanced reaches it is common for deposition of sediment to be offset by erosion of the banks. In this way the river maintains of roughly constant size. Removing sediment may have a localised effect on flood risk to adjacent land however the river will normally re-adjust quickly to re-establish a similar channel to what previously existed. Excessive removal can de-stabilise the river causing unexpected erosion and deposition upstream and downstream.

In deposition reaches, particularly where they are constrained, sediment builds up in the channel and over time increases the frequency at which water spills out onto adjacent land.

It was found that the three sites chosen for this project each represented one of these categories.

The River Feshie site was found to be strongly depositional. This is naturally the case because there is a lot of sediment in the catchment upstream and the river has the power to erode and transport it to the downstream end. The change in channel slope as it meets the River Spey means that a lot of sediment stops at this point. It would naturally spread out at this point over a wide area. Historic straightening and embankments have constrained the river to a much smaller area but has not stopped deposition occurring at this site. This means that the channel quickly fills up with sediment. As it does this the channel becomes smaller and floodwater spills out onto the adjacent land more frequently. This is not helped by the fact that the channel is higher than the adjacent land in a lot of places. Removing the sediment from the channel is one way of reducing the flood risk to the adjacent land. Climate change is expected to result in more frequent higher flows which will result in more sediment being deposited so the burden of maintenance will increase with time. Removing sediment in this way would not make much difference to very large flood events which spill out further upstream. Other options for dealing with flood risk were identified including setting back of embankments to provide more space for the water and sediment to spread out or realigning the channel to lower ground.

The River Tay site was found to be balanced. It would naturally be slightly depositional but a number of changes within the catchment mean that it has changed to balanced in recent years. There has been both erosion and deposition within the reach in recent years. Overall the channel seems to have increased in size due to the increase in high flows over the last five years or so. Computer flood modelling was used to show that removing a large amount of sediment from this reach would have little or no effect on flooding of the adjacent agricultural land.

The River Dee site was found to be erosional. The nature of the upstream catchment means that the amount of sediment being transported into this reach is relatively low. The size of the catchment though means that there are still very high flows from time to time. This means that over time more sediment leaves the reach than comes in from upstream. Despite this sediment is deposited in parts of the reach as floods recede giving the impression of deposition. Computer modelling was used to show that removing a large amount of this sediment had no appreciable effect on flooding of adjacent land.

Based on these three example sites we can tentatively conclude that removal of sediment can be a valid option for managing flood risk to adjacent land where the reach is depositional in nature. This is particularly the case where the reach has been historically modified and constrained. However there are other valid options which should be considered and the long term costs and benefits of each option weighed up. Removal of sediment where a reach is either balanced or erosional is unlikely to result in appreciable and long lasting benefits for flood risk to adjacent land.

Introduction

There have been a number of large flood events across Scotland in recent years, including severe floods in December 2015 and January 2016. These events caused significant changes in many rivers across the country. One of the more obvious changes has been the erosion, transport and deposition of sediment in river channels.

In this report sediment is defined as any non-organic natural material moved by a river. Images of river sediment are shown in Figure 1 which includes:

- clay, silt and sand (particles less than 2mm in diameter);
- gravel (particles 2mm to 64mm in diameter i.e. up to tennis ball size);
- cobbles (particles 64mm to 256mm in diameter i.e. up to football size);
- boulders (particles larger than 256mm in diameter).

This report investigates the link between sediment deposits in river channels and flood risk to adjacent agricultural land. The investigation was undertaken by assessing three separate sites across Scotland. The sites were selected by the National Farmers Union of Scotland (NFUS). The assessments were carried out by Alasdair Matheson (Senior Hydromorphologist) and Fiona McLay (Senior Specialist Scientist (Hydrology)) from the Scottish Environment Protection Agency (SEPA). The assessments were peer reviewed by Professor Malcolm Newson, Chief Executive of River Catchment Services, who has over 40 years' experience in research and applications in hydrology and river processes.

The sites chosen by NFUS were:

- River Feshie at the confluence with the River Spey near Kincraig;
- River Tay downstream from the confluence with the River Tummel near Ballinluig;
- River Dee at Ballater.

In each case the NFUS identified the section of river where there were sediment deposits, the areas of adjacent agricultural land affected by flooding and the frequency of flooding. At all three sites the sediment of interest was coarse in size i.e. gravel, cobbles and small boulders.

Figure 1: Examples of river sediment. Top left is clay, silt and sand. Top right is sand and gravel. Bottom left is gravel and cobble. Bottom right is cobble and boulder (including that really big boulder mid picture!).

The purposes of the assessments were to identify:

- the significance or otherwise of sediment deposits at each location in relation to flooding of the areas of farmland identified;
- where sediment deposits are significant in relation to that flooding, the likely effectiveness of different management interventions, taking account of:
    - their sustainability;
    - any potentially serious consequences, including to wider flood risk.
- a general framework for ascertaining circumstances under which removing sediment deposits may be an appropriate and effective means of significantly reducing flooding of adjacent farmland, taking account of wider catchment implications including downstream flood risk.

Other issues, such as the role of sediment deposits in land drainage and river bank erosion were not within the scope of the assessments.

The assessment at each site consisted of a combination of field and desk based analysis. Initially meetings were held at each site with representatives of the affected agricultural land to understand the mechanism of flooding and the history of river management. The site visit was also used by the SEPA staff to record natural and artificial river features which would help explain river processes. Other sources of existing information such as historic mapping, aerial imagery, topographic surveys, geological mapping, river flow data and previous studies were also collated. This was all then used to build up a picture of river processes and the relevance of sediment deposits to flooding of adjacent agricultural land at each site. For the River Tay and River Dee sites new computer flood models were constructed and used to augment the conclusions.

The remainder of this report contains a section for each site with an overview of the relevant collated information, how this explains the river processes, and the conclusions which can be drawn from this regarding sediment deposits and flood risk.

Finally, the conclusions for each site were used to draw out some general principles relating to the role of sediment deposits in flooding. This is presented in the final section of the report.

River Feshie

Location

The River Feshie site is located just upstream from its confluence with the River Spey (Figure 2). Immediately upstream from this confluence the River Spey flows through Loch Insh. This loch prevents the downstream transport of coarse sediment in the River Spey. The assessment therefore focuses on coarse sediment transport and deposition in the River Feshie.

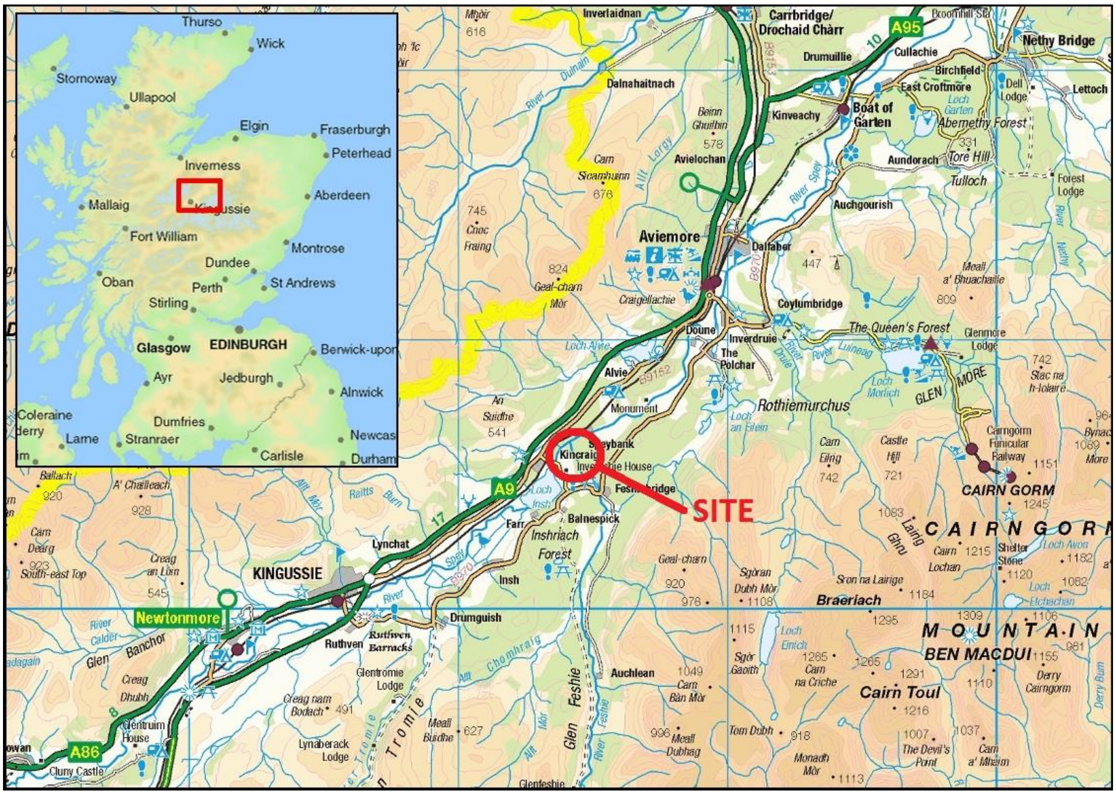

Figure 2: Location of River Feshie site.

The section of river channel where sediment deposits were identified and the areas of adjacent agricultural land affected by flooding are shown in Figure 3. On the site visit the land managers reported that this land flooded several times a year and that sediment deposition across the agricultural land added to the damage caused directly by the flood waters. We have therefore looked at the impact of the identified sediment deposits on flood events which occur several times a year.

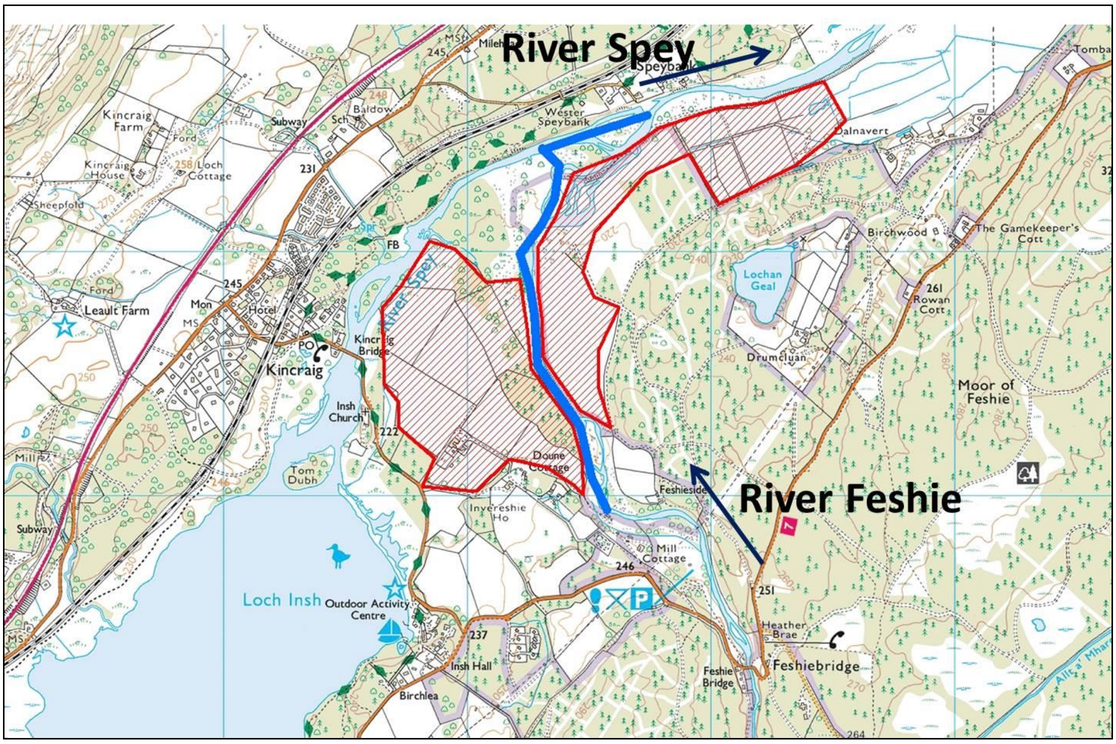

Figure 3: River Feshie site showing section with sediment deposits (blue line) and areas of adjacent agricultural land affected by flooding (red hatched).

Upstream Catchment

The main stem of the River Feshie is approximately 39km long. The source is high in the Cairngorm Mountains at an altitude of over 800m. It has a catchment area of approximately 230km^2. There are numerous tributaries joining the main stem along its length including four that are significant watercourses in their own right: the River Eidart in the upper catchment and the Allt Fhearnasdail, Allt Ruadh and Allt a Mharcaidh in the lower catchment.

Sediment sources

British Geological Society (BGS) mapping of superficial geology (i.e. consolidated sediment) within the catchment is shown in Figure 4. This shows that there are significant areas of sediment throughout the catchment which can be eroded and transported by watercourses passing through them.

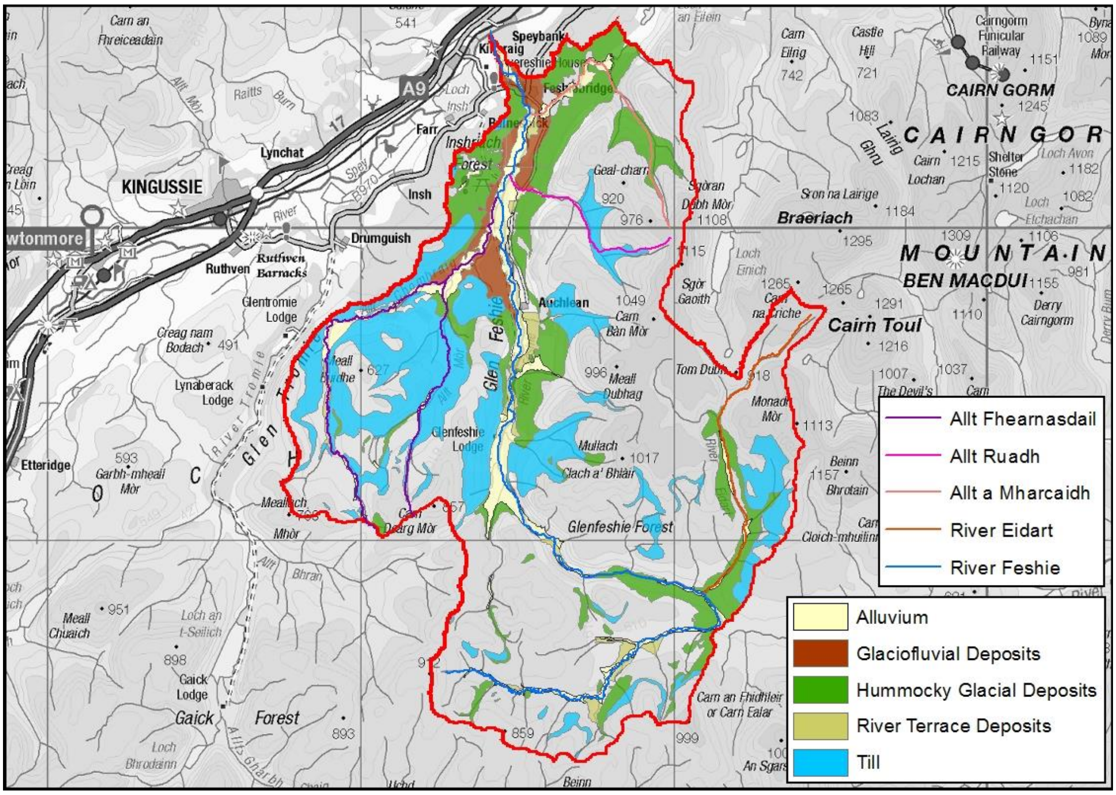

Figure 4: River Feshie catchment (outlined in red) showing superficial deposits. *©Crown copyright. All rights reserved. SEPA lic. no. 100016991. © British Geological Survey*

There are significant areas of alluvium and river terrace deposits both of which are sediments that have already been eroded, transported and deposited by the river from further up the catchment. The till, glaciofluvial and glacial deposits are sediments laid down by glaciers as they moved and retreated many years ago.

Channel slope

The slope of the river channel from its source to the confluence with the River Spey is shown in Figure 5.

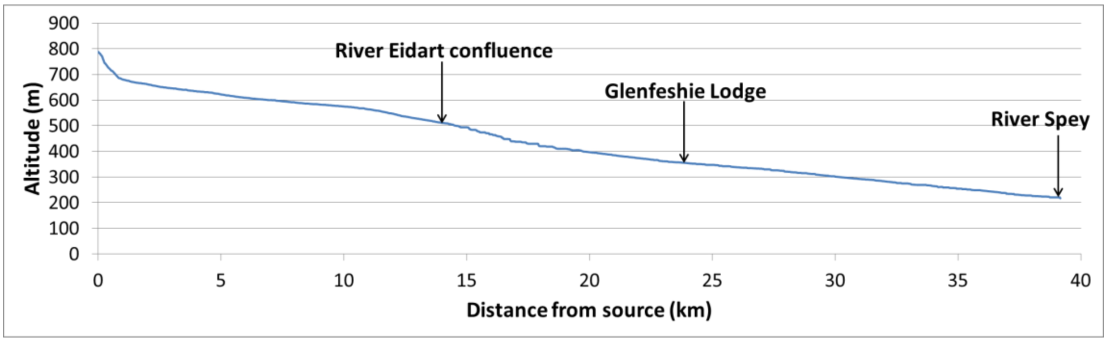

Figure 5: Slope of River Feshie from source to River Spey confluence.

This shows that, apart from a very steep section at the upstream end and a relatively short section between the River Eidart confluence and Glenfeshie Lodge, the river has a fairly constant slope. This is around 1 in 100 or 1% and is considered moderate/steep for a river.

A river derives its ability to erode and transport sediment through a combination of the volume of water and the slope. The mountainous catchment of the River Feshie means that there is frequent heavy rainfall and sometimes snowmelt. These can runoff quickly down the steep valley sides into the river. This means that the water level in the channel can rise quickly to high levels. In other words it is a "flashy" river.

The combination of high flows and moderate/steep slope mean that the River Feshie can erode and transport a lot of sediment all along its length. It has been estimated that on average 20,000 Tonnes[1] per year of sediment is carried along the river near the downstream end. That is about 4½ Olympic sized swimming pools worth sediment. This is quite exceptional for a Scottish river and as such the River Feshie is well-known and well-studied for the braided and wandering characteristics this creates (Figure 6).

It is notable that there is no clear significant change in channel slope at the downstream end of the river where it meets the River Spey.

Figure 6: Aerial image of a typical braided and wandering section of the River Feshie near Glenfeshie Lodge. Note the multiple channels and large areas of exposed sediment in the channel which show that frequent erosion, transport and deposition occurs. The active channel is up to 200m wide in places.

[1] Werritty, A & Brazier, V. 1991b. *Geomorphological aspects of the proposed Strathspey flood alleviation scheme*.

Historic flows

We have operated a river gauging station on the River Feshie at Feshie Bridge (approximately 2.5km upstream from the River Spey confluence) since 1993. Figure 7 shows the highest flow recorded each year since then. A simple linear trend line has been added to this chart which shows an upward trend. It is also notable that there have been two very high flows in the last three years.

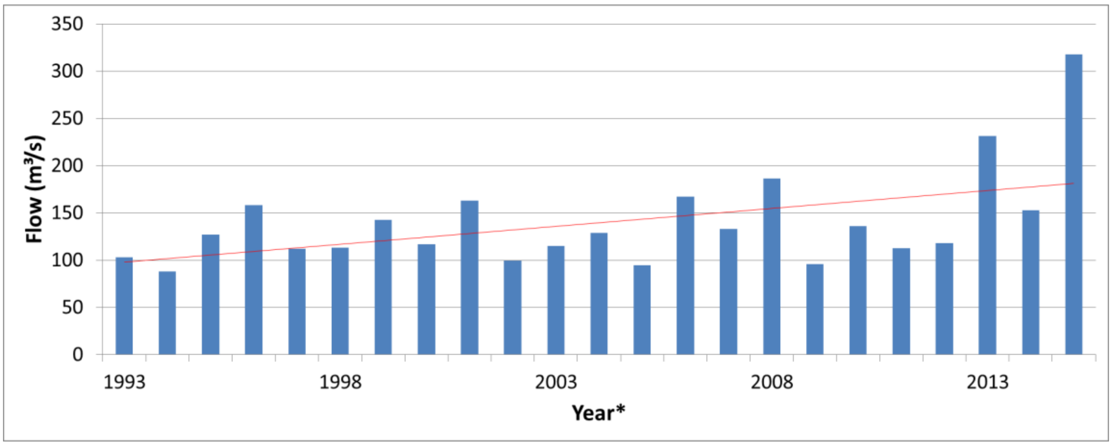

Figure 7: Highest flow recorded in each year since 1993 on the River Feshie at Feshie Bridge. *Hydrological year which runs from start of October to end of September.

Sediment is not transported along rivers constantly. Instead it moves like a jerky conveyor belt with movement only happening during higher flows. Research[2] suggests that the transport of coarse sediment starts to happen when the flow reaches somewhere around 80% of the flow which would fill a natural channel to the top of the bank[3]. It can be assumed that flow above this threshold value is a measure of the energy available to erode and transport sediment.

The sum of monthly maximum flows over this threshold in the last ten years is 60% higher than for the previous 14 years. This is a strong indication that there has been a significant increase in the energy available for sediment transport in the River Feshie in the last ten years compared to the previous 14 years when recording of flows started.

Human modifications

Compared to other Scottish rivers the River Feshie has been subject to relatively few human modifications such as channel realignment, bank reinforcement and

[2] Ryan, S.E., Porth, L.S., Troendle, C.A., 2002. *Defining phases of bedload transport using piecewise regression*. Earth Surface Processes and Landforms 27,971–990.

[3] 80% of bankfull flow or Qmed (1 in 2 year return period flow).

embankments. The main modification seems to be large scale deforestation of the catchment in the 19th century. McEwan[4] suggests that deforestation, particularly of the floodplains, increased the availability of sediment for erosion and transport. Evidence for this was seen in the increase in braiding of the river following the deforestation.

Summary

From the review of the catchment upstream from the site of interest we can conclude that:

- there is a lot of coarse sediment available for erosion and transport;
- the combination of slope and flow means that the River Feshie can erode and transport coarse sediment along its whole length;
- there has been a recent increase in flow and therefore sediment transport.

Reach of interest

Channel slope

Figure 8 shows the slope of the river channel between Feshie Bridge and a point on the River Spey approximately 1.8km downstream from the Feshie confluence. It is clear from this that there is a significant reduction in channel slope downstream from the confluence. It is also notable that the slope along the River Feshie upstream from the confluence is relatively constant. The implication of this is that the River Spey is likely to be less capable of transporting the sediment brought down by the River Feshie.

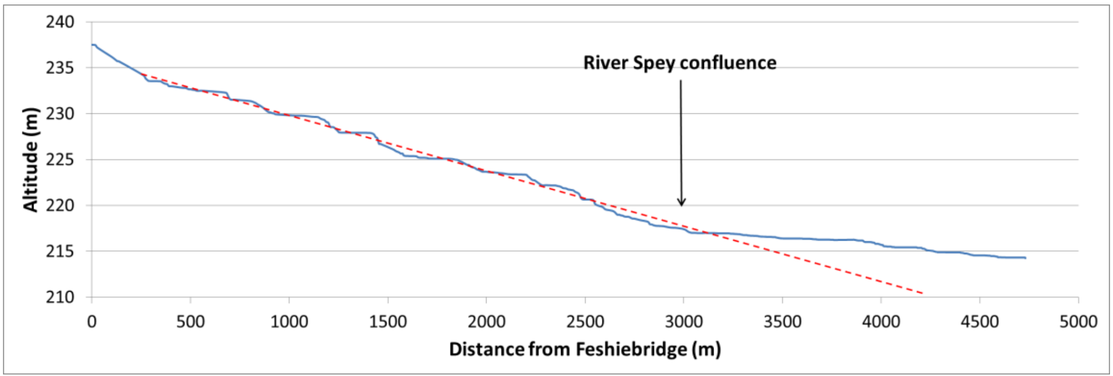

Figure 8: Slope of river channel from Feshie Bridge (solid blue line). Red dotted line has been added to show the relatively constant slope upstream from the River Spey confluence and the significant lowering of slope downstream.

[4] McEwan, L.J., *River channel planform changes in upland Scotland, with specific reference to climate fluctuation and landuse changes over the last 250 years*. 1985, University of St Andrews

This reduction in sediment transport at the confluence is not just a recent phenomenon. The landscape in this reach provides evidence that large scale deposition of sediment has happened here over a very long time period.

The River Feshie is a tributary of the larger River Spey. Tributaries which transport large volumes of sediment often create alluvial fan features where they meet the wide flat floodplain of the larger river. The reduction in slope causes large scale deposition of sediment. This deposition forces the channel to constantly change direction. Over time the sediment is spread out in a fan shape. The channel constantly moves back and forth over the fan depositing sediment as it goes and building up the fan into a cone shape. The point at which it starts to spread out is normally close to the edge of the valley of the larger river.

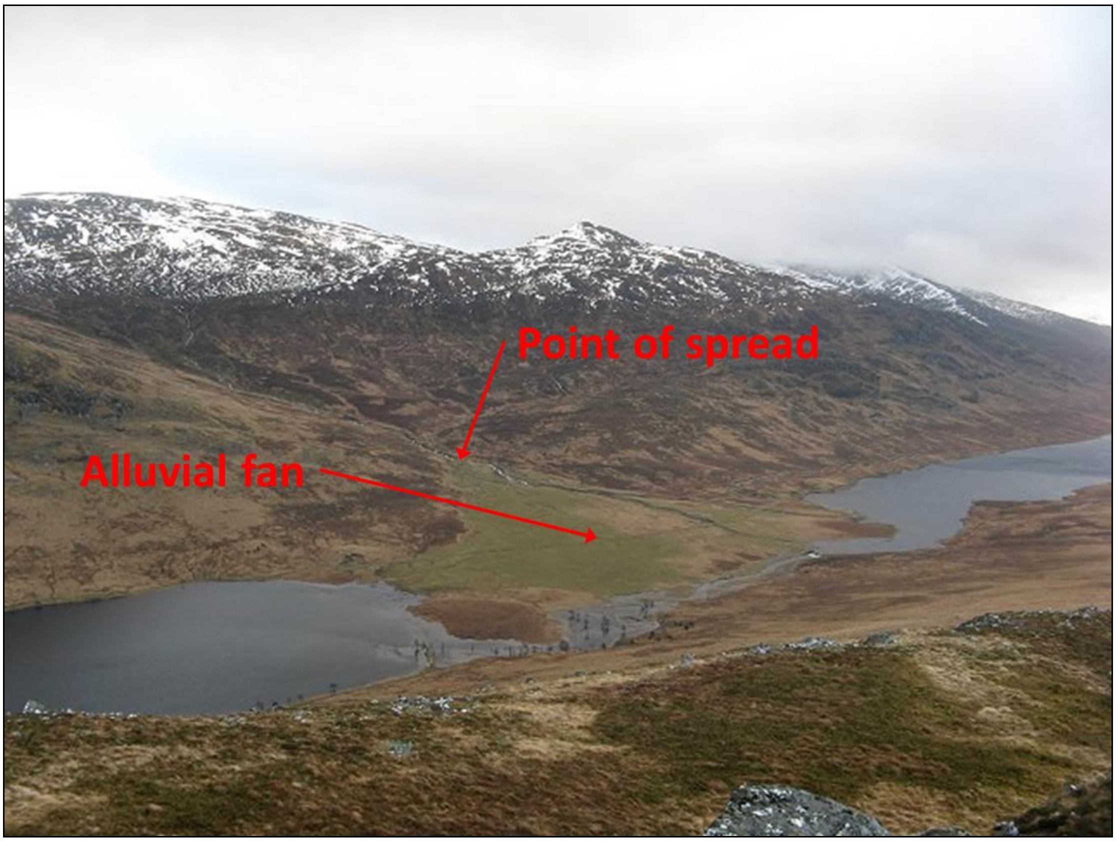

Figure 9: Example of alluvial fan (background photo © Richard Webb /www.geograph.co.uk/ CC-BY-SA-3.0)

The downstream end of the River Feshie is a very well-known and studied example of an alluvial fan. Figure 10 shows a recent aerial image of the reach with the approximate extent of the alluvial fan outlined in red. The historic point of spread (or apex) is also indicated. A number of old channels are also visible on the image which confirms that the channel has moved across the fan over time. During flood events both the water and sediment would have spread out across the fan. The channel would have been very dynamic, changing every time there was a high flow.

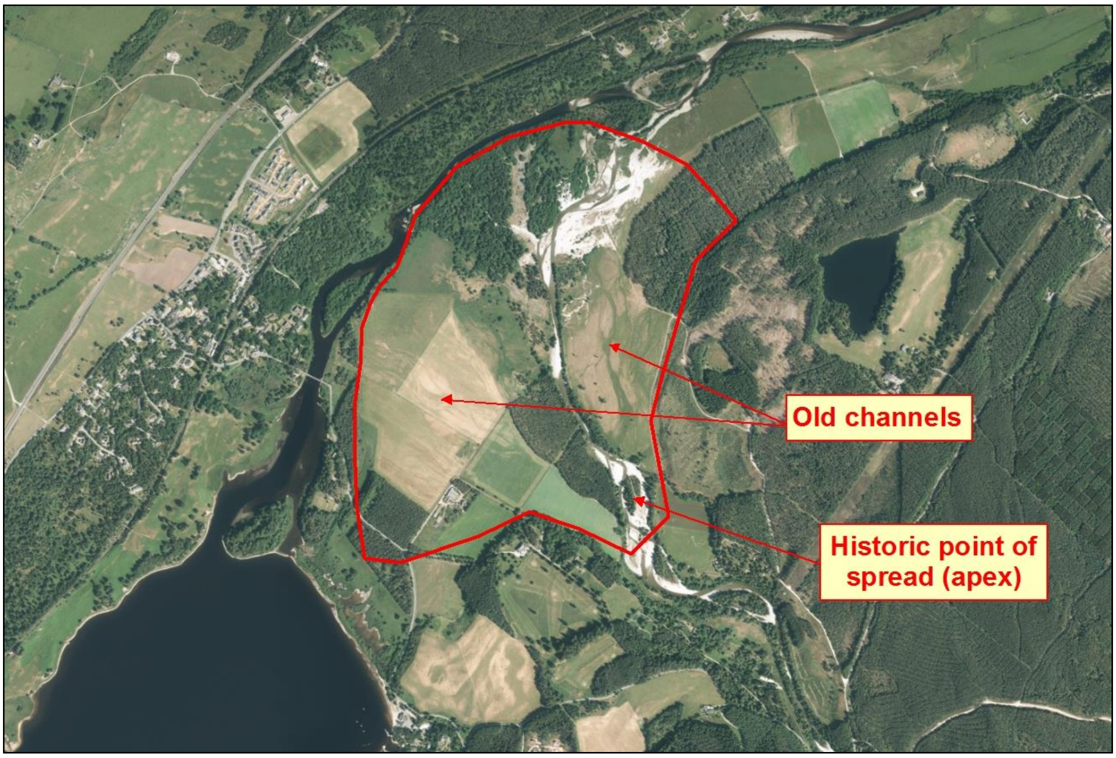

Figure 10: Aerial image of alluvial fan at the downstream end of the River Feshie. © Getmapping

Human modifications

There have been some significant human modifications made to the channel in this reach over time. We can tell this from analysis of historic mapping.

The oldest detailed map of this area is the Roy Military map from around 1750 (Figure 11). This is more of a detailed sketch than an accurate map but gives a very good insight into the landscape at the time. It shows the spreading out of flow and sediment and appears to be mostly unaltered by humans. On this map there are no sediment deposits in the River Spey channel downstream from the confluence. This implies that very little, if any, of the sediment coming down the River Feshie was getting into the River Spey.

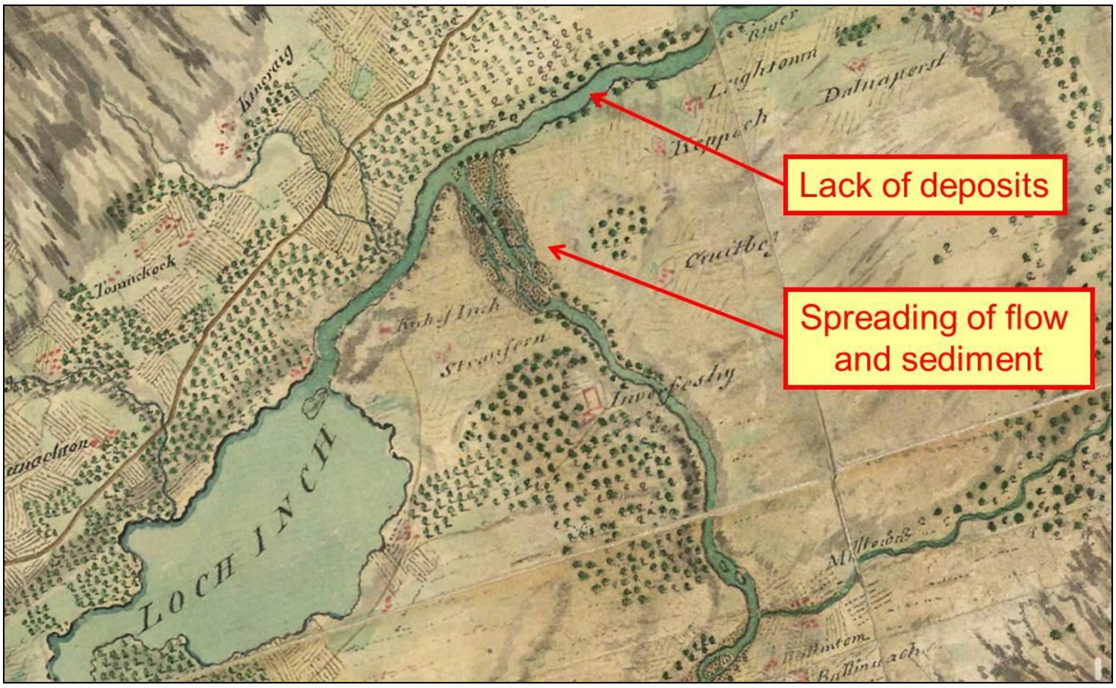

Figure 11: Roy Military Map (c1750). Reproduced by permission of the British Library

By around 1860 the 1st Edition Ordnance Survey (OS) mapping (Figure 12) shows that the channel had been modified. There is evidence of channel straightening and widening, and construction of embankments. Again there are no sediment deposits in the River Spey downstream from the confluence.

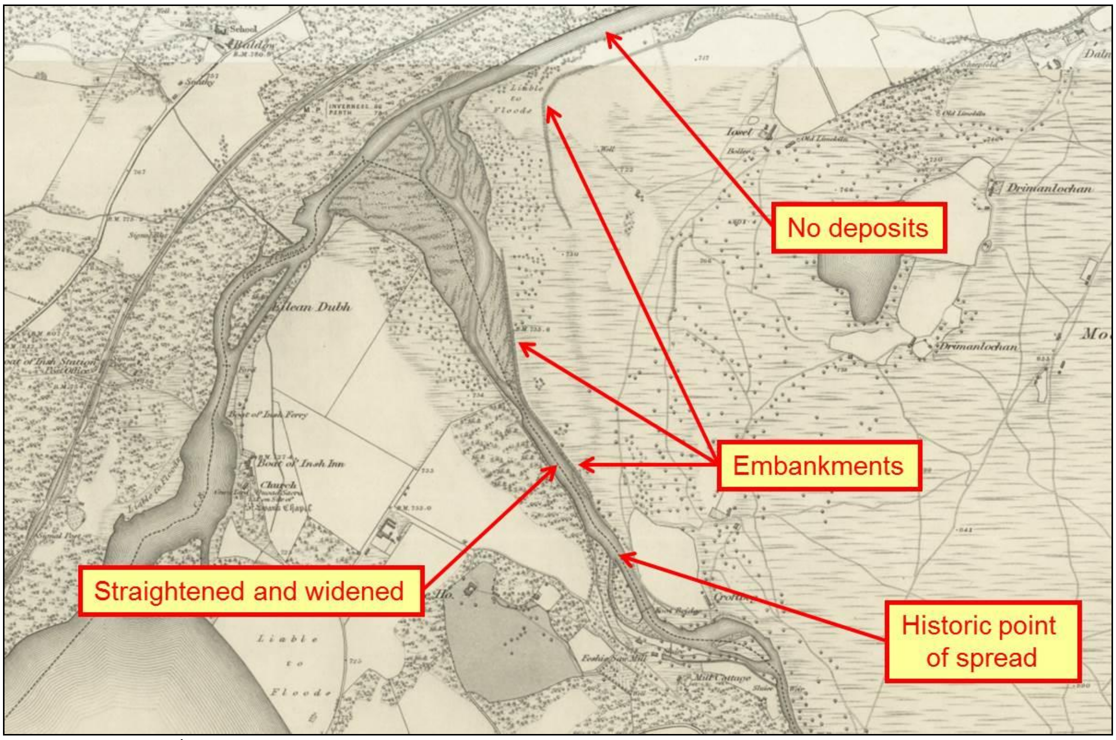

Figure 12: 1st Edition OS Map (c1860). Reproduced by permission of the National Library of Scotland

Straightening dynamic channels such as the River Feshie creates a number of effects. These are best be explained by an experiment done using flume tanks by

Little River Research and Design. A video of the experiment can be viewed at http://serc.carleton.edu/details/files/19087.html.

It shows that immediately after straightening there is an increase in sediment being transported downstream. This is because the straight channel is more efficient at transporting the sediment.

At the same time there is an increase in sediment coming from upstream through a process call headcutting. This happens because channel straightening leads to a lowering of the bed upstream (river channel becomes deeper) which then also destabilizes the banks. The result is increased erosion and increased sediment input to the channel.

The channel then very quickly starts to recover to its pre-straightened form as deposition once again becomes the dominant process. By the end of the video the overall channel corridor has increased in width.

Evidence of these effects can be seen on the OS map from around 1900 (Figure 13). It appears that sediment has been pushed downstream into the River Spey where it has deposited. Sediment deposition has narrowed the straightened channel and there have been changes upstream of this which suggests headcutting.

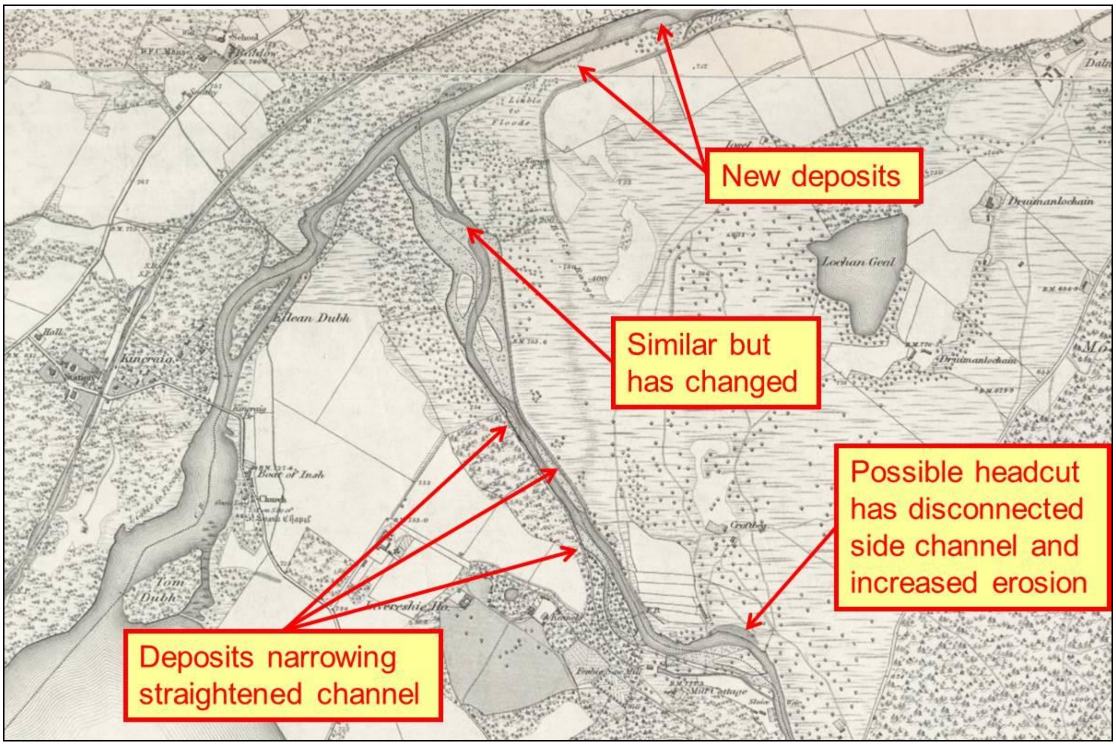

Figure 13: OS Map from c1900. Reproduced by permission of the National Library of Scotland

Further changes can be seen by comparing the channel outline from the c1900 OS map with recent aerial imagery (Figure 14). The upstream part of the straightened channel has become much more sinuous i.e. it has reverted to the type of channel which probably existed prior to straightening. The downstream part of the straightened channel remains largely straight but the straightening has been extended downstream by a significant distance.

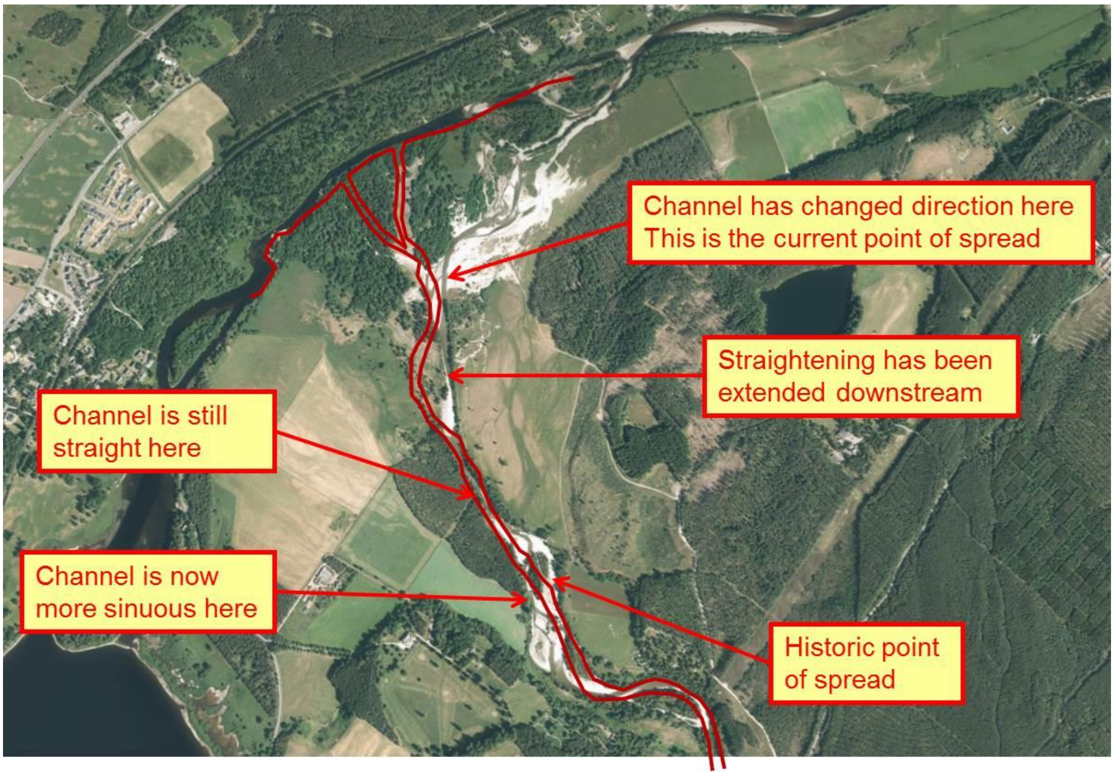

Figure 14: Recent aerial image with outline from c1900 OS map (brown lines) overlaid. © Getmapping

It is very likely that the section which remained straight has required regular maintenance to keep it this way. In contrast the section which has become more sinuous has probably not been maintained as regularly.

As can be seen clearly on the aerial imagery, the overall effect of the straightening is that the point of spread is now considerably further downstream.

Sediment and flood risk

From the above analysis of the reach it is clear that:

1. it is naturally a section of river where large amounts of sediment have been deposited creating the alluvial fan;
2. it is naturally a very dynamic section of river where frequent changes in channel direction would be expected as sediment builds up and spreads out across the fan;

3. straightening of the channel in the late 18th or early 19th century has moved the point of spread downstream by a considerable distance;

4. through continued deposition of sediment the straightened channel is constantly trying to revert to the natural dynamic channel which is wider, more sinuous and constantly changing;

5. the straightened channel requires regular management to keep it straight.

This has significant consequences for flood risk to the adjacent agricultural land. In order to understand this more fully it is useful to look at the profile of the land in the reach. Figure 15 shows a plan of the reach with two cross-section lines marked. The cross-sections are shown in Figure 16 and Figure 17.

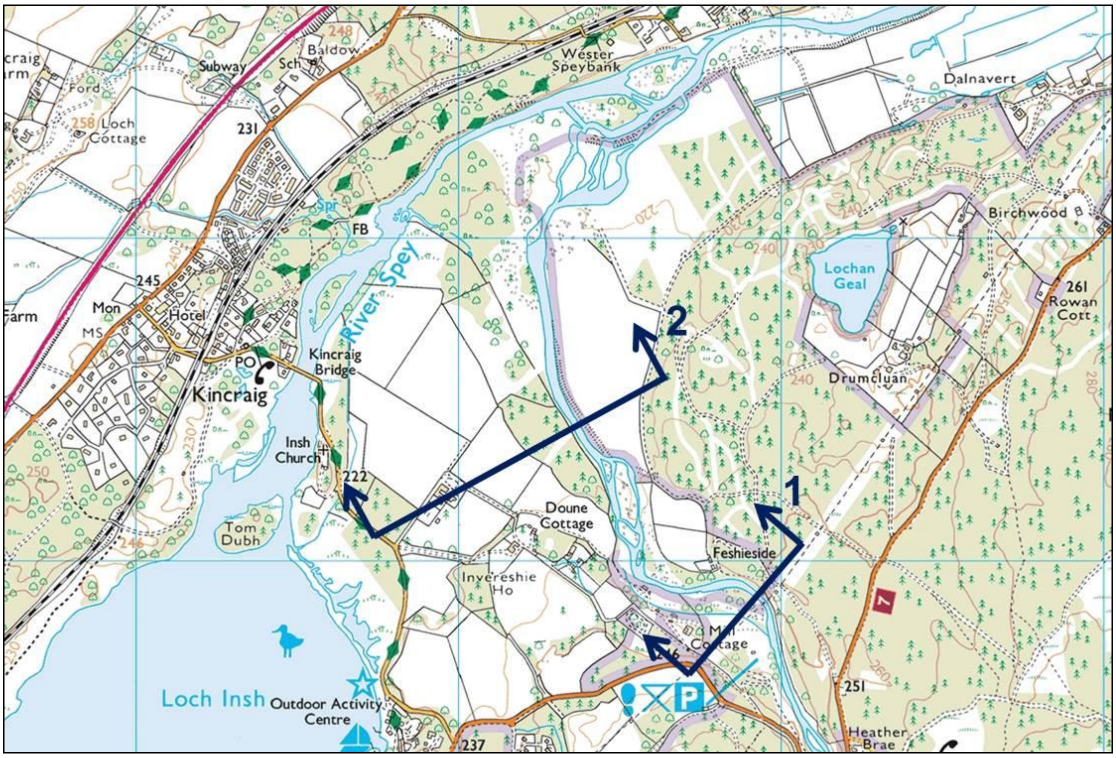

Figure 15: Plan of reach showing location of cross-sections.

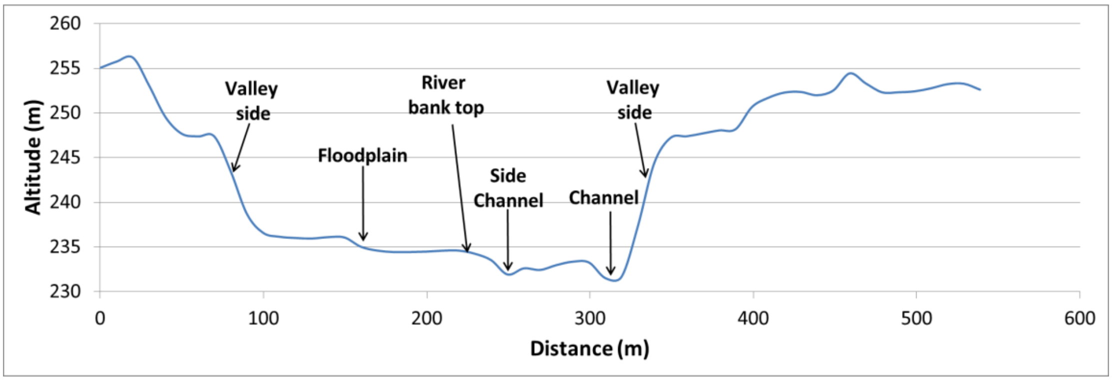

Figure 16: Cross-Section 1.

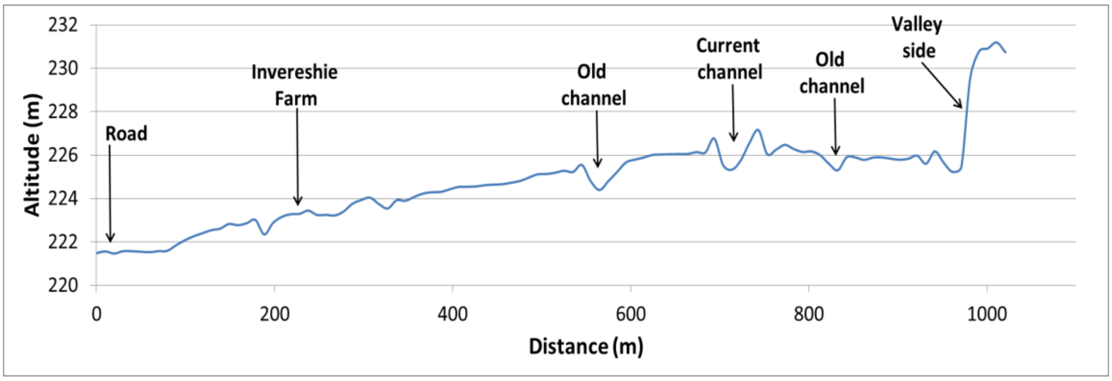

Figure 17: Cross-Section 2.

Cross-Section 1 is upstream from the historic point of spread of the alluvial fan. This shows a typical river cross-section with the channel being the lowest point and a relatively wide and flat floodplain at a slightly higher level all between the steep valley sides.

The main channel, side channel and small island between them can be considered to be the overall channel at this point. This is quite wide compared to the main channel. During high flows water will spread out first into this overall channel and then onto the floodplain. Deposition of sediment does not seem to be an issue at this point in the river.

Cross-Section 2 is on the alluvial fan. The current channel is located at the highest point. It has embankments on both sides of the channel to prevent flow from spreading out across the fan. The old channels visible on the aerial imagery can also be seen in this cross-section. The main channel is much narrower than the overall channel in Cross-Section 1. Any build-up of sediment in this narrower channel will quickly reduce the amount of flow it can carry before the embankments overtop. When the embankments overtop flow will spread out across the fan flooding the adjacent agricultural land.

This process was observed during the field visit. Sediment appeared to be building up in the channel between Cross-Section 2 and the current point of spread. With distance downstream from Cross-Section 1 the capacity of the channel to carry flow decreased as a result of this build up. Near the current point of spread the bed of the channel was higher than the adjacent land and almost as high as the top of the embankments. As a result water was spreading out onto the adjacent land at relatively low flows. Further upstream (Figure 18) there was also deposition of sediment on the adjacent land from higher flows which had overtopped the embankments. Overtopping of the embankments had also caused partial breaching in places further increasing the frequency at which flow spreads out onto adjacent land.

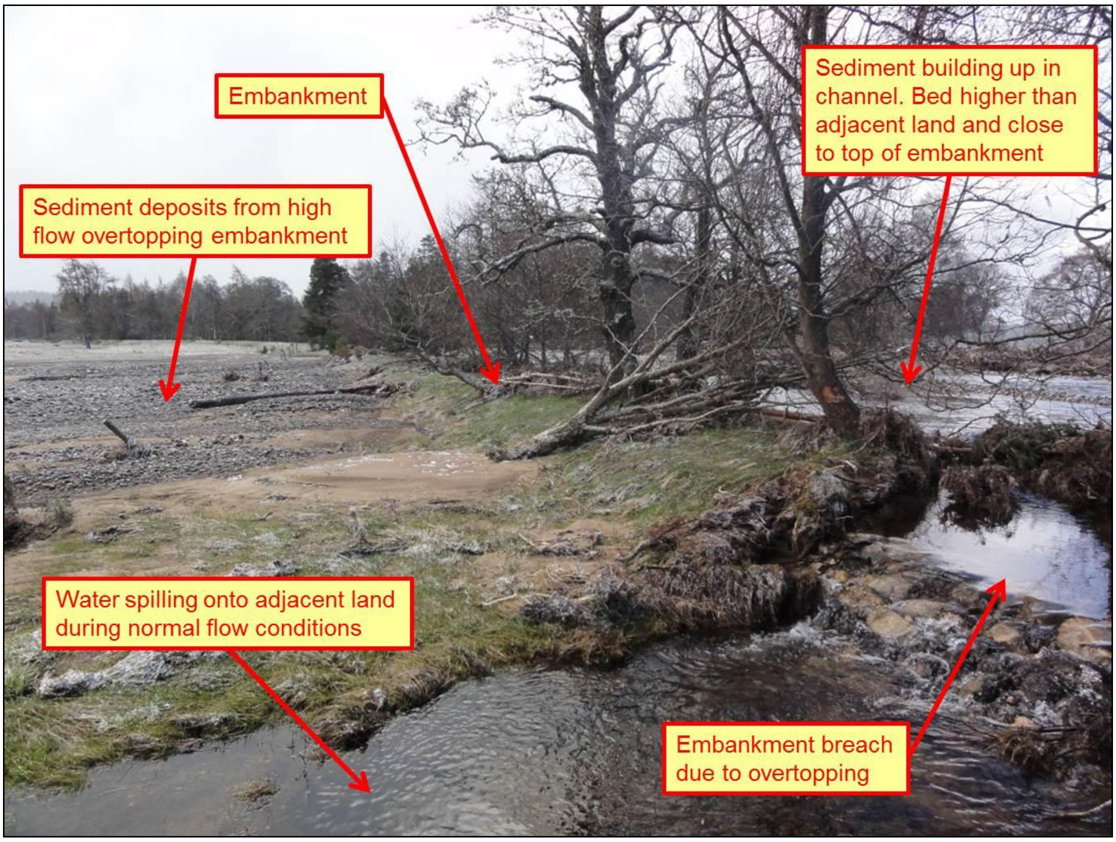

Figure 18: River Feshie between Cross-Section 2 and current point of spread looking upstream.

With distance upstream from this point the amount of sediment deposition in the channel reduced and the banks became higher indicating that there was less overall build-up of sediment.

As sediment builds up in the channel near the point of spread it causes more sediment to deposit just upstream. In this way the sediment that is building up in the channel is causing the point of spread to move upstream (Figure 19). As this happens the water spills out of the channel onto the adjacent land more often at this point and there is a high risk that the channel will change direction during a flood and start to flow across the agricultural land. At very high flows water spills out onto the adjacent land much further upstream.

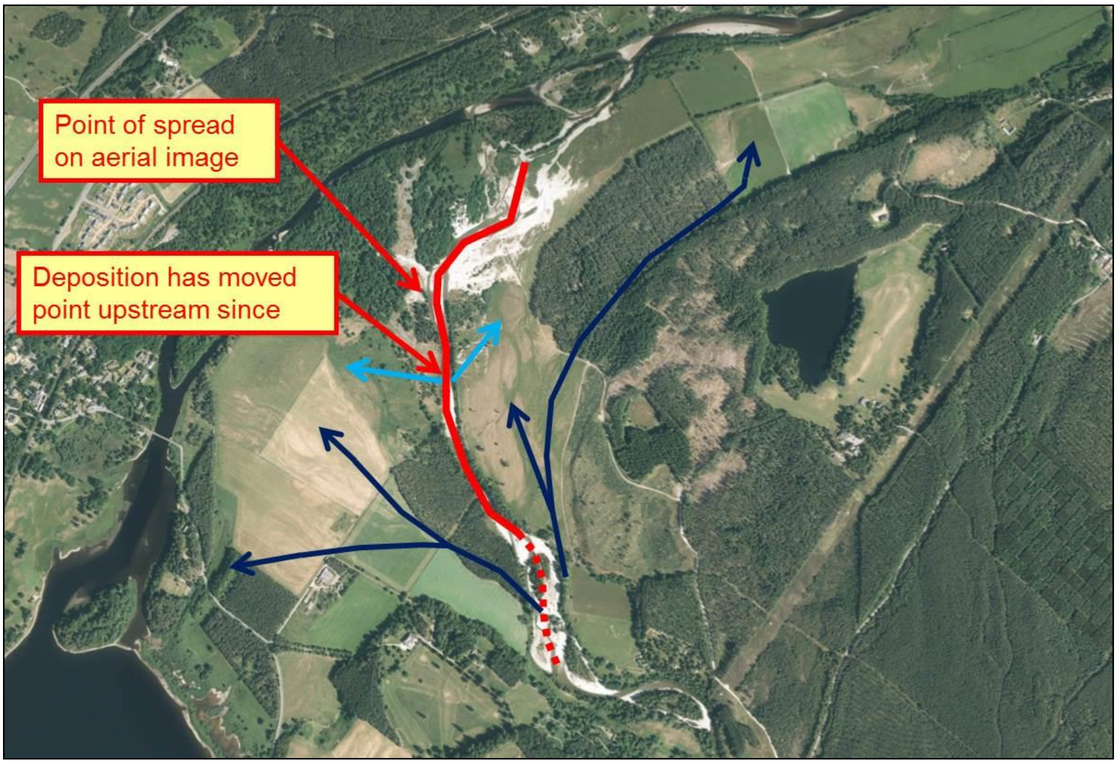

Figure 19: Recent aerial image of reach showing area where sediment is building up in the channel (solid red line), regular over bank flow paths (light blue arrows) and over bank flow paths during very high flows (dark blue arrows). Dotted red line indicates possible buildup of sediment in the channel but further detailed survey would be required to establish this. © Getmapping

Conclusion/Management options

The field and desk assessment of the River Feshie just upstream from the confluence with the River Spey shows that sediment deposition in the channel is strongly linked to the flooding of adjacent agricultural land. This is due to the natural tendency for sediment deposition at this point in the river combined with the constraints imposed on the channel by historic human modifications.

The channel straightening and artificial embankments have prevented the river from spreading out across the alluvial fan. Despite the constraint it is clear that the channel is still subject to deposition of sediment. As there is limited space to accommodate this deposition in the channel between the embankments it quickly fills up forcing flow over the banks.

Anecdotal evidence suggests that regular management of this reach has been carried out in the past (probably since it was first straightened) to manage the risk of flooding. In order to maintain the status quo this would need to continue. It is however likely that the effects of climate change will make this task more onerous. The predicted increase in the frequency of heavy rainfall will translate into more frequent high flows and more sediment being delivered to the reach from upstream. Care would need to be taken that the scale of works was appropriate. Removing too much sediment could trigger channel instability upstream which would quickly increase the amount of sediment coming back in. "Little and often" is likely to be the best approach although amounts will vary depending on the size of flood events.

Other options for managing the river are available but would result in some loss of use of the adjacent land for agriculture. The first option (Figure 20) would be to set back the current constraints i.e. the embankments. This would create a corridor for the channel where it could spread out during high flows. This would also provide much more space for deposition of sediment. It is likely that the sediment would still need to be managed but less often and this could be done in dry areas rather than in the wetted channel. It may be possible to gradually build up these setback embankments over time using sediment removed from the channel and then just allow the current embankments to fail. This would need very careful consideration and design.

The second option (Figure 21) would be to move the whole channel to a lower part of the fan. This would allow it to spread out within a corridor similar to that created by the setting back of embankments. One of the old channels could be used. Provided enough space was given to the river this option could significantly reduce the burden of channel maintenance in the long term. Again this option would need very careful consideration and design.

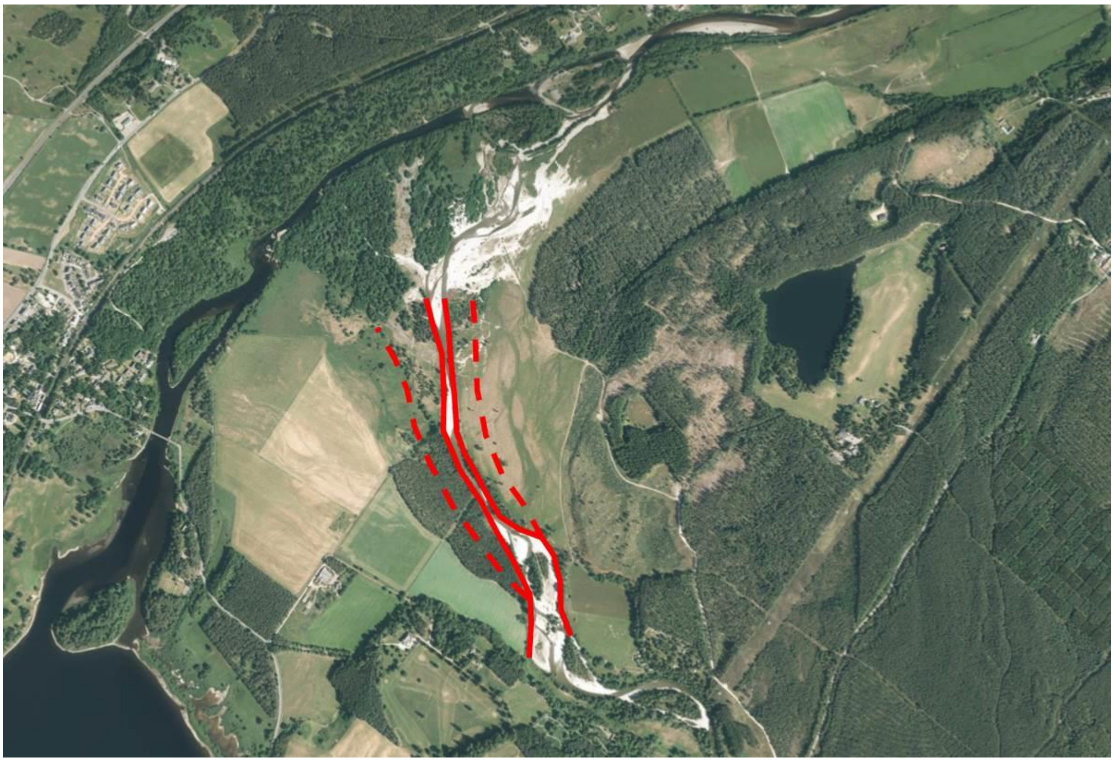

Figure 20: Aerial image of reach overlaid with option to setback existing embankments. Solid red lines show current line of embankments. Dotted red lines show indicative location of setback embankments. © Getmapping

Figure 21: Aerial image of reach overlaid with option to realign channel to a lower part of the alluvial fan utilizing an old channel. © Getmapping

River Tay

Location

The River Tay site is located just downstream from its confluence with the River Tummel between Dunkeld and Pitlochry (Figure 22).

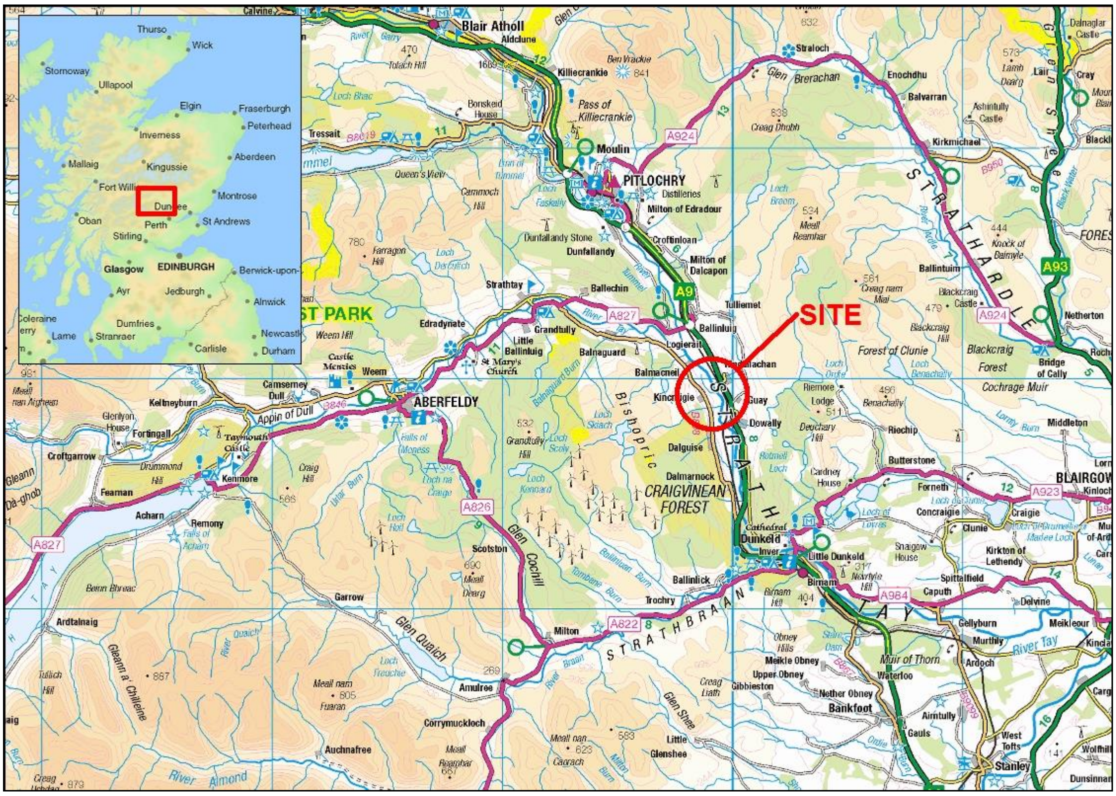

Figure 22: Location of River Tay site *©Crown copyright. All rights reserved. SEPA lic. no. 100016991*

The section of river channel where sediment deposits were identified and the areas of adjacent agricultural land affected by flooding are shown in Figure 23. On the site visit, the land owner reported that the land flooded several times a year, but that flooding was predominantly in winter when the land was not used for grazing. We have therefore looked at the impact of sediment deposits during small flood events which occur several times a year.

In this case it was also highlighted that the railway bridge at the downstream end of the reach may be a contributory factor in flooding. A brief assessment of this was therefore also undertaken.

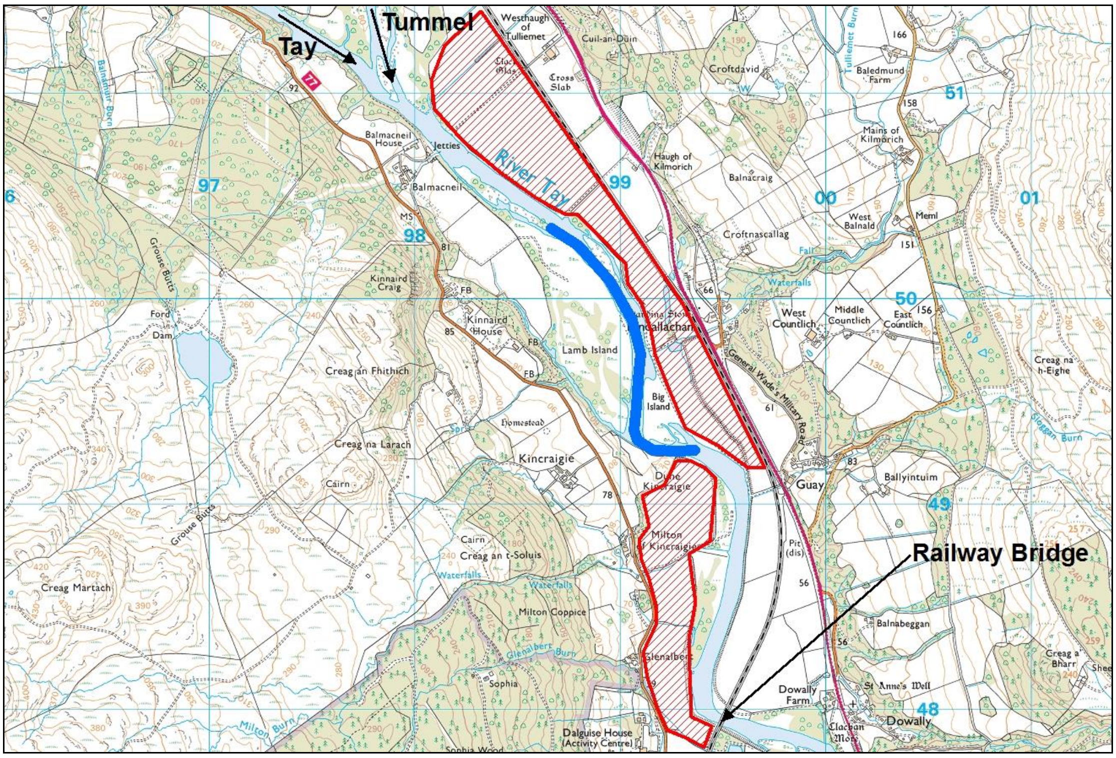

Figure 23: River Tay site showing section with sediment deposits (blue line) and areas of adjacent agricultural land affected by flooding (red hatched)

Upstream Catchment

The River Tay is Scotland's largest river. It has a total catchment area of about 4770km^2. The catchment area upstream from this site is about 2900km^2. This is a substantial part of the catchment and means that the River Tay is already relatively large at this point; typically 80-90m wide compared to 110-120m near the downstream end at Perth.

The upstream catchment stretches from Rannoch Moor and Tyndrum in the west to Dalwhinnie in the north and the Forest of Atholl in the East. Many of the streams which come together to form the River Tay catchment start high in the Grampian Mountains at an altitude over 800m.

Sediment sources

British Geological Society (BGS) mapping of superficial geology (i.e. consolidated sediment) within the catchment is shown in Figure 24. This shows that there are significant areas of sediment throughout the upstream catchment which can be eroded and transported by watercourses passing through them.

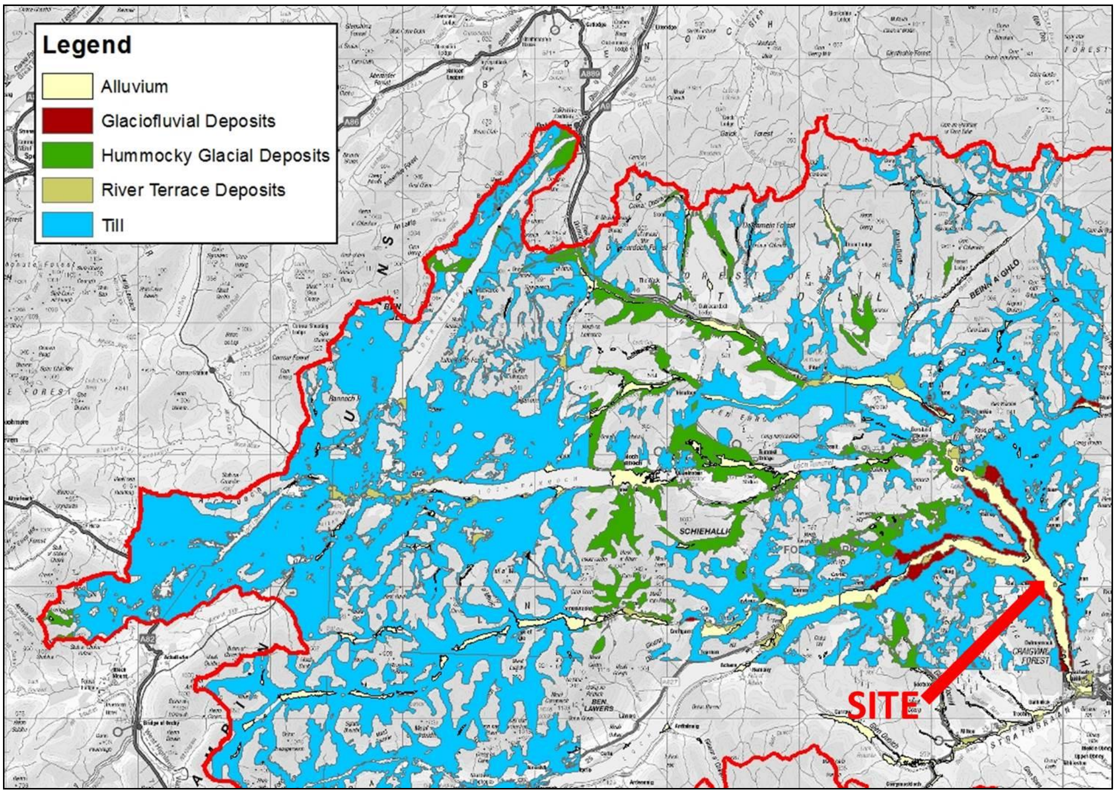

Figure 24: River Tay catchment upstream from site (outlined in red) showing superficial deposits

The upstream catchment is dominated by till and hummocky glacial deposits. There are also significant areas of alluvium and river terrace deposits along the various watercourses which come together to form the River Tay. These are sediments that have already been eroded, transported and deposited by the river from further up the catchment. The largest of these areas is along the main stem River Tay and River Tummel upstream and downstream from the site.

The central and western part of the upstream catchment has several large lochs (Figure 25). Despite the fact that many of these are now reservoirs used for hydro power generation most were originally natural lochs. These lochs would historically have trapped any coarse sediment transported from upstream and therefore lowering the overall amount of sediment being transported towards the site. In contrast there are very few natural lochs in the northern part of the upstream catchment which feeds into the Rivers Garry and Tummel. We would therefore expect more sediment to be transported down these rivers towards the site.

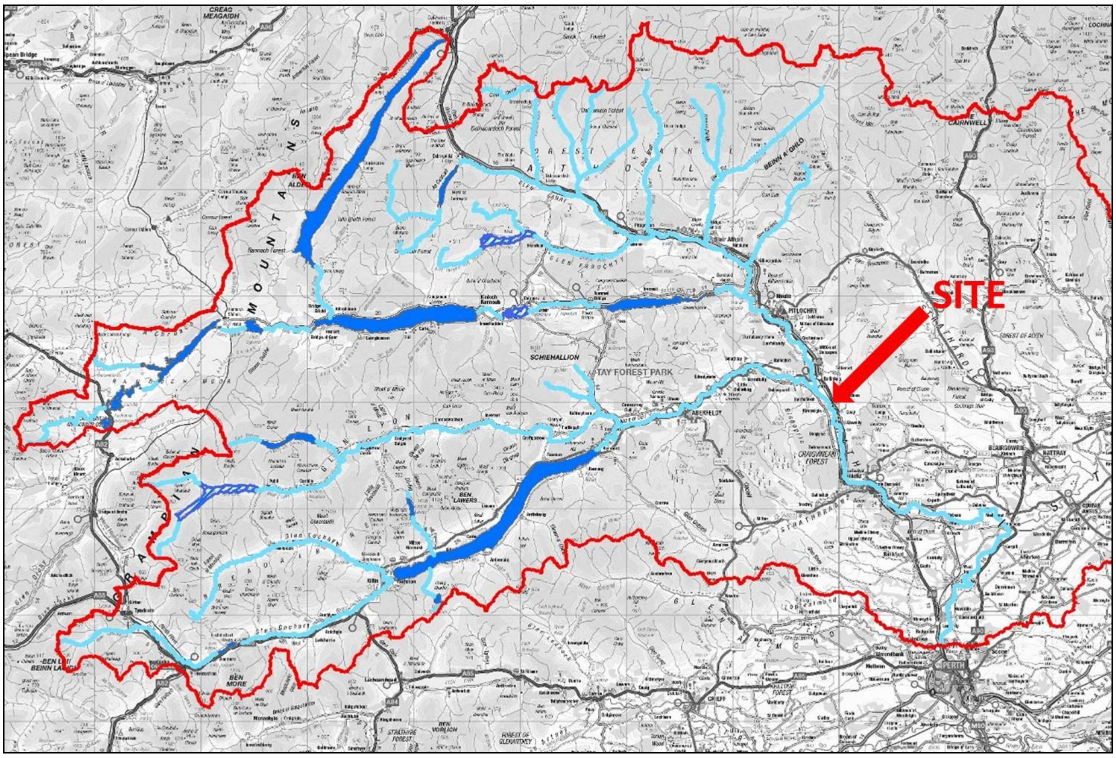

Figure 25: River Tay catchment (outlined in red) with main river channels highlighted in light blue and large lochs/reservoirs shaded in dark blue. Artificial reservoirs (i.e. where no natural loch existed) are hatched.

Human modifications

One of the main human modifications in the River Tay catchment upstream from the site has been the large scale development of hydro power. This started in the 1930s and saw the construction of dams on many of the watercourses in the catchment. Some dams were built on natural lochs whilst others were built on river channels and they vary in size. These dams can prevent sediment from being transported downstream by trapping it in the impounded area of water upstream from the dam. This is particularly the case where large dams have been placed on river channels which naturally transport a lot of sediment. One notable example of this is the large dam on the River Tummel at Pitlochry which is only 10km upstream from the site.

Despite this, recent aerial imagery (Figure 26) and observations from field survey show that sediment is still moving from the River Tummel into the River Tay. This sediment must be sourced from the River Tummel between the dam at Pitlochry and the confluence with the River Tay. The imagery and observations also show that there is much less (almost no) coarse sediment moving in the River Tay upstream from the confluence with the River Tummel. In other words, it appears that most of the sediment being transported into the study reach comes from the River Tummel.

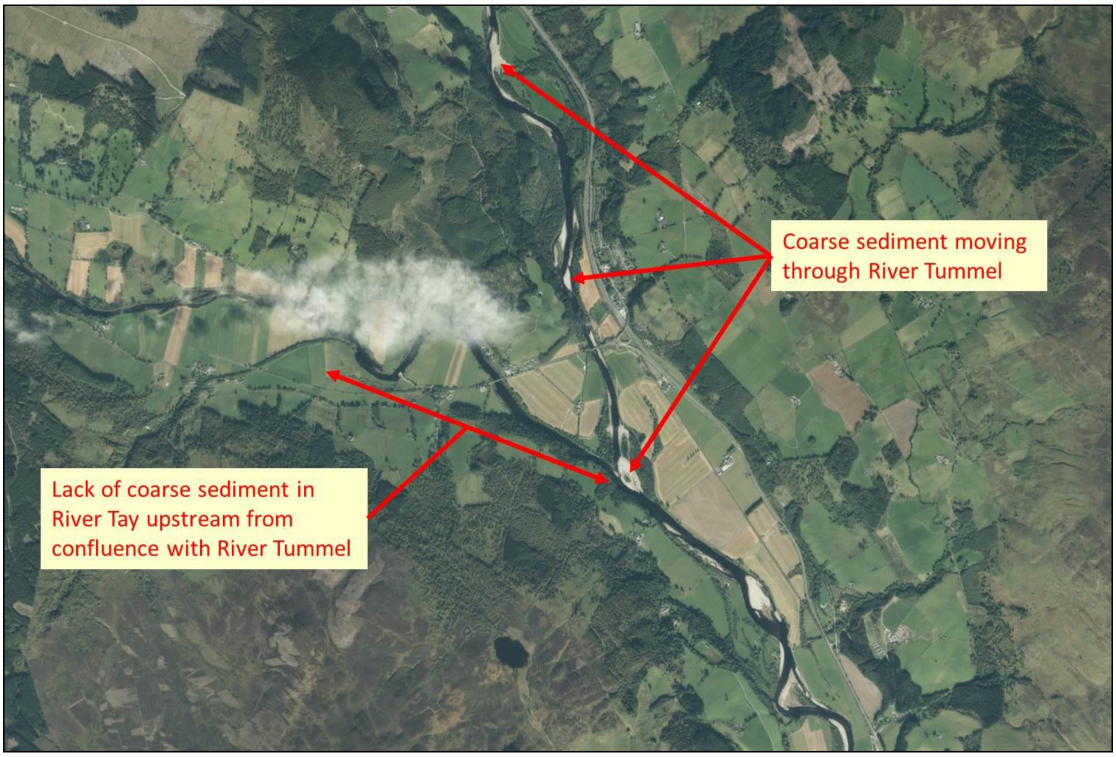

Figure 26: Recent aerial image of Tay/Tummel confluence. Light coloured areas in river channel indicate mobile coarse sediment moving through river.

Channel slopes

The above observation can be further explained by looking at the slope of the channels upstream from the confluence. Figure 27 shows the slope of both the River Tay and the River Tummel upstream and downstream from the confluence. This shows that for approximately 3km upstream from the confluence the River Tay channel has a very low slope i.e. it is quite flat. This very low slope means that the river does not have the energy to transport much, if any, of the coarse sediment coming from upstream.

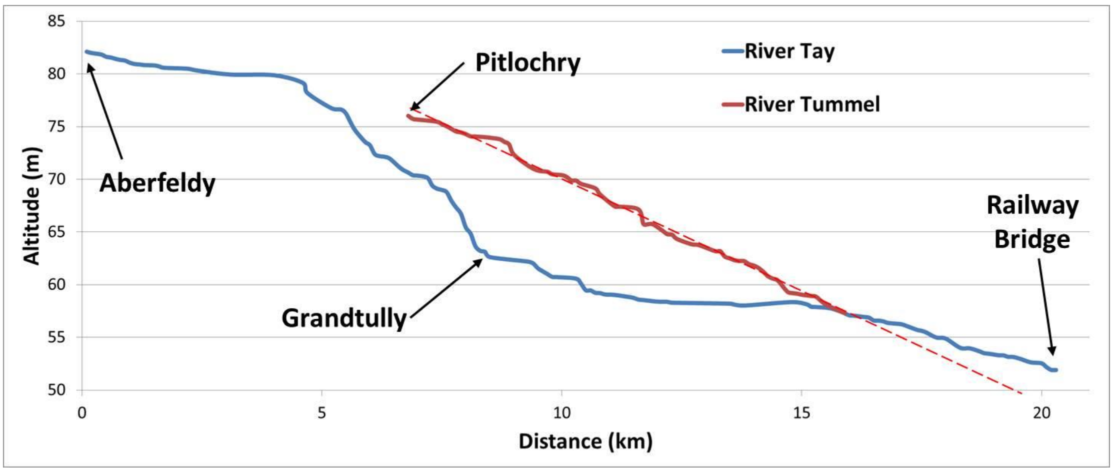

Figure 27: Slope of River Tay and River Tummel upstream and downstream from confluence. Red dashed line added to emphasize reduction in slope downstream from confluence.

In contrast, the River Tummel upstream from the confluence to Pitlochry is much steeper. This means that it has more energy to transport coarse sediment downstream. The process of transporting sediment downstream uses up energy. The dam at Pitlochry stops sediment being transported downstream. This means that the river immediately downstream from Pitlochry has energy but no sediment. As a result the energy is used to erode sediment from the river channel and floodplains downstream from Pitlochry. The superficial geology map (Figure 24) shows that there are substantial reserves of sediment in the floodplains downstream from Pitlochry which the river can access. By the time the River Tummel reaches the confluence with the River Tay it has introduced a lot of sediment into the river channel.

Figure 27 also shows that there is a reduction in the slope of the channel downstream from the confluence. Reduction in the slope of a river normally means that there is a simultaneous reduction in energy and the ability of the river to transport coarse sediment. In such cases it is normal to observe a build-up of sediment in the channel around this point. Channels which experience a build-up of sediment are characteristically very dynamic. At low flows there are usually multiple "threads" of flow around and between islands. The layout of islands and "threads" of flow frequently change in response to spate flows.

This is exactly what can be seen on the Roy Military Map from c1750 (Figure 28) in the River Tummel upstream from the confluence. There is similar multi-thread channel shown downstream from the confluence within the study reach however it is not to the same extent as upstream. This implies that a lot of deposition happened upstream from the confluence but that some sediment was transported into the River Tay where some was also deposited.

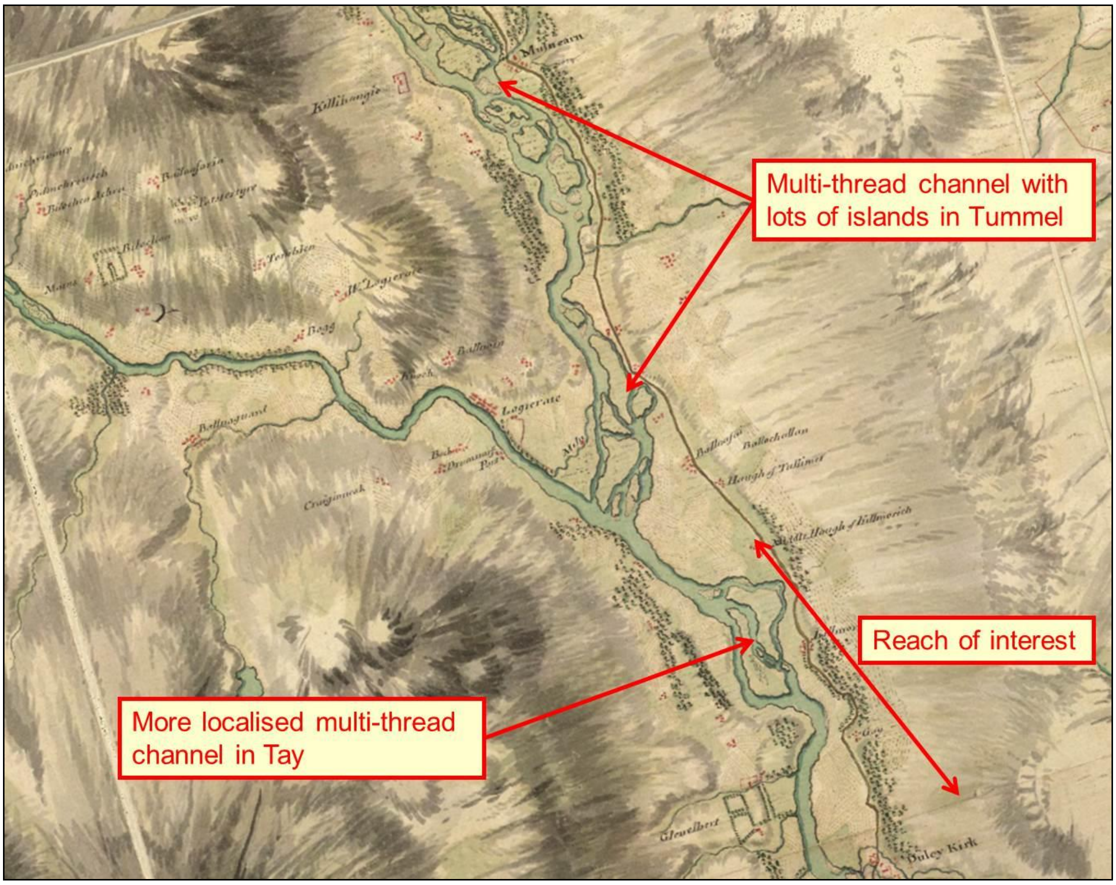

Figure 28: Extract from Roy Military Map c1750 around River Tay and River Tummel confluence (courtesy of National Library of Scotland). Reproduced by permission of the British Library

Summary

From the review of the catchment upstream from the site of interest we can conclude that:

- there is a lot of coarse sediment available for erosion and transport;
- most of the sediment transported into the study reach comes from the River Tummel rather than the River Tay;
- a lot of the sediment being transported down the River Tummel would naturally be deposited upstream from the confluence with the River Tay but some would pass on into the River Tay.

Reach of interest

Changes over time

Figure 28 shows that in c1750 the channel through part of the study reach may have been prone to deposition of sediment. The localised multi-thread channel suggests that there was sediment build-up in this part of the reach. The channel upstream and downstream is single thread suggesting it has a greater ability to transport the sediment coming from upstream. The reason for the localised change is not clear but may have been due to the localised narrowing of the river valley (Figure 31) and/or localised bedrock outcrop in the channel bed immediately downstream. There is anecdotal evidence of localised bedrock outcrop on the channel bed but it could not be seen/verified during the recent survey due to the depth of water.

In c1867 a similar pattern was recorded on the 1st Edition Ordnance Survey (OS) map (Figure 29). It appears that part of the multi-thread channel had been cut-off from the main channel by this time. This appears to have been a man-made occurrence and may have been associated with construction of the railway line. Otherwise, the channel still has a localised multi-threaded section through the reach implying that deposition of sediment was still occurring.

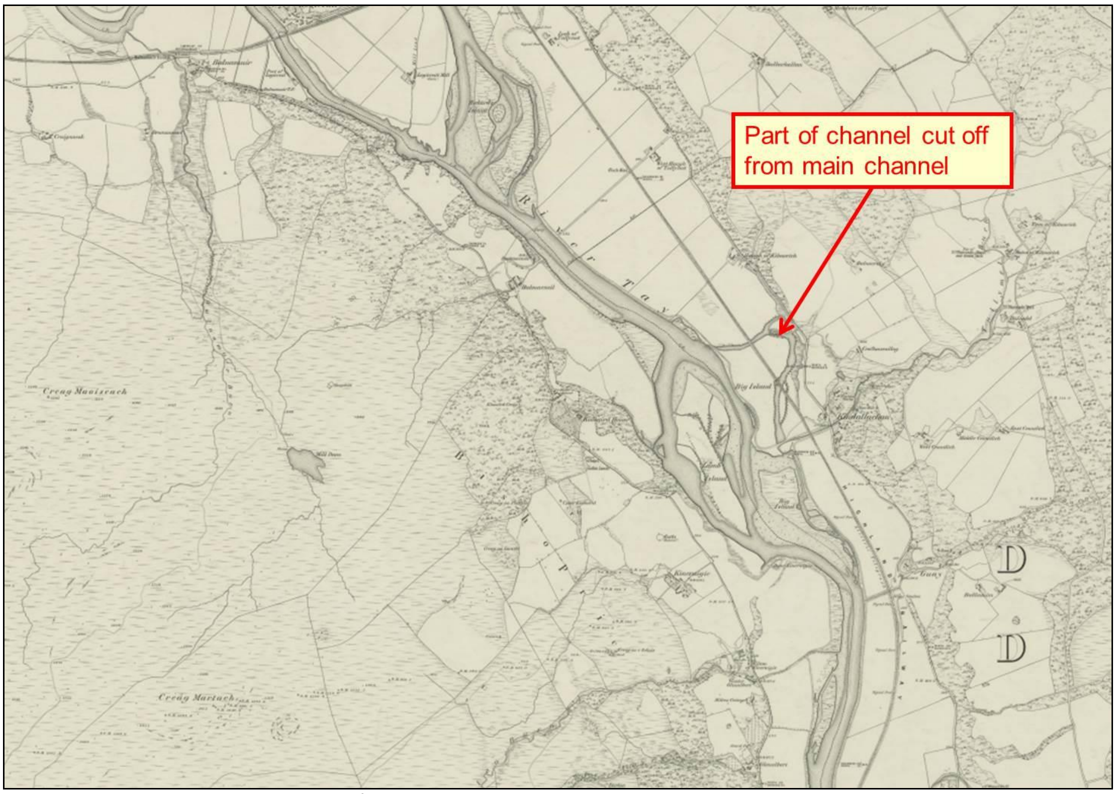

Figure 29: Extract from 1st Edition Ordnance Survey map c1867 (courtesy of National Library of Scotland) showing reach of interest. Reproduced by permission of the National Library of Scotland

In c1947 the OS One Inch map (Figure 30) still shows a similar pattern implying that not much had changed in terms of river processes. That is not to say that the channel had not changed shape in this time, which it obviously had in places, but that overall the movement of sediment was similar.

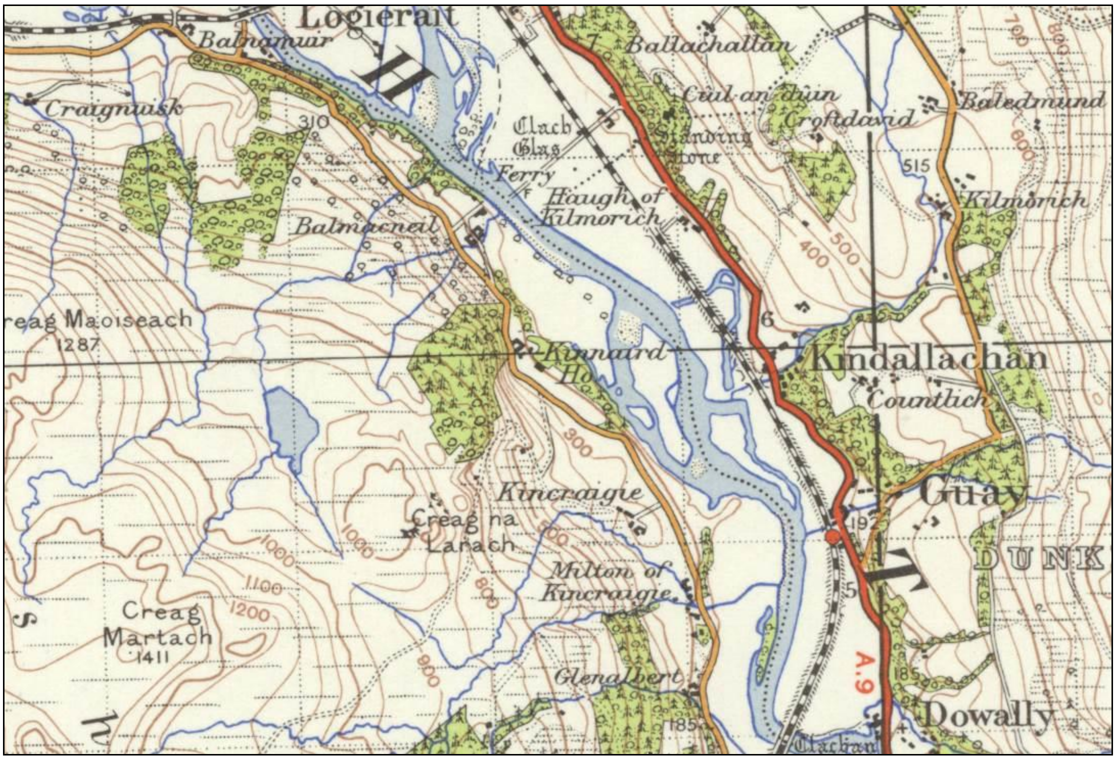

Figure 30: Extract from Ordnance Survey One Inch map c1947 (courtesy of National Library of Scotland) showing reach of interest. Reproduced by permission of the National Library of Scotland

All of the above maps contrast with the pattern of the channel in recent years (Figure 31). The previously multi-threaded section of channel in the reach is now dominantly single thread. This implies that there has been a significant change in the way sediment moves through the reach. The change to single thread means that the channel now has more energy available to move sediment through the reach, reducing the amount of sediment deposition and the characteristic multi-threaded channel this creates.

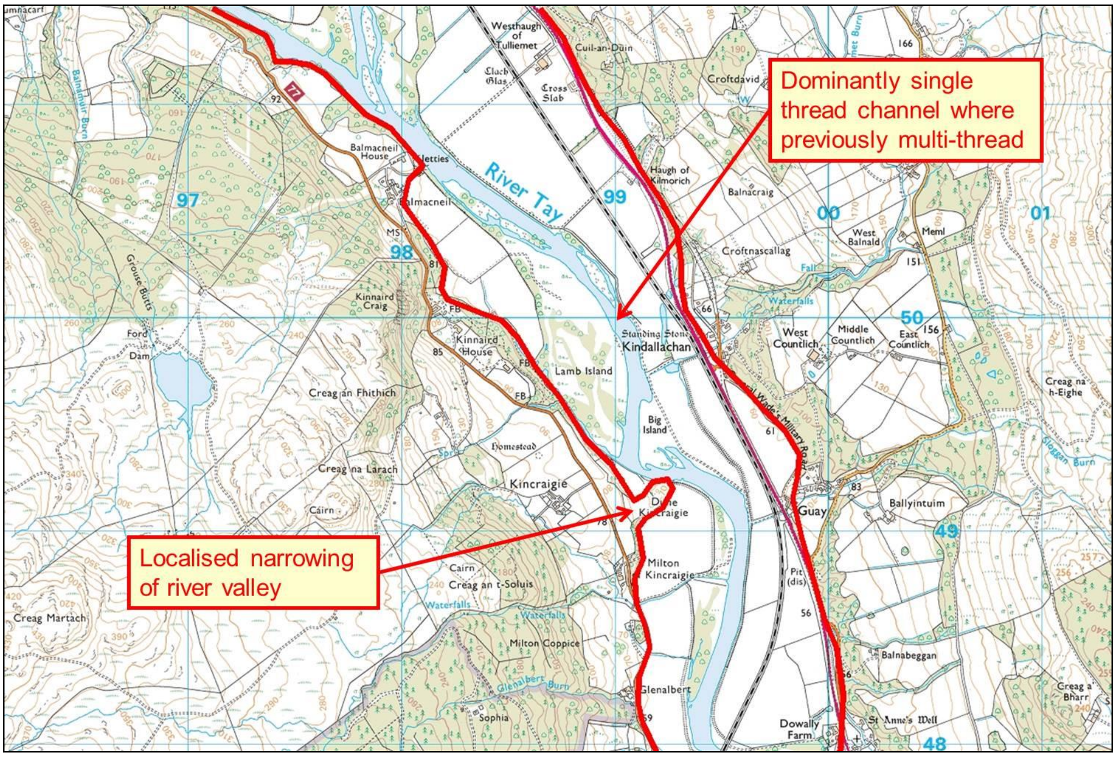

Figure 31: Extract from most recent 1:25,000 scale Ordnance Survey map showing reach of interest. Thick red lines have been added to highlight the edges of the natural river valley.

The Ordnance Survey One Inch 7th Series map published in 1961 (surveyed sometime between 1954 and 1961) show that the process of change from multi-thread to single thread had started (Figure 32).

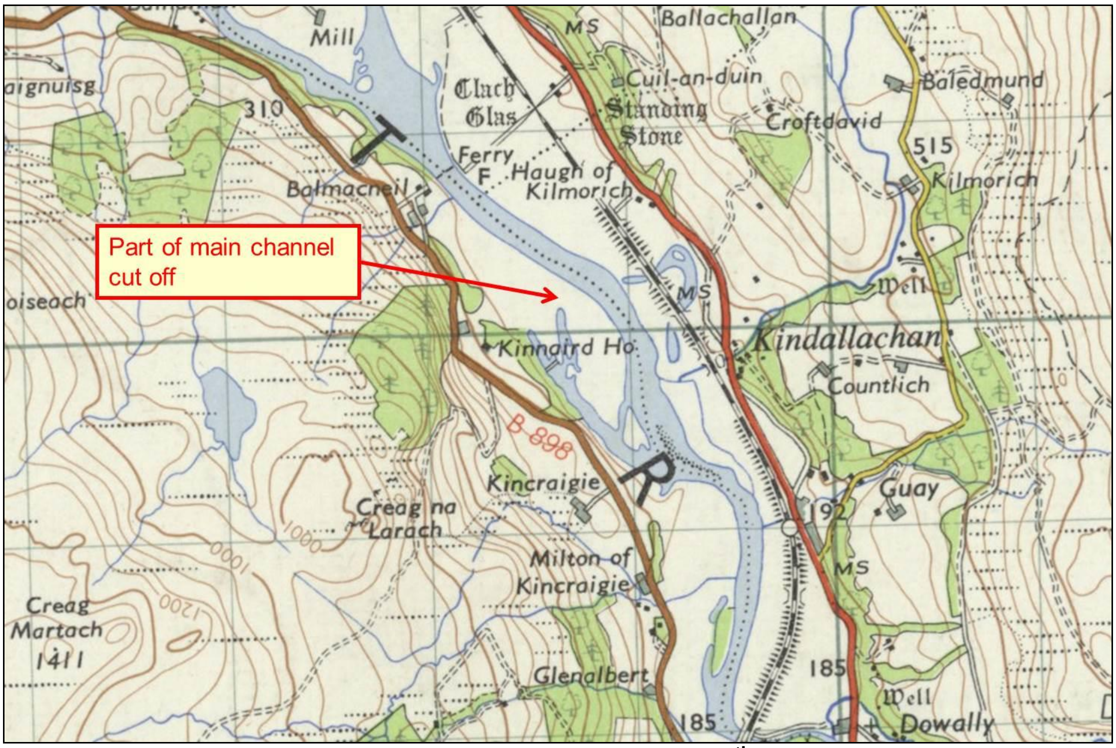

Figure 32: Extract from Ordnance Survey One Inch 7th Series map showing reach of interest Reproduced by permission of the National Library of Scotland

There are a number of possible explanations for this change:

- **Hydro power development upstream.** We have already seen that even the dam at Pitlochry is unlikely to have impacted on the amount of sediment being transported to the reach. As well as building dams, development included the transfer of water from the River Spey catchment into the River Tay catchment. This may have increased peak flows in the River Tay. We do not have the data available to investigate this. Increased peak flows would mean that the river has more energy to move sediment.

- **Change in flows.** We have operated river gauging stations on the River Tay upstream and downstream from this reach since the 1950s. We have also operated a river gauging station on the River Tummel at Pitlochry since 1973.

  Sediment is not transport along rivers constantly. Instead it moves like a jerky conveyor belt with movement only happening during higher flows. Research[5] suggests that the transport of coarse sediment starts to happen when the flow reaches somewhere around 80% of the flow which would fill a natural channel to the top of the bank[6]. It can be assumed that flow above this threshold value is a measure of the energy available to erode and transport sediment.

  Using the maximum monthly flows from the Caputh gauging station on the River Tay we can see that the amount of energy in the river was relatively low in the 1960s, 1970s and 1980s (Figure 33). We can also see that the 1990s and 2000s were high and the last ten years in particular has seen a significant increase. This pattern is repeated at the Pitnacree gauging station on the River Tay upstream from the reach. We do not have pre 1950s data so it is not possible to tell if this increase is significant in the longer term.

- **Channel modifications**. As can be seen in Figure 34 the channel is now more constrained by embankments than it would naturally be. Rivers which are constrained carry more water in the channel during high flows. This in turn increases the amount of energy in the channel (rather than spreading out on the floodplain) and subsequently increases the amount of sediment that can be transported. Many of these embankments are also shown on c1867 OS map however and we would therefore have expected to see the impact from these before 1947. It is possible that heightening of the embankments

[5] Ryan, S.E., Porth, L.S., Troendle, C.A., 2002. *Defining phases of bedload transport using piecewise regression*. Earth Surface Processes and Landforms 27,971–990.

[6] 80% of bankfull flow or Qmed (1 in 2 year return period flow).

over time may have increased their effect. It is however not possible to tell if they have been heightened.

It is not possible to attribute the change to just one of these factors. Instead it is more likely that a combination of factors has led to the change.

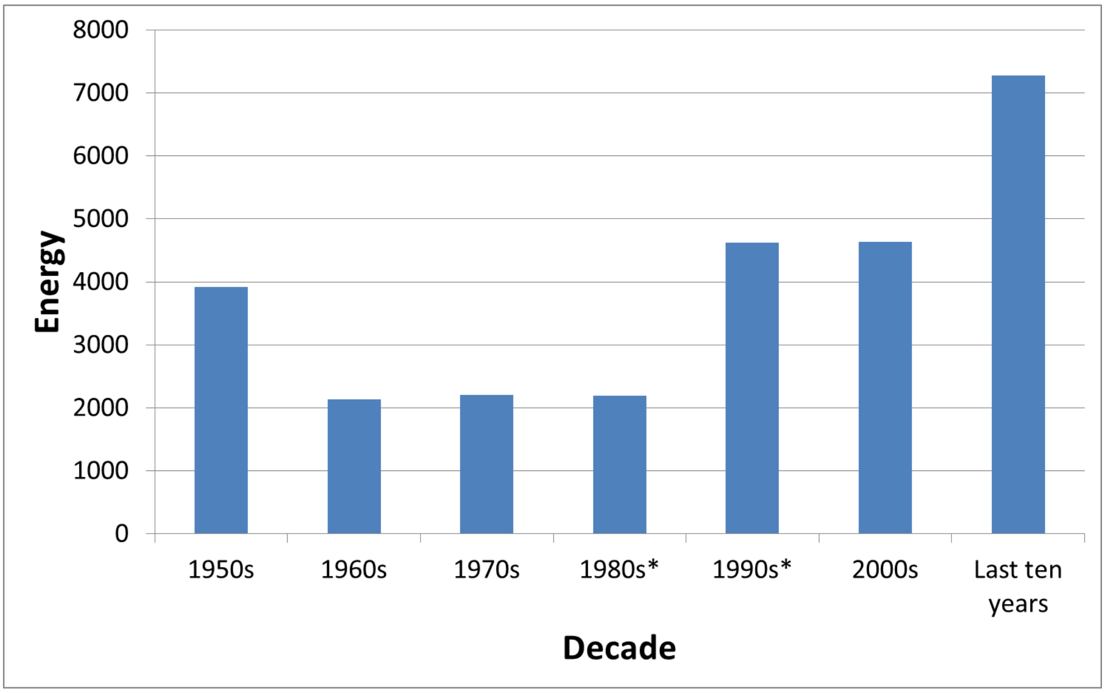

Figure 33: Energy available to transport sediment at Caputh river gauging station on the River Tay downstream from the reach. (* denotes decade with missing data. Figures increased on pro-rata basis to account for missing data)

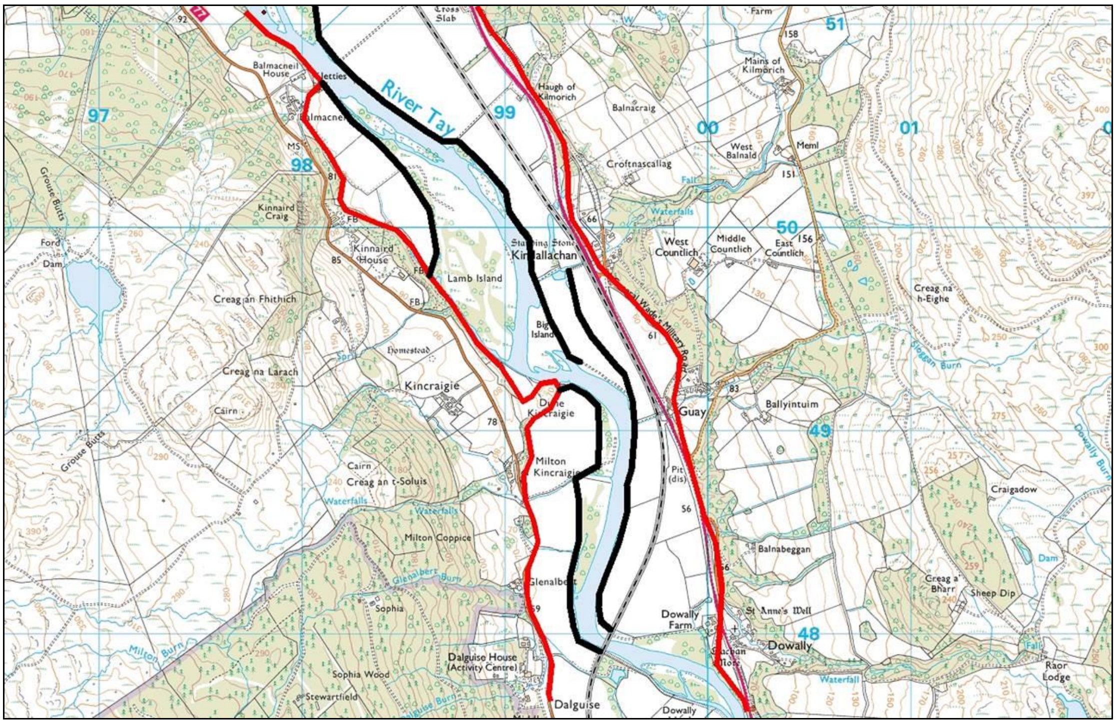

Figure 34: Extract from most recent 1:25,000 scale Ordnance Survey map showing reach of interest. Thick red lines show edges of the natural river valley. Thick black lines show location of embankments.

Recent changes

The last ten years have seen a number of high flows in the River Tay (Figure 33). This has caused some obvious changes in the channel. Figure 35 shows the line of the channel banks on a recent aerial image (c2014) overlaid on the most recent Ordnance Survey 1:25,000 map.

This highlights two main areas of change. In both areas the channel between the banks has become wider but there has also been a change in the size and shape of sediment deposits in the channel.

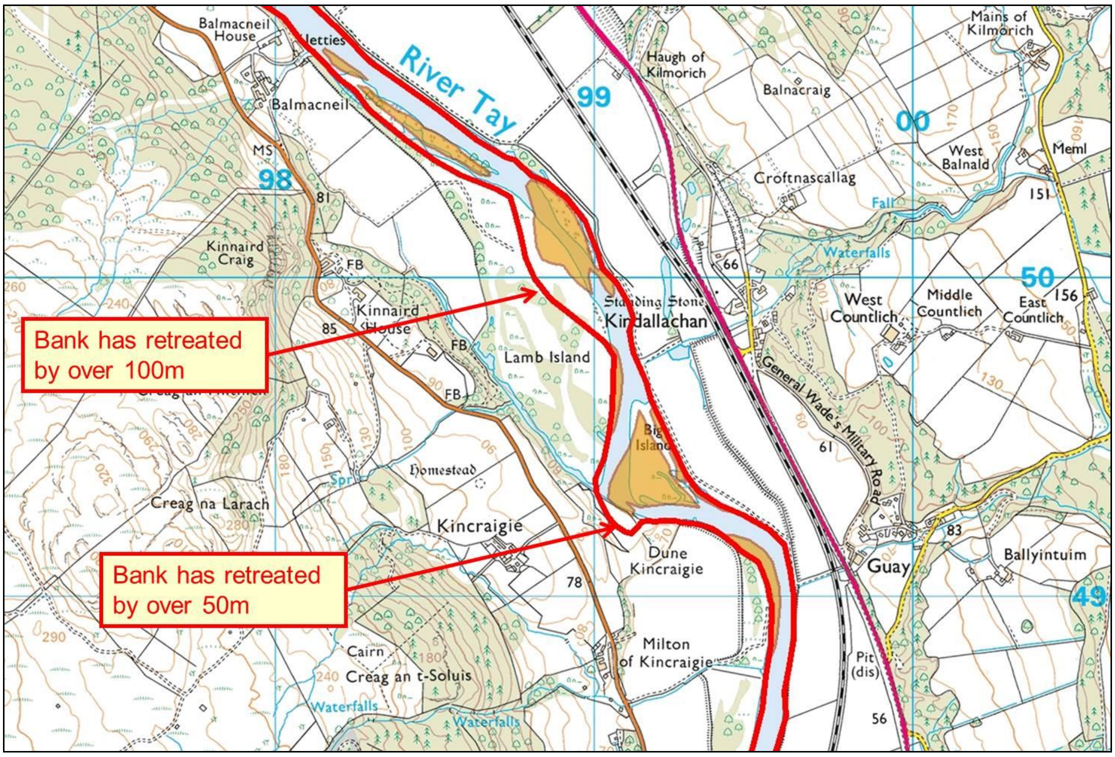

Figure 35: Most recent Ordnance Survey 1:25,000 map with channel bank lines from c2014 aerial image overlaid in red and areas of sediment in the channel shaded in orange.

In 2011 a LiDAR survey of the river corridor was carried out. LiDAR (Light Detection and Ranging) involves measurement of the ground surface from an aeroplane using laser technology. This technique can identify the level of solid ground very well (even where there is vegetation) but it cannot penetrate water. It is therefore not possible to tell what the river bed is like unless it is dry at the time of the survey.

In 2015 a manual survey of the river corridor was carried out in connection with flood modelling work for the upgrade of the A9 road. This comprised numerous cross-sections of the river including points across the river bed regardless of whether they were under water or not.

These surveys were compared to identify changes in the channel between the surveys. Allowances were made for the fact that the LiDAR survey did not capture the river bed. The comparison suggests that at most of the 2015 cross-sections the channel has remained a similar size or has increased in size.

This can be clearly illustrated at one of the cross-sections where there was sediment in the channel. Figure 36 shows the location of the cross-section and Figure 37 shows the comparison of cross-sections derived from the 2011 and 2015 surveys. Between the surveys sediment has been deposited on the island to an average depth of about 0.2m and the right bank of the channel has moved by about 17m. The overall effect was that the channel was bigger in 2015 than in 2011.

Figure 36: Aerial image of reach showing location of one of the cross-sections where comparison of 2011 and 2015 surveys was undertaken. © Getmapping

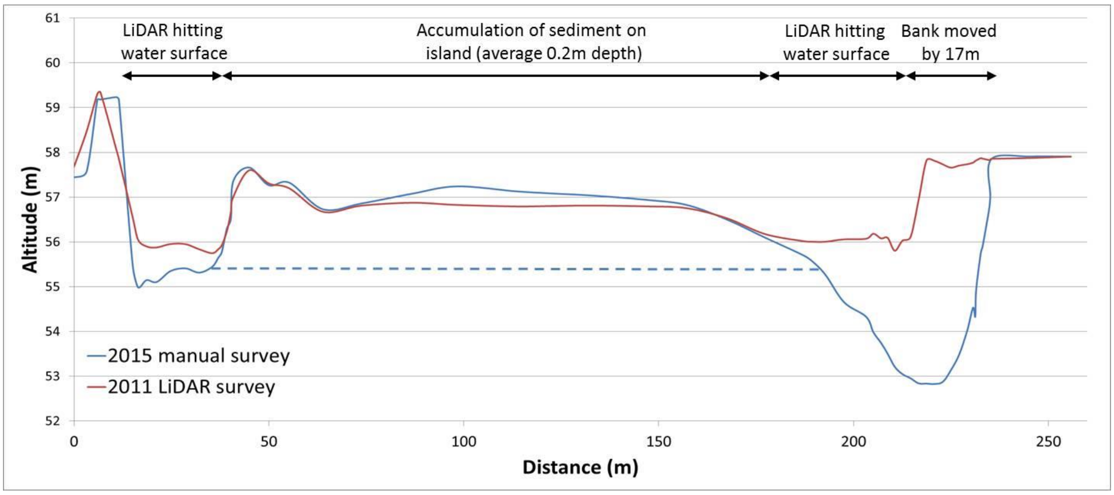

Figure 37: Comparison of cross-sections derived from 2011 LiDAR survey and 2015 manual survey. Dashed blue line represents the level to which the island was lowered in the flood model.

Flood modelling

Based on the 2015 cross-sections, we constructed a computer-based model of the river with which we could simulate the extent of flooding during high flows. We initially simulated a flow which only just started to spill out from the channel onto adjacent land. At this flow, which is likely to happen several times a year, only small parts of the areas of land identified as regularly flooding were inundated. The worst affected area was the low lying Lamb Island area (Figure 38 Baseline). We then simulated a higher flow (likely to happen once every 5 or ten years) which inundated more of the identified areas (Figure 39 Baseline).

We then changed the cross-section shown in Figure 37 in the model to simulate lowering of the island by about 1.5m. The model was then re-run with the two separate flows (Figure 38 Island lowered and Figure 39 Island lowered). Comparing between the "Baseline" and "Island lowered" results lowering of the island makes very little difference to the extent of flooding. At first glance the difference is hard to spot but there are very slight differences immediately upstream from the island. For the lower flow water level immediately upstream was lowered by less than 250mm. For the higher flow it was less than 180mm. In both cases this effect reduced with distance upstream. This makes very little difference to the extent of flooding. In other words, the removal of a large area and significant depth of sediment from the channel has made a negligible difference on the extent of flooding of adjacent land.

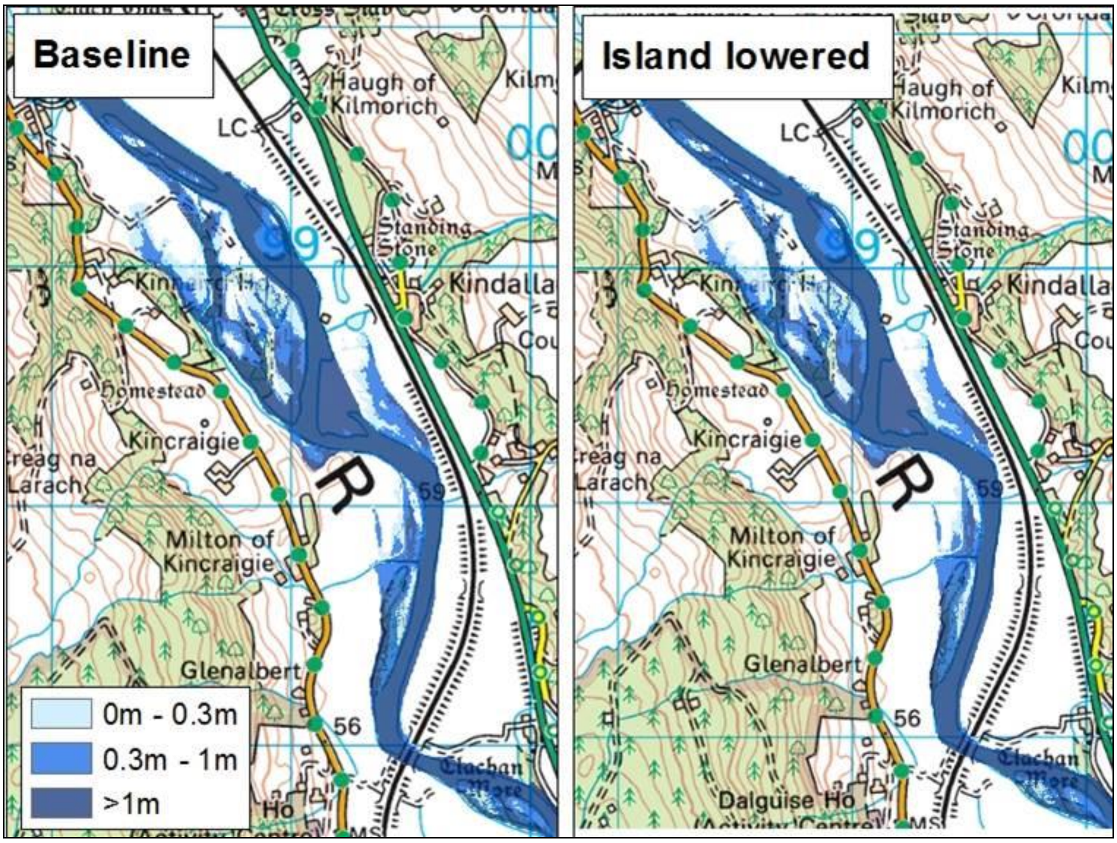

Figure 38: Predicted extent of flooding during a high flow which would occur several times a year. *©Crown copyright. All rights reserved. SEPA lic. no. 100016991.*

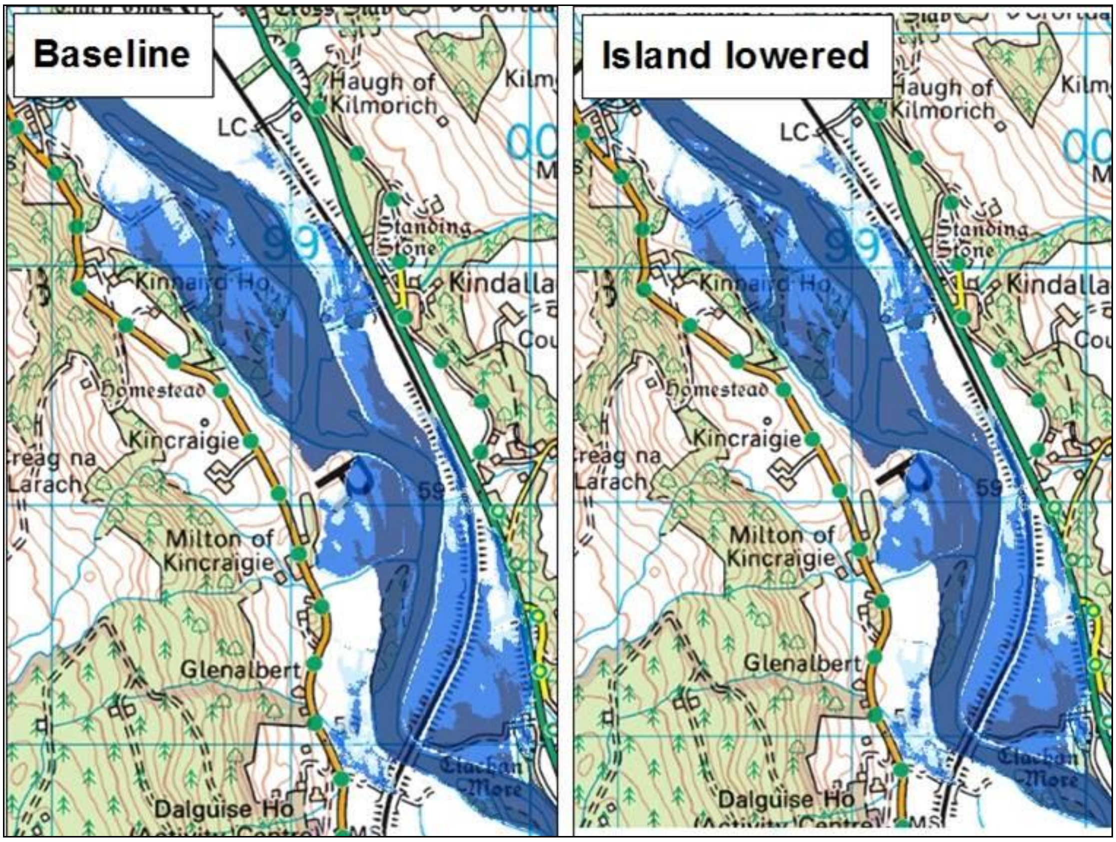

Figure 39: Predicted extent of flooding during a high flow which would occur once every five to ten years. *©Crown copyright. All rights reserved. SEPA lic. no. 100016991*

Using output from the flood model we were also able to see that constriction of the channel between the valley side and artificial embankment at Dune Kincraigie and through the railway bridge cause backing up of water during high flows.

Conclusions

The reach of interest has changed in character in the last 60 years or so. It was previously multi-thread but is now single thread. There is no single obvious reason for this change but it is likely to be due to a combination of factors including upstream modifications (principally hydro power development), a change in the pattern of flows (driven by a change in rainfall patterns) and other localised modifications to the channel such as embankments.

Prior to the change the reach was probably accumulating sediment, hence the multi-thread channel. The change to single thread implies that the channel is now more capable of transporting sediment through it. There is also evidence that in recent years the channel has become bigger due to the increase in high flows. This is despite the fact that there has been a visible increase in the areas of sediment in the channel. In other words there has been both erosion and deposition in the reach but overall slightly more erosion. This slight increase in erosion and adjustment of the channel shape in response to a change in flow suggests that the channel is in a state of balance. In other words over a long time period the amount of sediment coming into the reach is roughly the same as that leaving it but there will be fluctuations in both from time to time.

In this case, even removing a substantial amount of sediment from the channel did not have a noticeable effect on flooding of the adjacent land. There are other potential controls on water level during flooding in this case including the constriction of the channel between the embankment and the valley side at Dune Kincraigie and the railway bridge.

River Dee

Location

The River Dee reach is located immediately to the west and south of the village of Ballater (Figure 40).

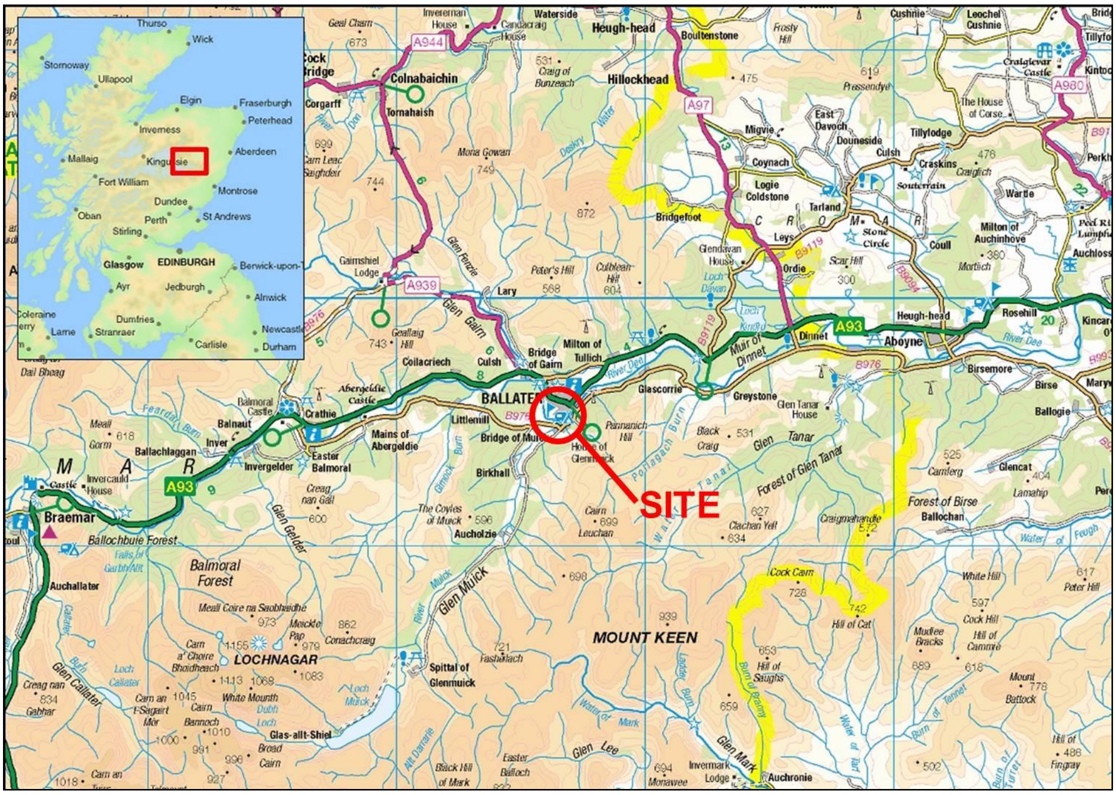

Figure 40: Location of River Dee site

The section of river channel where sediment deposits were identified and the areas of agricultural land identified as being affected by flooding are shown in Figure 41**.** In this case the areas affected are not immediately adjacent to the section of channel where sediment deposits were identified.

For the area to the south west of Ballater, it was quickly established that floodwater comes from the River Muick rather than the River Dee. Factors including the elevation difference between the River Muick and the River Dee and the topography of the surrounding land meant that we could quickly eliminate any connection between sediment deposition in the River Dee and flooding of this area. This was later verified by computer based flood modelling. A separate study on the River Muick would be required to establish any connection between sediment deposits in this river and flooding of that area. This is not part of the remit of this report.

The connection between the identified sediment deposits and the other areas to the north east of Ballater is by flow passing through the village during major floods, such as that in December 2015 when over 300 properties were flooded. It was understood from the site visit that the identified land does not flood from the Dee during smaller flood events. The focus of this study is therefore on the impact of the sediment deposits identified on flood risk during flood events such as that experienced in December 2015, but we also look at the impact of some sediment deposits further downstream nearer the areas of agricultural land identified.

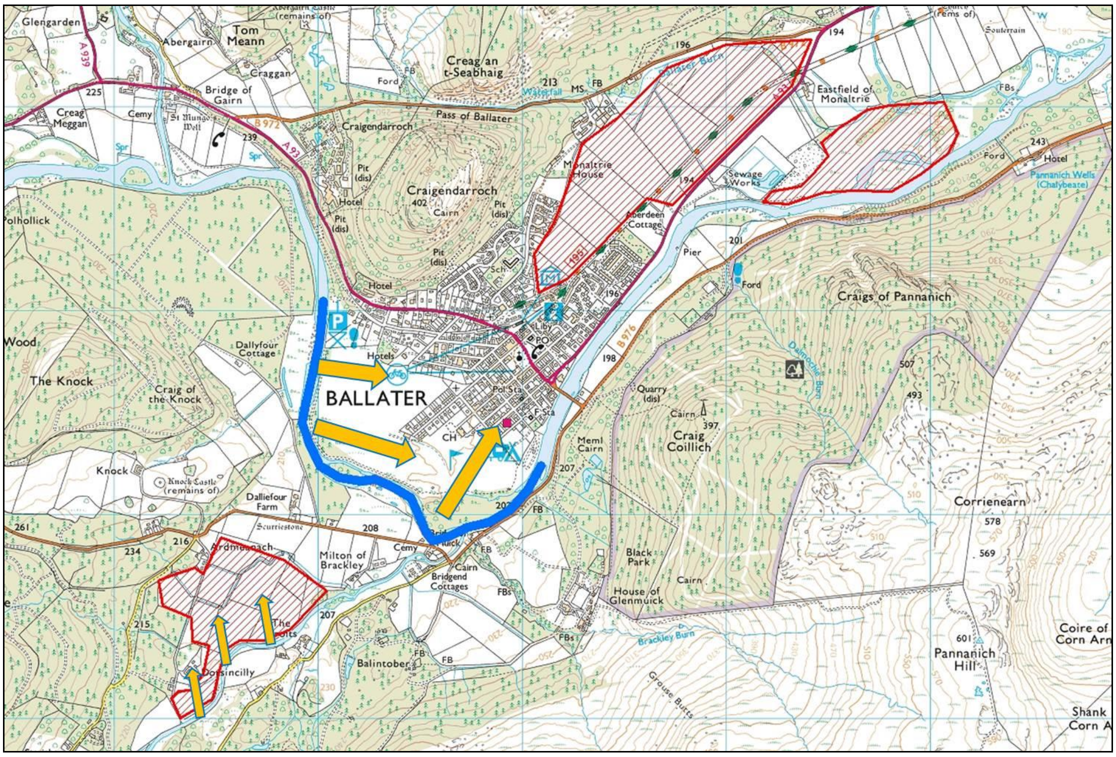

Figure 41: River Dee reach showing section with sediment deposits (blue line) and areas of adjacent agricultural land affected by flooding (red hatched). Orange arrows show the dominant flow path during floods.

Upstream Catchment

The River Dee is one of Scotland’s larger rivers. It has a total catchment area of about 2083km^2. The catchment area upstream from this reach is about 847km^2 (965km^2 if the River Muick is included). This is a substantial part of the catchment and means that the River Dee is already relatively large at this point; typically 40-50m wide compared to 70-80m wide at the downstream end.

The source is high in the Cairngorm Mountains at an altitude of over 800m. There are numerous tributaries in the upstream catchment some of which are significant watercourses in their own right. Upstream from Braemar there is the Geldie Burn, Lui Water, Ey Water, Quoich Water and Clunie Water. Between Braemar and Ballater there is the River Gairn and River Muick. These tributaries all start high in the Cairngorm Mountains.

Sediment sources

British Geological Society (BGS) mapping of superficial geology (i.e. consolidated sediment) within the catchment is shown in Figure 42. This shows that there are significant areas of sediment throughout the upstream catchment which can be eroded and transported by watercourses passing through them.

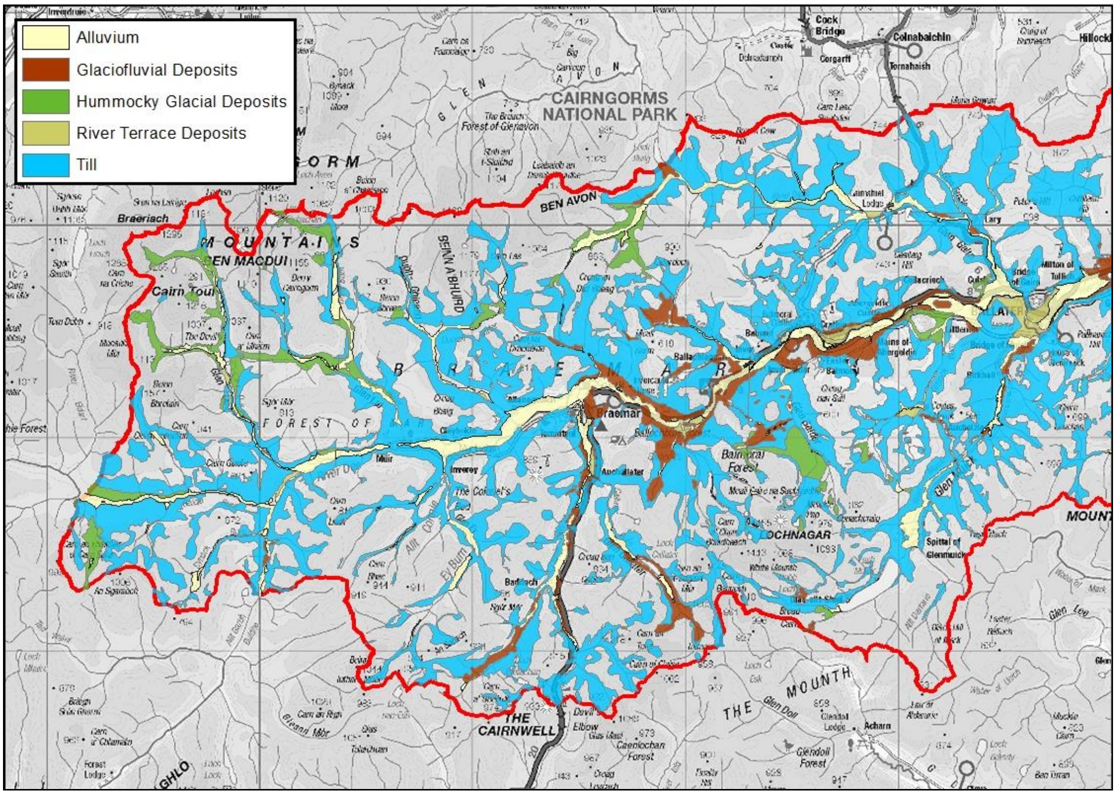

Figure 42: River Dee catchment upstream from Ballater (outlined in red) showing superficial deposits. *©Crown copyright. All rights reserved. SEPA lic. no. 100016991. © British Geological Survey*

Channel slope

Figure 43 shows the slope of the river from upstream of Braemar to downstream of Ballater. The short section upstream from Linn of Dee gives an indication of the steepness of the headwaters.

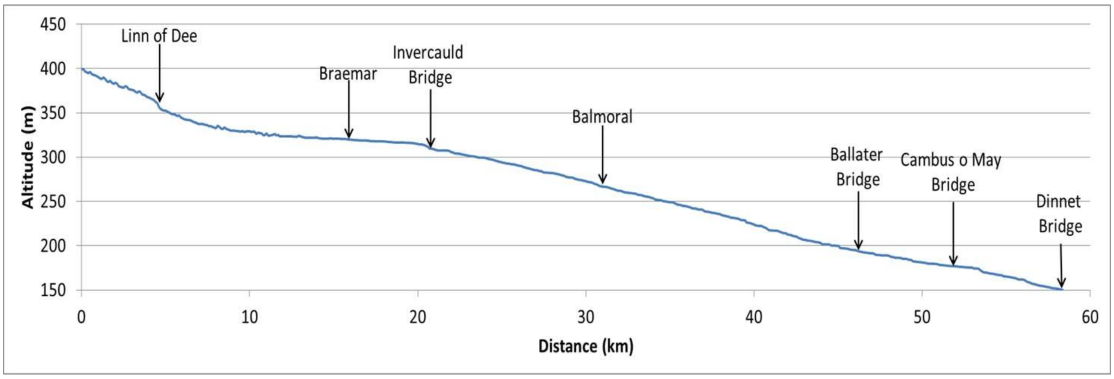

Figure 43: Slope of River Dee from upstream of Braemar to downstream of Ballater.

There is then a noticeable reduction in slope around Braemar and upstream from Invercauld Bridge. This means that the river is less capable of transporting sediment coming from the steeper headwaters upstream. We would therefore expect to see some deposition of sediment around this area. This can be seen on recent aerial images of this part of the river (Figure 44). Field observations confirm that there is some coarse sediment in the channel at Invercauld Bridge which suggests that some passes through from upstream.

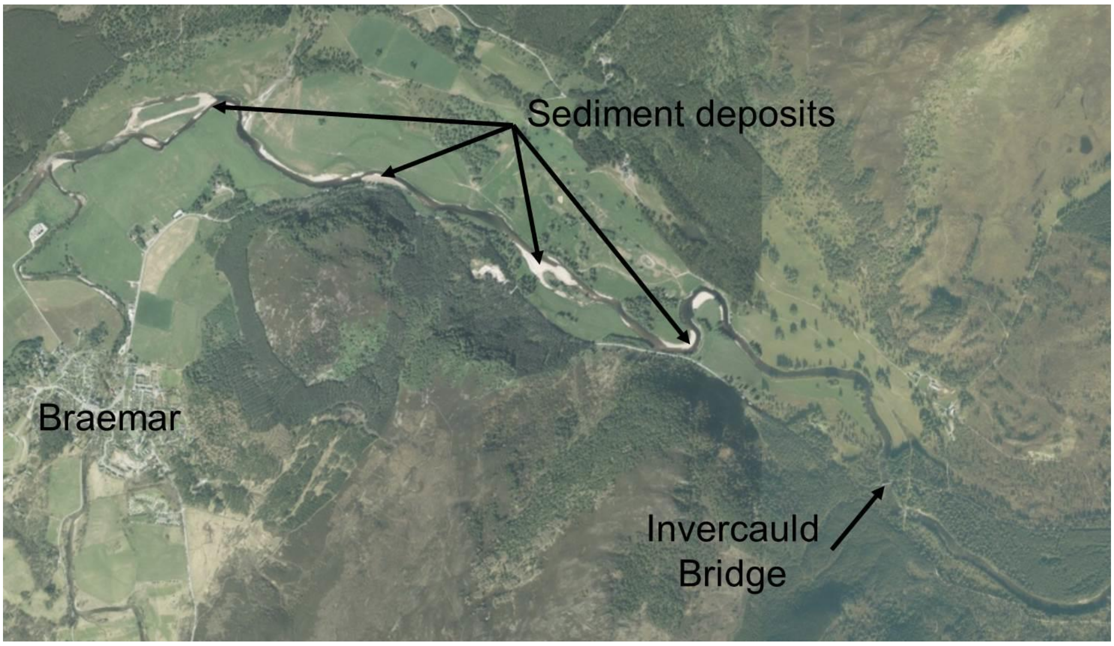

Figure 44: Recent aerial image of River Dee around Braemar showing extent of sediment deposits in the channel. © Getmapping

Between Invercauld Bridge and Ballater the slope increases and is fairly constant. This means that the river is more capable of transporting sediment. Recent aerial imagery of this section (Figure 45) shows that there is much less sediment deposited in the channel. The bed of the river in this section is generally very coarse consisting of cobbles and boulders. This suggests that coarse sediment can readily be transported through this part of the river.

Figure 45: Recent aerial image of a typical section of the River Dee between Invercauld Bridge and Ballater showing reduction in sediment deposits.
© Getmapping

Just upstream from Ballater there is a slight reduction in gradient and as a result an increase in the amount of sediment deposits in the channel (see recent aerial image Figure 46). A lot of this sediment is likely to be sourced from the section of river and tributaries between Invercauld Bridge and Ballater.

Figure 46: Recent aerial image of River Dee upstream from Ballater showing increase in sediment deposits in the channel. © Getmapping

Historic flows

We have operated a river gauging station on the River Dee at Polhollick (approximately 2.5km upstream from Ballater) since 1975. Figure 47 shows the highest flow recorded each year since then. There is no clear trend. It is however notable that there have been two very high flows in the last few years.

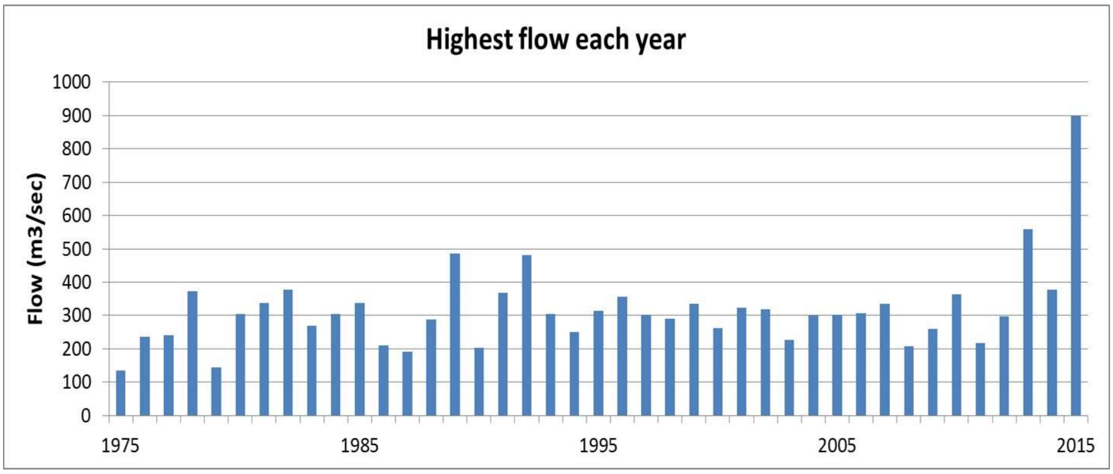

Figure 47: Highest flow recorded each year on the River Dee at the Polhollick gauging station just upstream from Ballater

Human modifications

McEwan (1985) presents evidence of channel straightening as early as 1734 and that bulldozing of confluences was common. Such activities commonly destabilise river channels leading to increased input of sediment as they readjust afterwards.

She also states that there is evidence of significant bank works even in the 17th and 18th centuries. The effect of this is less clear. In some cases it would reduce sediment input by preventing bank erosion but in other cases it would simply transfer and/or exacerbate erosion elsewhere.

She also points out that there was extensive felling of trees in the catchment in the 19th and 20th centuries but suggests that large flood events would still have been large flood events independent of land use changes. She states that deforestation, particularly of the floodplains and channel banks, is likely to have increased the availability of sediment for erosion and transport.

Summary

From the review of the catchment upstream from Ballater we can conclude that:

- there is a lot of coarse sediment available for erosion and transport however a lot of this sediment is deposited upstream of Invercauld Bridge;
- the bulk of sediment passing through the channel at Ballater comes from the channel and tributaries between Invercauld Bridge and Ballater;
- this is likely to mean that the sediment load at Ballater is relatively low for a river of this size;
- there has been no clear trend in flows in the river since gauging started in the 1970s but the last few years have seen some very high flows;
- this means that there has been a lot of energy available to erode and transport sediment recently.

Reach of interest

Changes over time

LiDAR (Light Detection and Ranging) is a technique used to survey the surface of the earth from an aeroplane. Recent LiDAR survey of the area around Ballater (Figure 48) shows that there are several old channels running across the golf course. This indicates that in the past (before the town of Ballater was established) the river was able to spread out across this area. It was able to do this because the valley becomes very wide at this point (see Figure 49 for indication of valley sides).

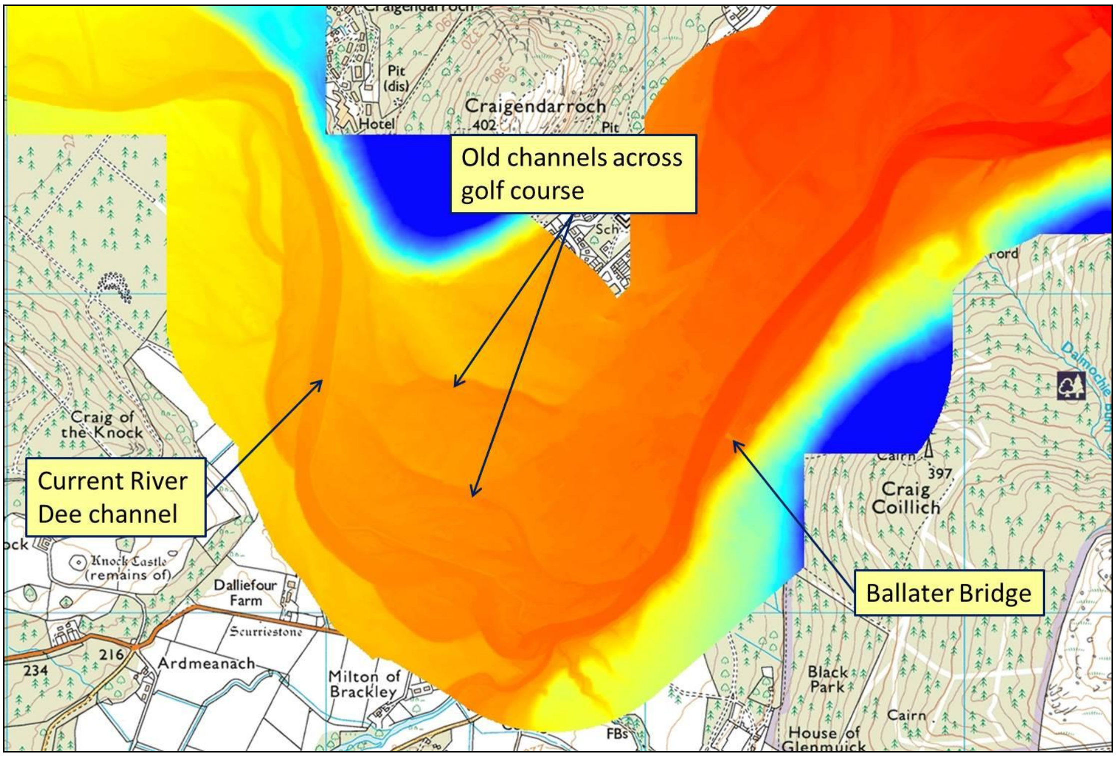

Figure 48: Map of Ballater overlaid with recent LiDAR survey shaded so that blue is high ground and red is low ground.

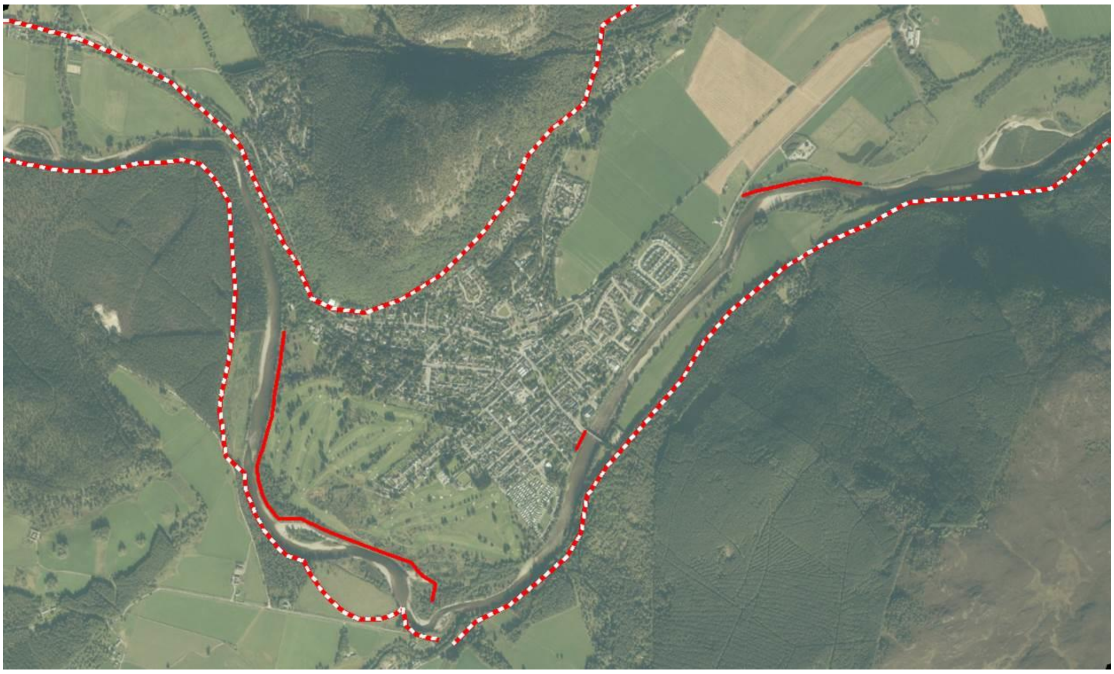

Figure 49: Recent aerial image of Ballater area. Red and white dashed lines indicate edges of River Dee valley. Solid red lines indicate extent of embankments.

The 1st Edition OS map from c1860 shows that the River Dee had roughly the same alignment as it does today albeit with some localised changes upstream and downstream from the River Muick confluence (Figure 50).

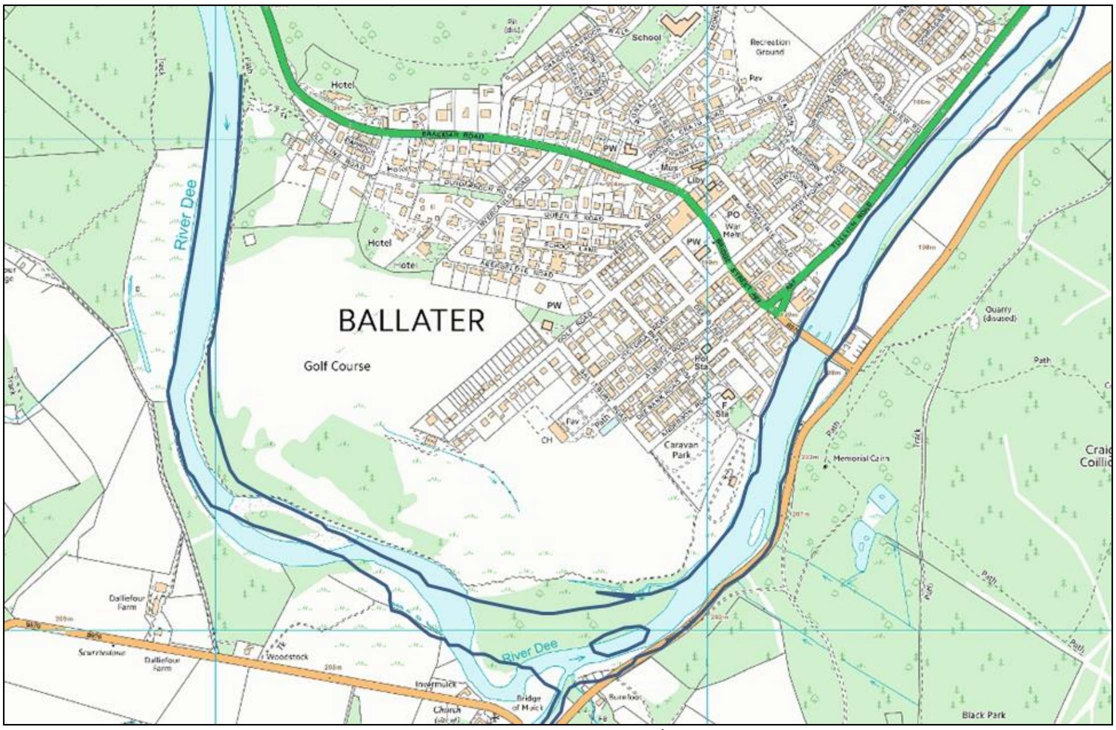

Figure 50: Outline of river channel shown on 1st Edition Ordnance Survey map from c1860 (dark blue lines) on current OS map.

Figure 49 also shows the extent of embankments adjacent to the river. It is not clear when these were constructed but they are not shown on either the c1860 or c1900 OS maps. An embankment raises the level of the ground adjacent to the river. This reduces the frequency at which water spills out of the channel onto the adjacent land.

As can be seen from Figure 49 the construction of the embankment around the golf course to the west of the village has created a very narrow corridor for the river to flow through. This is not a problem for normal flows however when flows increase this presents a constriction to the flow. It is a like when a finger is placed over the end of a hosepipe. Two things happen during high flows; the water speeds up through the constriction and backs up behind the constriction.

As a result of water backing up behind the constriction, water level rises higher than if the river was less constrained. We used a computer model of the river to show that the narrowest point between the valley side and the embankment is the first point at which water overtops the embankment during very high flows such as those experienced in December 2015 (Figure 51).

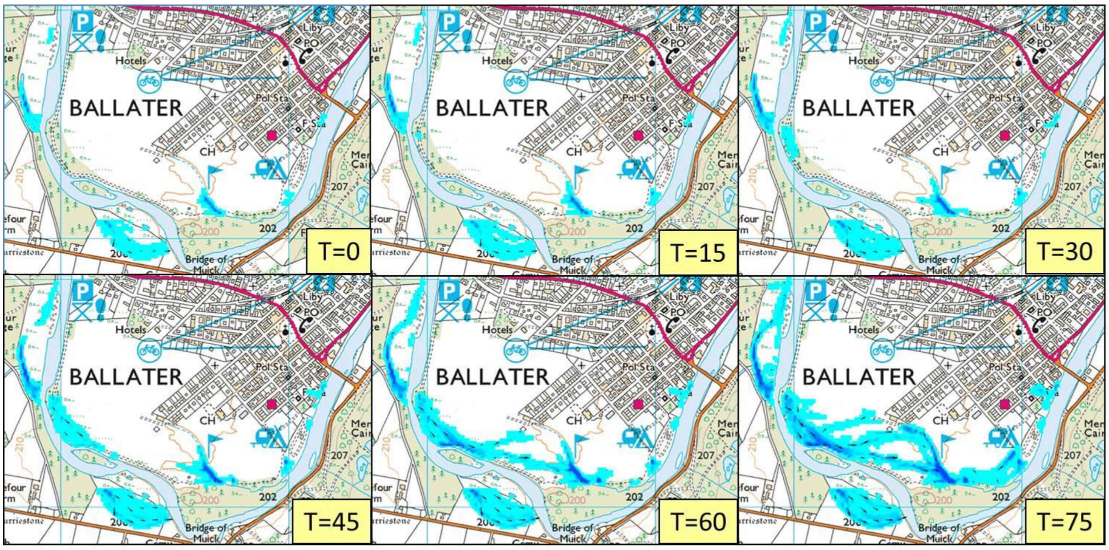

Figure 51: Output from computer based flood model of the River Dee at Ballater showing the spread of flow across the floodplain after the embankment is overtopped. Note that the first point of overtopping is where the river is most constrained by the embankment. T=0 is the time at which the embankment is just about to overtop. Each image then shows the extent of flow after every 15 minute interval.

It is common that historic or poorly constructed embankments breach soon after they are overtopped. The rush of water down the steep rear face causes scour reducing the structural integrity of the embankment. As the fast flowing water hits the ground at the bottom of the steep face a scour hole develops undermining the foundation of the embankment further weakening it. Ultimately the scour results in collapse of the embankment.

The embankment at the narrowest point failed during the floods of December 2015. It is very likely that this is the way that it failed. The result would have been a sudden rush of water across the golf course and through the village and there are anecdotal reports that this is what happened.

The other effect of the narrowing is the speeding up of flow through the constriction. The result of this is clear to see in this case. There has been extensive and severe erosion of the bank of the river downstream on the outside of the bend. This is known locally as the Red Brae (Figure 52). It is approximately 9m high, 300-400m long and it is estimated that it retreated by up to 20m between 2011 and 2016, probably mostly during the floods of December 2015.

Figure 52: Severe erosion on the outside bend of the River Dee at Ballater immediately downstream from constriction caused by the embankment.

Recent changes

As indicated in the section above, there have been some major changes to the river channel in recent years. By comparing LiDAR surveys from 2011 and 2016 we can identify changes in the height of the ground along the river. Where the ground was lower in 2016 than it was in 2011 there has been erosion and where the ground was higher in 2016 than it was in 2011 there has been deposition.

As has already been noted, LiDAR cannot penetrate water so the wetted river bed cannot be seen at the time of survey. Despite this, we know that the flow on the day of each survey was low (below the mean annual flow). The flow during the 2016 survey was lower than during the 2011 survey. We estimated that as a result of this the water level would have been between 0.1m and 0.15m lower during the 2016 survey than the 2011 survey at Ballater.

We first compared the surveys over a 5km length of channel around Ballater (Figure 53). We found that there had been roughly 100,000 Tonnes of erosion and 55,000 Tonnes of deposition between 2011 and 2016. This means that there was net erosion of about 50,000 Tonnes. Allowing for the difference in water level this would reduce to overall net erosion of about 38,000Tonnes. This is equivalent to about 8½ Olympic sized swimming pools worth of sediment.

Figure 53: Aerial image of 5km reach at Ballater overlaid with comparison of LiDAR between 2011 and 2016. Red areas show erosion (land lower in 2016 than 2011) and blue areas show deposition (land higher in 2016 than in 2011). Light colours indicate small changes and dark colours indicate large changes.

Figure 53 shows that erosion was prevalent throughout the reach and particularly along the margins of the channel. There were two main areas where erosion was significant; the outside of the bend at the Red Brae area and the channel bed upstream from Ballater Bridge. There was also considerable deposition on the inside of the bend at the Red Brae area. For this reason we also compared the surveys but just for this area (Figure 54).

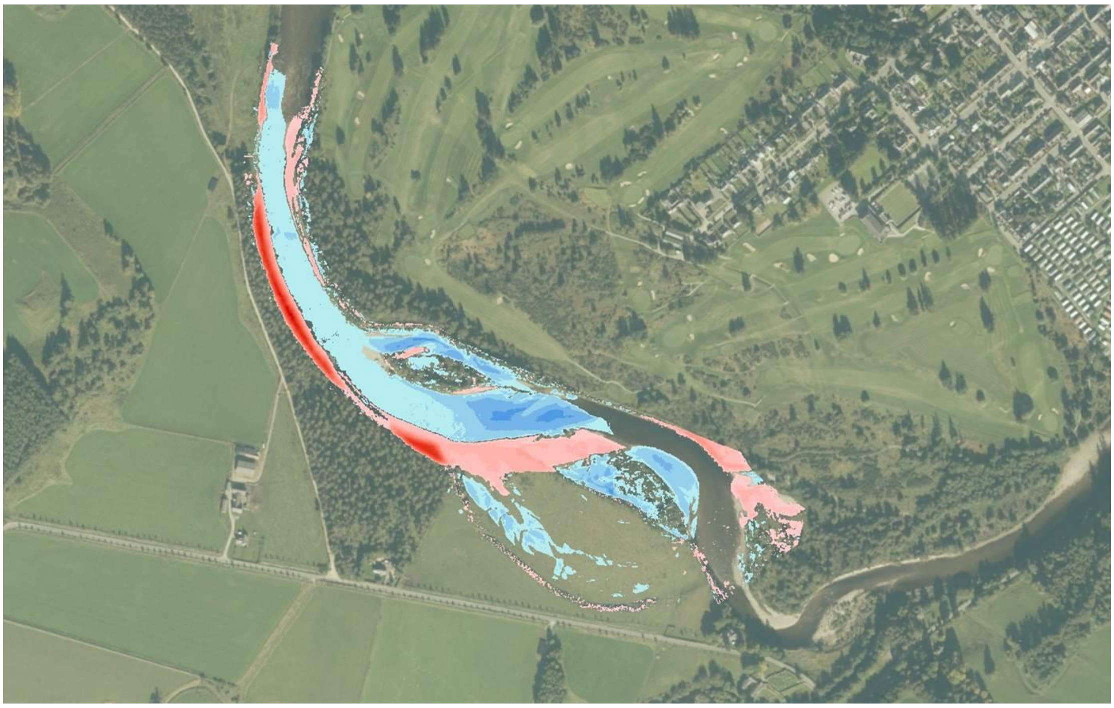

Figure 54: Aerial image of the "Red Brae" area overlaid with comparison of LiDAR between 2011 and 2016. Colours as per Figure 53. © Getmapping

We found that in this area there was net overall erosion of about 18,000Tonnes (allowing for water level difference). This is equivalent to about 4 Olympic sized swimming pools worth of sediment. It is interesting that despite the appearance of significant areas of "new" sediment following the floods in Dec 2015 in particular (e.g. **Figure 55**), there has in fact been net erosion. In other words, the large flood events have re-distributed sediment in the channel but overall the channel is now slightly bigger.

Figure 55: Significant area of recently deposited sediment in the side channel opposite the Red Brae. Sediment had been removed from this side channel in 1994 following concerns about flooding and erosion of the Red Brae opposite.

It is also interesting to look at where sediment has been deposited and the implications this has for flood risk. To do this we compared two of the cross-sections at the Red Brae area from 2016; one at the narrow point where the embankment breached and the other where the side channel filled up with sediment (approximately 350m downstream). The location of the cross-sections is shown in **Figure 56** and the cross-sections are shown in Figure 57.

Figure 56: Aerial image of Red Brae area showing location of cross-sections.

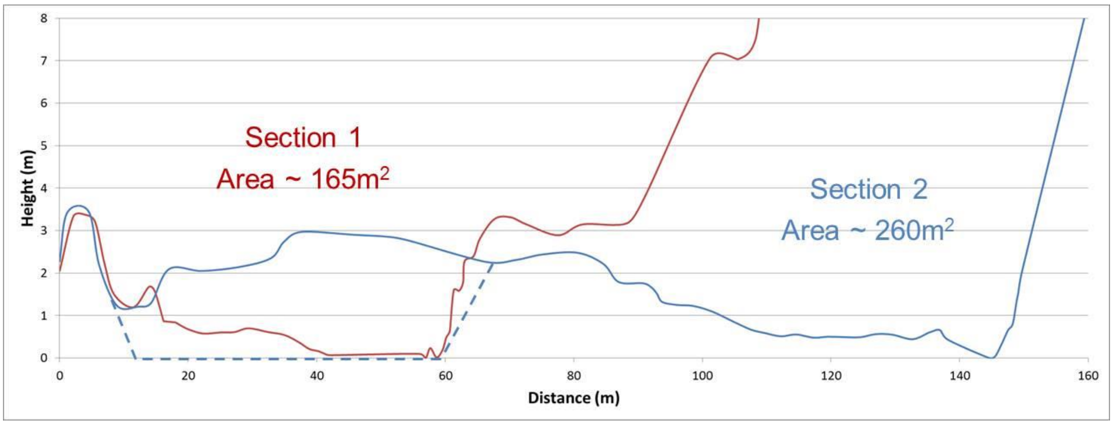

Figure 57: Comparison of cross-sections from Figure 56**. Cross-sections are drawn as if looking downstream. The datum is taken as the lowest point in each cross-section. The dotted blue line shows modification to Cross-Section 2 for flood modelling (see section below). The area was calculated under a horizontal line drawn from the highest point on the left bank.**

We do not have accurate historic cross-sections for this point in the channel so we cannot confidently tell how these sections have changed. At Cross-section 2 it appears there has been significant deposition in the side channel but there has also been significant erosion on the outside of the bend. Even if there has been net deposition in this section this would make limited difference to flood risk. The reason for this is that the cross-section is significantly larger than the narrower section upstream. In basic terms, the larger cross-section can carry more water before overtopping the left bank. Since the smaller cross-section is upstream it is this that controls when the left bank overtops. This finding is validated by the flood model output in Figure 51.

Flood modelling

To further investigate the role of sediment deposits in flood risk we removed a large area from Cross-Section 2 (dotted blue line in Figure 57) to simulate removal of sediment from the side channel and re-ran the computer flood model. The removed sediment would equate to about 30,000Tonnes of sediment (about 6½ Olympic sized swimming pools) which would be a sizeable engineering operation. This is roughly equivalent to works that were carried out in 1994.

The modification makes no appreciable difference to when the left bank at Cross-Section 1 overtops in an event like the one in December 2015. At the flow which just overtops the bank there would be a lowering of water level at Cross-Section 2 however this would only equate to about 0.2m. As flow continues to rise this effect reduces until at the very high flows there is no discernable difference (Figure 58). This shows that in this case significant removal of recently deposited sediment makes minimal or no difference to flood risk. Recent history also shows us that even the little effect achieved would reduce over time i.e. the sediment removed in 1994 has already returned.

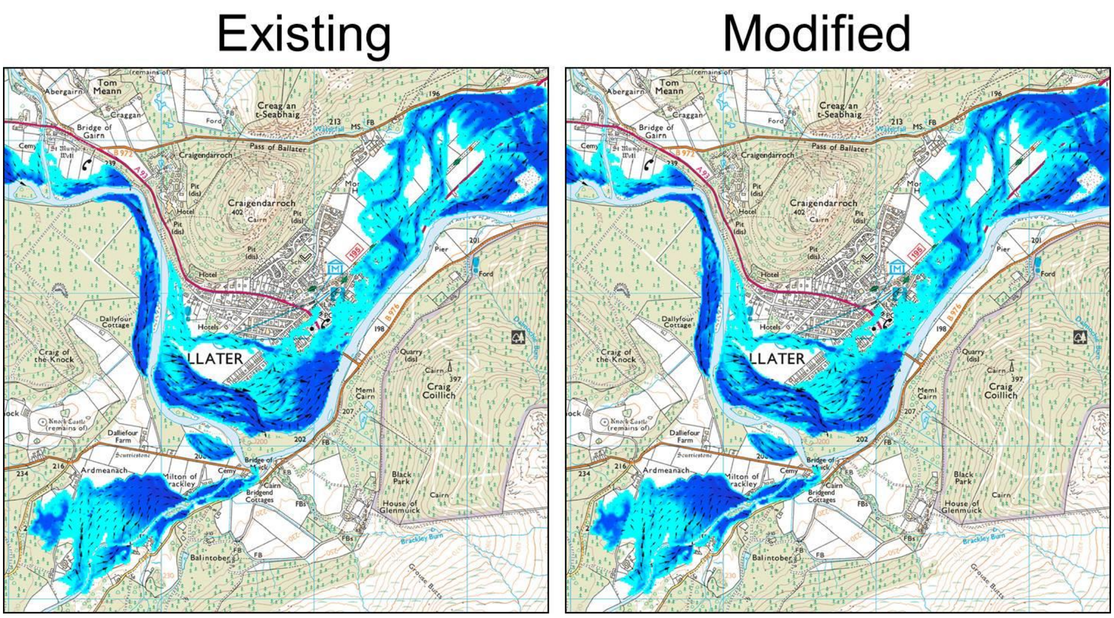

Figure 58: Output from computer flood model showing flood extent at a very high flow (equivalent to flood event in Dec 2015) for current channel (existing) and modified channel as per Figure 57.

We also investigated what would happen if the sediment in the channel opposite the sewage works downstream from Ballater was removed. Removing even a large amount of sediment from this section would only have a small and localised effect on flood risk to the adjacent land. It would also have a small negative effect on land downstream by increasing flow and slightly elevating water levels. If sediment was removed it is very likely that it would quickly re-establish meaning that the small benefit gained would also be short lived.

Conclusions

The amount of sediment coming into the River Dee at Ballater from upstream is likely to be relatively low for a river of this size. This is principally due to variations in the slope of the river upstream which means that a lot of the sediment coming from the upper catchment does not get this far.

The river is however still subject to very high flows at this point. High flows generate the energy to erode and transport sediment. The combination of high flows and relatively low sediment input in this part of the river means that overall there is erosion. This has probably been exacerbated by the occurrence of several very high flows in recent years.

It is notable in this case that despite our finding that there has been overall erosion there has clearly also been localised deposition. The deposition has occurred in already large sections of the river and as such has no bearing on flood risk. Removal of this sediment would make no appreciable difference to flood risk.

In this case, although the embankment provides protection from flooding of adjacent land up to a certain level of flow the constriction caused by it raises water level quickly at this point during flood events making it the first point where flood water overtops the embankment.

General Principles

The three sites studied represent the three different states of sediment transport which can exist in rivers. These are

- **Depositional** - over a long period of time sediment accumulates within a reach[7]. The River Feshie site is an example of this.
- **Balanced** - over a long time period the amount of sediment coming into a reach roughly equals the amount leaving it. The River Tay site is an example of this.
- **Erosional** - over a long time period more sediment leaves a reach than comes in from upstream. The River Dee site is an example of this.

Identifying which of the three states a reach of river is currently in requires careful assessment. A purely visual assessment alone cannot be relied on to confidently identify this. This was illustrated clearly at the River Dee site where despite it being net erosional there was a lot of recently deposited sediment. In other words, just because we can see sediment in the channel we cannot assume that the reach is depositional. In fact, we would expect to see sediment deposits in the channel for all three states.

It is also important to think about how sediment is being transported through river *reaches* rather than just one particular point. Reaches can vary in length from a couple of hundred meters to several kilometres. It is rarely appropriate to assess the state of a river based on what is happening at one bend. Identifying appropriate reaches needs to be part of the assessment.

Studying the link between sediment deposits and flood risk at the three sites *suggests* that

- Sediment management may be a valid option for reducing flood risk in **depositional** reaches. This is particularly the case in depositional reaches which have been artificially constrained by bank protection and/or embankments. A “little and often” approach will help to avoid instability which may make the situation worse in the long run. There are other

[7] In this context a reach of river is a length of river which is defined by the processes of erosion and deposition. The length varies depending on many factors such as underlying geology, channel slope, discharge and sediment input. Reaches are normally 100s of meters if not then kilometres in length.

options which are worth considering though and these may offer a more sustainable and cost effective solution in the long term. These include setting back constraints or creating more space for the river to spread out so that deposition of sediment does not reduce channel capacity so quickly.

- Sediment management in **balanced** or **erosional** reaches is unlikely to provide much if any reduction in flood risk. In both cases there is also a risk that removing sediment from the reach will destabilise it and create more problems than it solves.

In the case of the River Feshie the deposition of sediment is a natural phenomenon. This is caused by the change in slope of the river as it joins the River Spey. In its natural state sediment would spread out over a wide area as it was deposited and so build up slowly. Now that the channel is confined between embankments the sediment cannot spread out and so builds up much more quickly in the channel.

Other things which can cause deposition in rivers are:

- **Bedrock in the channel bed**. This prevents lowering of the river bed and therefore controls the slope of the river upstream. Because of this it is common to find a low channel slope upstream from bedrock which promotes deposition of sediment.

- **Natural or artificial constrictions on the channel**. When a channel is constrained (i.e. prevented from spreading out onto a floodplain) water level during high flows rises higher than if it was unconstrained. This causes backing up of water upstream. This backing up can slow down flow such that sediment drops out upstream from the constriction. A narrow or low bridge would be an example of an artificial constriction where this could happen.

- **Lochs or reservoirs**. Water entering a loch or reservoir becomes very deep and very slow moving. It can therefore not move a lot of the sediment coming from upstream. Most coarse sediment will therefore be deposited upstream from a loch or reservoir. The location and extent of deposition will depend on the slope of the channel upstream and any fluctuation in water level on the loch or reservoir.

- **Artificial channels through naturally low lying land.** Low lying flat areas of land have frequently been drained to improve the land for agriculture or other use. These areas would naturally have been wetland or boggy bits of land with no obvious river channel. Drains or ditches created in these areas often have a low slope and so are prone to deposition of sediment. This is normally fine sediment (sand and silt) which can become colonised by vegetation. This vegetation can then encourage further deposition of sediment.

This study has been based on three sites which cover the range of sediment transport reach types. The findings are in line with well understood theories about how rivers work though. The general principles drawn out will therefore be applicable to many situations. We have also recently carried out a review of nine local authority flood alleviation schemes where sediment was thought to be a possible cause. In only two out of the nine schemes was dredging of sediment identified as a solution. In the other seven cases dredging had little benefit, was not cost effective or artificial constrictions (bridges/culverts) had a bigger influence.

This study has shown that careful investigation of a particular site using all available sources of information can lead to a good understanding of the interaction between sediment deposits and flood risk.