THE GREAT TAY FLOOD OF JANUARY 1993

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Flooding is a natural process which each year sees rivers across the United Kingdom rise out of their banks and occupy floodplains which have been developing over many thousands of years. In relatively recent times the growth of towns and cities on floodplains has caused society to become more vulnerable to the effects of flooding which, although often lasting for no more than a few days within periods of tens of years, can nonetheless be severe. Defences built to protect settlements from the flood hazard are rarely able to afford total protection. In January 1993 river levels at Perth, at the foot of the UK's largest river, reached their highest stage since 1814. This paper explores the causes of the flood, its historical context, and examines its impact and implications.

Introduction

The Tay flood of January 1993 was, in one sense, history repeating itself as a major event with some similar characteristics had occurred just three years previously. However, the peak flow at Perth was 30% greater in the second event, with a disproportionately large increase in the damage caused.

The Tay flood of February 1990 had significance not only in a regional context – flooding many rural and urban properties, inundating tens of square kilometres of floodplain and dislocating transport links – but also on a national scale. It appeared as the culmination of a remarkably wet phase in Highland Scotland, and in a year which was later to witness severe drought in eastern and southern England[1]. The flood was thought to be the highest since November 1951, and its magnitude alerted the local community to the very real dangers of flooding in Perth. Few would have thought, after a 40-year period of relatively minor flooding problems, that a much greater event would visit the Tay just three years later.

The peak flow recorded in February 1990 at Ballathie gauging station, 8 km upstream of Perth (Figure 1), was 1965 m^3s^{-1}. By comparison the peak on the 17th January 1993 reached 2268 m^3s^{-1} and the corresponding daily mean flow of 1965 m^3s^{-1} represents a new record for the UK National River Flow Archive. In the week preceding the 17th, large snow accumulations had built up throughout the catchment, down to low levels, and with the passage of two frontal systems on the 14th and 16th bringing heavy rainfall and temperature rises (both of which contributing to snowmelt), large volumes of runoff were generated. The resulting flood was the largest at Perth since 1814. In many parts of Perth, including the city centre and much of a large housing estate to the north, properties were severely inundated, with attendant economic and social costs. In the rural catchment, over 50 km^2 of farmland was inundated, floodbanks were breached, villages were isolated and major transport links were dislocated. The weather conditions responsible for these dramatic events form the starting point of this account.

Weather Conditions

January 1993 was unusual from a meteorological perspective in a number of ways. The month was characterised by a remarkable succession of Atlantic frontal systems[3], including what may have been the deepest depression to pass over the UK this century. Each brought to Scotland either rain, snow or both and by mid-month rivers in many areas were at moderately high levels. The wintry conditions experienced from the 8th to the 14th produced substantial snow depths not only on high ground, but also over coastal areas. Roads were blocked on the 11th in many of the usual Highland trouble-spots and also, for example, on the Fife coast where such problems are much less frequent.

Rainfall over the first ten days of January was equivalent to the monthly average at many localities in the Tay catchment, and the weather continued in the same very unsettled vein over the next few days[4]. Over the night of 14th January, a temperature rise of typically 4–6°C, accompanied by moderately heavy rainfall, resulted from the passage of another vigorous weather system. This rainfall was most intense in the headwaters of the adjacent Earn catchment, 58.6 mm being recorded at Lochearnhead. The overall effect was a widespread melting of snow at elevations up to 400 m. Temperatures remained high throughout the 15th, and meltwater produced very high flows in many coastal and lowland rivers, while headwater streams displayed a more modest response, though on the Tay at Ballathie (despite a mostly upland catchment) the peak flow for the 15th of 1025 m^3s^{-1} was close to the mean annual flood value.

After an overnight fall in temperature, another general rise occurred on the 16th, associated with the passage of a further warm front and bringing more heavy, wind-driven rain. While there had been substantial snowmelt at lower altitudes, some snow remained in these areas, along with deeper accumulations at higher levels. Moreover, much of the recent rain had accumulated within the snowpack, bringing it to a very unstable state in many areas. In some cases, e.g. at mid-altitudes in the Braan and Almond catchments, the snowpack became mobilised under its own weight, and flowed down slopes in a manner analogous to the failure of a saturated soil. Daytime temperatures on the 16th were sufficiently high to exceed freezing point on the highest mountains, while approaching 10°C at 250 m, e.g. at Kindrogan in the Ardle catchment. Coupled with the rainfall, snowmelt occurred throughout the catchment, and with rivers still at high flows, it was inevitable that extreme rates of runoff would occur.

Generation of the Flood Peak

Unlike the 1990 flood, the feature which so importantly characterised this event was the large amount of runoff contributing to the main flood peak from *all* major sub-catchments. In particular, the River Isla and other tributaries at the bottom of the Tay system (Figure 1) made large contributions to the peak, while in 1990 their effect was either minor or, in the case of the Isla, negative. Flow from the Isla on that occasion was so small in comparison with the main river that Tay floodwaters were able to cause reverse flow in its lowest reaches. Some details are provided here to illustrate the magnitude of the water fluxes involved, and the importance of the timing from individual sub-catchments in producing the final peak.

Figures 2a–c show the hydrographs recorded on the Tay and its main tributaries through the 1993 event. It can be seen that peaks emerging from adjacent catchments were often coincident in time, notably at the Garry-Tummel, Tay-Tummel and Tay-Isla confluences, such that the resulting downstream peaks were the highest possible with the given input hydrographs. The likelihood of such coincidences is low, and reflects the nature of the developing weather pattern over the area at that time.

It is important to note the impact of the hydropower schemes of the area. Four of the large storage reservoirs in the Tummel-Garry and Breadalbane schemes – Lochs Lyon, Ericht, Errochty and Loch an Daimh – were able to continue storing water without any spillage throughout the entire event and, receiving water from approximately 15% of the catchment to Perth, thus afforded substantial reduction of the downstream peak that would otherwise have resulted. Further attenuation was afforded by floodwaters taking up capacity in many other reservoirs which had filled, and then lost water as spillage, during the event; unfortunately draw-down rates severely limit the potential for providing alleviation capacity within these reservoirs. The modest initial increase in runoff from the highly regulated Tummel valley can be seen in Figure 2(a). Flows in the Tay at Kenmore (Figure 2b, station 15016) were also slow to rise, but as a result of the natural damping effect of Loch Tay; the result at the Tay-Lyon confluence was a modest time-displacement of peaks from the two rivers.

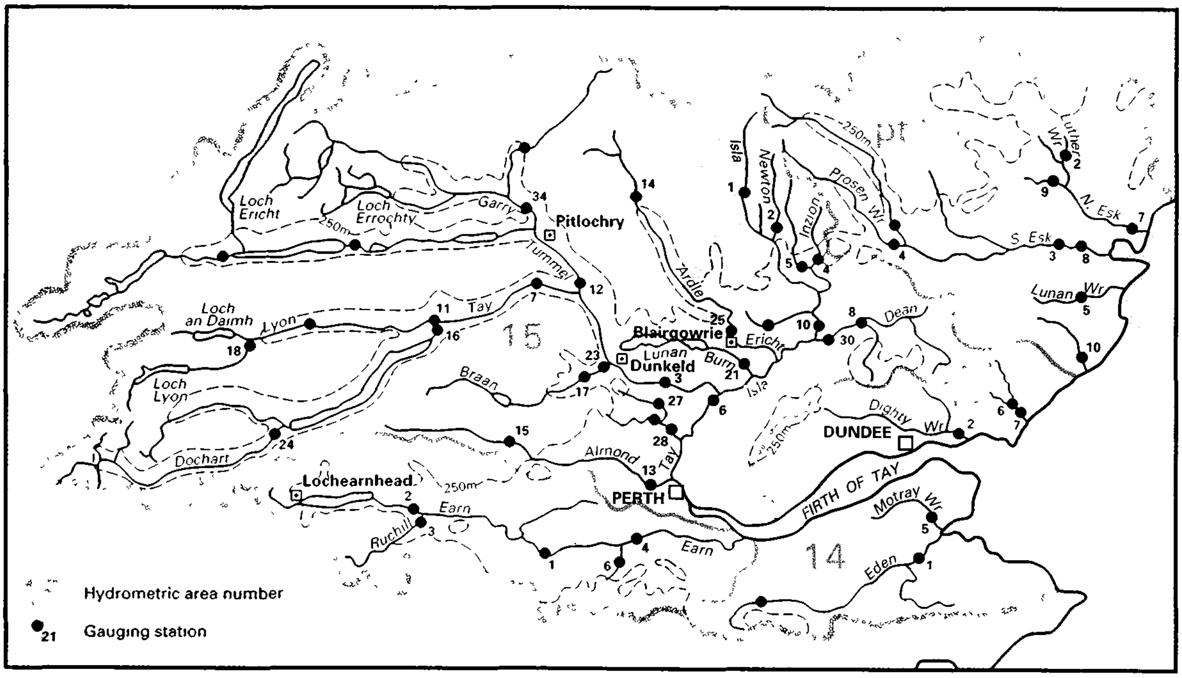


Figure 1 The catchment of the River Tay
(Gauging station reference details appear on page 137; to derive the full station number see page 35)

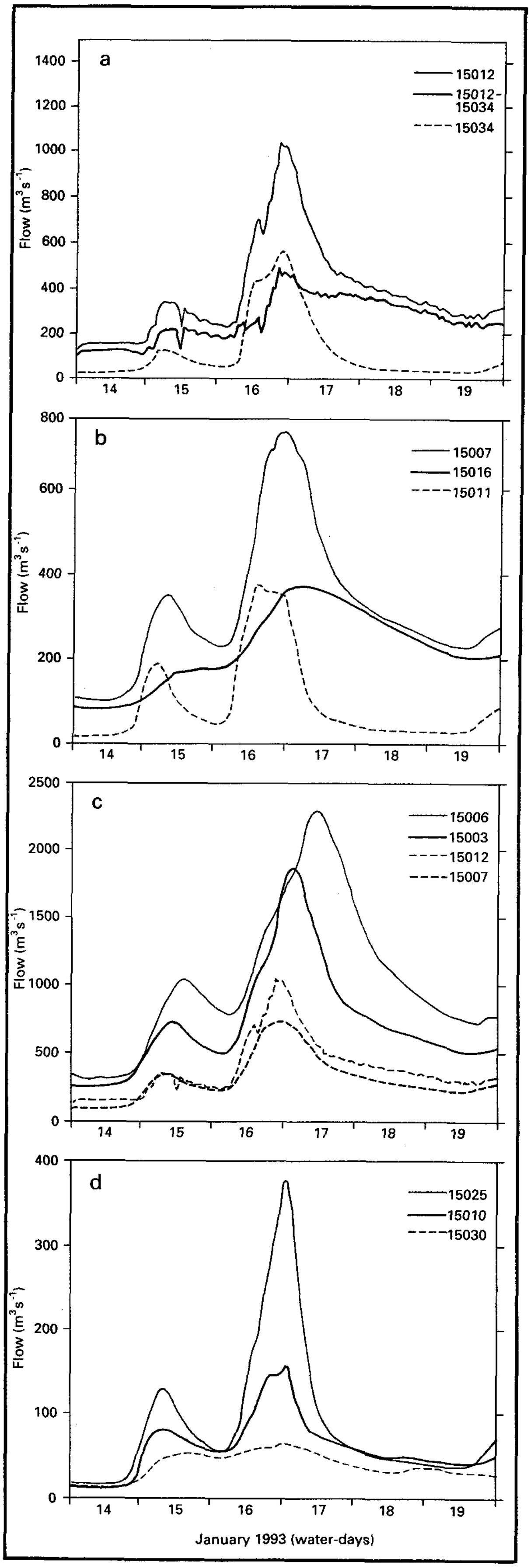


Figure 2 Hydrographs of the River Tay and major tributaries during the flood of January 1993 (The key gives the relevant gauging station numbers - see Fig. 1 for station locations)

On the Tay floodplain downstream of the Tummel confluence, large areas of agricultural land are protected from flooding by an extensive network of floodbanks, and a similar situation applies on the floodplain of the lower Isla. As these rivers rose to unusually high levels, the floodbanks were overtopped and often breached, causing extensive inundation. The result was further attenuation of the flood wave although the high flow in the Tay was such that this effect is thought to have been modest. Suggestions have been made[5] that flood damage may be reduced by locating embankments further away from the main river channel, but hydraulic modelling of these areas[6] suggests that the present configuration is near-optimal in terms of flood wave attenuation, and it is unlikely that major changes will follow this most recent flood.

As mentioned above, the role of the River Isla in the January 1993 flood proved to be very different to that of February 1990, and Figure 2c shows the increase in the flood peak from 1873 m^3s^{-1} at Caputh to 2269 m^3s^{-1} at Ballathie, below the Tay-Isla confluence. For hydraulic reasons, it is not possible to operate a current meter gauging station on the lower Isla, but the behaviour of the three principal rivers in this catchment can be seen in Figure 2d, and it is evident that the Dean Water (15030), draining the eastern extremity of the catchment (230 km^2), produced only very modest rates of runoff. With the highest recorded flow in the Tay just 8 km upstream of Perth, and no floodplain storage available to significantly reduce the peak, major flooding in Perth was inevitable. However, the recent installation of a flood warning system provided the potential to reduce the effects of such inundation.

Flood Warnings

A request by the local authorities and other organisations for the Tay River Purification Board to develop a warning system for the Rivers Tay and Earn was one of the consequences of the 1990 flooding. By the end of 1990 a system was operational on the River Tay and was extended to cover the Rivers Earn and Isla by the autumn of 1991. The warning system was based largely on the existing hydrometric network, modified by the installation of a telemetry based data logging and alarm system. A number of new gauging stations were installed where gaps existed in the hydrometric network, most notably in the catchments of the Rivers Tummel and Garry, and these helped to increase warning lead times.

Three levels of warning are currently in use[2,7]: Yellow (flooding possible - minor flooding of low lying agricultural land), Amber (flooding likely - agricultural land, some roads and high risk properties), and Red (serious flooding likely - agricultural land, properties, communications; flood defences at risk). The rural areas of the catchment and smaller communities are organised into flood warning groups of 5–10 people, most of which receive Amber and Red warnings. The Yellow warning is issued only to farming groups with very vulnerable land. All flood warnings are issued by the Tay River Purification Board to Tayside Police who pass on the warnings to the flood warning groups, the public and other bodies.

Since January 1991 the system has been activated on several occasions, principally for Amber level warnings, and these soon provided the Board, Police and warning groups with some experience of the system. It was to receive its first significant test in the floods of January 1993. At 1030 hours on Thursday 14th January the Board, with regard to the weather forecast for thaw and overnight rain, contacted the Control Room of Scottish Hydro-Electric Plc for an assessment of the storage situation in the Tummel-Garry and Breadalbane Hydro-Electric Schemes. The Board and Scottish Hydro-Electric were then in regular contact throughout the period of the flood events.

At 1130 hours on the 14th the Board issued formal Yellow warnings to the farming flood warning groups in the upper and middle reaches of the Tay and Earn catchments. These were precautionary warnings to indicate that river conditions in excess of bankfull could develop overnight. As well as issuing these warnings through the formal channels of Tayside Police, the Board also contacted the leaders of these warning groups to explain the reasons for issuing the warnings in advance of the developing river conditions and the Board's concern for potentially more severe flooding.

On Friday 15th most flood risk areas were elevated to Amber status as river levels rose throughout the day. By 1030 hours the River Earn was placed on Red alert and this status remained throughout the weekend. On the River Tay the first Red warnings for the upper reaches were issued at 1445 hours on the 16th and these were extended to cover the whole river including Perth by 1900 hours.

In most upper catchments the Red warnings were issued some three to four hours ahead of the onset of severe flows. When the Red warning for Perth was issued, the flow at Ballathie gauging station was 923 m^3s^{-1}. This was some 10 hours before the flow in this reach exceeded 1500 m^3s^{-1}, the threshold at which serious flood problems are expected to develop in Perth, and 24 hours before the flood peak passed through the city.

After the Red warnings were issued the Regional Emergency Control Centre (RECC) at Perth & Kinross District Council was issued with regular updates of rising river levels. At a meeting on the evening of Saturday 16th January, the RECC was told that serious flooding would develop in Perth the following day and that there was a serious risk of overtopping of the North Muirton flood defences.

Generally the flood warning system performed well, with warnings issued sufficiently in advance for losses to be reduced. This was particularly evident in rural areas where livestock and machinery losses were minimised. In some cases warnings were ignored resulting in avoidable losses and instances of people being rescued from inundated properties.

In the Perth area where warnings are disseminated via the local authority services rather than by a cascade system, problems arose, particularly in the North Muirton area where failure of the floodbanks gave rise to sudden inundation as the flood approached its peak level. Consequently losses of household possessions, commercial equipment and stocks were substantially greater than should have been the case given the substantial lead times provided by the flood warning system. These problems have subsequently been addressed by the development of the Perth Business Community Cascade Warning System, and improved procedures for a door-to-door warning of domestic properties by Tayside Police.

Damage and Disruption

The effects of the flood were felt over a wide area, mostly in the middle and lower reaches of the Tay, and the lower reaches of the Tummel and Isla. Its impact encompassed a wide variety of effects.

The Catchment above Perth

In the rural part of the catchment, the clearest impact of the flood was in the area of land inundated: a total of 52 km^2 was identified on the basis of aerial photography, ground survey and local knowledge[8]. This area is more than 50% greater than the area flooded in 1990, mostly as a result of the much greater extent of flooding in the Isla catchment; all floodplain areas in the Tay and Tummel valleys were inundated in both events.

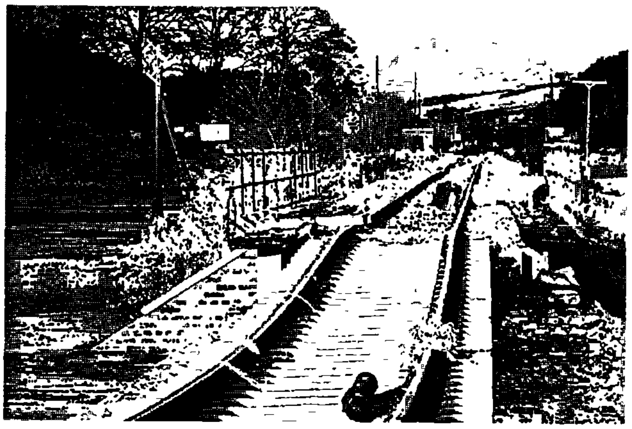
As mentioned above, much of the floodplain throughout the Tay system is protected from moderate floods by floodbanks, and in an event such as this, areas normally protected are inundated by overtopping and breaching of the banks. A total of 73 breaches were identified in the Tay catchment after the 1993 flood, resulting predominantly from initial overtopping, but occasionally as a result of bed scour[5]. The reinstatement of these banks represents a major financial burden for the farmers affected.

The repeated failure of floodbanks in certain locations has been shown to be a feature of the Tay area over at least the last 150 years[5]. Frequently, this results from super-elevation of water levels on the outside of bends, leading to overtopping. However, the construction of embankments over former river channels in-filled with coarse, unconsolidated material is also cited as an important reason for repeated breaching at a number of locations, the two factors often interacting at the same location (see Figure 3). Water returning to rivers from floodplain areas also overtops floodbanks and was responsible for several breaches; in one case at Dalguise (north of Dunkeld) this resulted in the breach of a railway embankment by water which had entered the floodplain through another breach 2.5 km upstream. Similar damage occurred at an immediately adjacent location in the February 1990 flood (see Plate 1).

The rapid flow of water through such breaches generally results in scour of the surrounding soil and, coupled with widespread sediment deposition over farmland, represents further economic loss for farmers. In addition much of the fertile floodplain was planted with winter crops, and in many cases the extent of damage, with surface water lying for weeks after the flood, precluded any recovery of these. Because of silt clogging soil pores, fears have also been expressed regarding the effects of the inundation on fertility in future years.

As previously noted, one fortunate aspect of the flood in agricultural areas was that due to warnings issued by the Tay River Purification Board, and the prolonged threat of banks being overtopped, there were no livestock losses reported. Previous events, in which there has been no flood warning system, have resulted in hundreds of livestock deaths.

a.



b.

Plate 1 The Tay in flood near Dalguise
a: February 1990 b: January 1993
(Photos: a – Scot Rail b – Tay RPB)

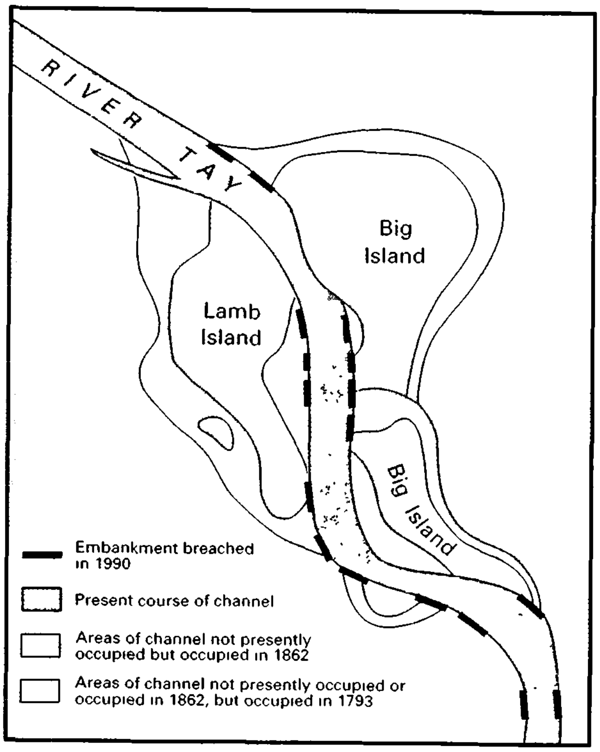


Figure 3 Location of flood embankment breaches during the February 1990 flood (near Guay, downstream of the confluence with the River Tummel)

Source: Gilvear, D.J. et al (1993) Mechanisms of floodbank failure during large events on the Rivers Tay and Earn, Scotland. Quart. Jour. Eng. Geol., 27, 319–332.

Transport links invariably suffer in floods, and the 1993 event was no exception. The high water levels reached on floodplain areas blocked many roads and at Almondbank a bridge collapsed into the flooding River Almond. Some roads in the Isla catchment were blocked for several days because of water becoming trapped behind floodbanks. Landslips, caused by saturated soils, further added to the situation. Several communities including Pitlochry, Dunkeld and Blairgowrie were cut off for a time.

The previously described breaching of the railway embankment at Dalguise dislocated the Perth-Inverness route for some weeks. In the Earn catchment to the south, bed scour caused the collapse of a bridge carrying the Perth-Glasgow railway, causing additional disruption for three months and contributing to a joint repair bill in excess of £1.1 million.

Finally, flooding of properties in the rural catchment must be considered. Data collation is neither simple nor necessarily very accurate, but the *Factual Report* produced for Tayside Regional Council in May 1993[8] shows that housing, some industrial areas, holiday lodges and wastewater treatment plants were all affected in various parts of the Tay catchment. In many cases, flooding of property resulted from small burns rather than main rivers overtopping their banks. Many of the most vulnerable properties are in farmsteads lying on the floodplains: these were completely surrounded by floodwaters and often inundated even though buildings stood at higher elevations than their immediate surroundings.

Perth

Flooding of property in Perth affected many more properties than in the catchment upstream, and also occurred on a much more extensive scale than in the February 1990 event. Most important was the inundation of the North Muirton housing estate on the north side of Perth, as a result of overtopping and then multiple breaching of a flood embankment. Approximately 780 properties were affected, causing in excess of £10 million of damage. A further £1 million of costs was incurred through the provision of temporary accommodation by Perth & Kinross District Council, owners of most of the affected properties; some houses were not fully repaired until almost a year after the flood.

In the city centre many properties, generally shops and offices, were affected by direct flooding from the River Tay. While water depths at street level were generally quite modest, many buildings have basements and this is where much of the damage was sustained. Even when warnings had been received contents were still sometimes damaged, for example at the Perth City Museum and Art Gallery, where defences had been overwhelmed by the flood. Despite the issue of warnings well in advance of damage levels being reached, it seems the response was, in many cases, either limited or inadequate.

Damage in the city centre extended beyond the effects of direct flooding. Through groundwater, the sewerage and drainage system and a mill lade which runs through the city centre, basement flooding occurred in further areas which were not directly inundated. However, no assessment of the total cost of damage has yet been made.

Many residential properties in the city centre were also affected. In the streets surrounding the North and South Inches, houses have been built with ground floors elevated slightly above the surrounding ground level such that in the past only basements were flooded – a clear indicator of many years experience of flooding. However, in recent years many of these basements have been converted into flats, thereby exacerbating the flooding problem. The benefits of historical adaptation to flood risk are thus rather less now than they have been previously.

The planners responsible for the North Muirton development responded to the flood hazard by erecting a flood embankment around the estate. In January 1974, the then recently developed estate was flooded following failure of the existing embankment. The local authority reacted by rebuilding the defences to a higher specification based on a 100-year return period event, then assessed at approximately 2100 m^3s^{-1}. These defences were successful in February 1990 in affording the desired protection, if only by a small margin. The local topography and the design of the floodbank, however, are such that if the design flood is exceeded, a large number of properties sustain major damage. This is exactly what happened in January 1993, with some properties flooded to a depth of 2 m, and is the principal reason for the great local significance attached to the flood.

Historical Perspective

At 162 m^3s^{-1}, the mean flow of the Tay is the highest of any river in the UK, reflecting its large and wet catchment, and it is to be expected that its floods will be large in comparison with other UK rivers. The most salient point to emerge from the description of this particular flood is the way in which a number of factors combined to produce a peak flow which, although not unprecedented in the period of flow measurement in this country, was the largest to be witnessed in the UK in over 20 years, and registered an exceptional impact in terms of the amount of land and the number of properties inundated. The synchrony of flood peaks emerging from the Garry and Tummel sub-catchments, the Tummel and Tay, and then the Tay and Isla seems remarkable, resulting from the timing, extent and spatial distribution of first snowfall, then melt-inducing pulses of rain and temperature increases, and finally producing the major flood which swept through Perth.

Also remarkable is the occurrence of such a large flood only three years after another which was noteworthy in its own right, and in a series of large peaks from 1989 (and general wetness since 1982) which is unprecedented on the Tay in records which commenced in 1947. Conventional risk analysis treats flooding as an entirely random process, and assumes the climate which generates floods to be unchanging through time – such that the risk of exceeding any given flood level is invariant between years. However Table 1, which gives levels of major floods at Smeaton's Bridge in Perth since 1814, shows a clustering of major events. Distinct periods containing concentrations of floods can be identified, separated by intervening periods with few major peaks. Clusters are apparent around 1850, 1910, 1950, and 1990. Nothing is known about the incidence of any other peaks around the time of the largest known peak in 1814, caused in part by ice-jamming in the bridge. Clustering has also been found in a number of long UK seasonal and annual runoff records[9], supporting the suggestion of inter-dependence within runoff records. The information

TABLE 1 FLOOD LEVELS AT SMEATON'S BRIDGE, PERTH (METRES OD)

Year	Date	Level
1814	February 12	7.0
1847	October 7	6.11
1851	January 19	5.65
1853	January 20	5.79
1868	February 1	5.90
1894	February 7	5.64
1903	January 31	5.64
1909	January 18	5.52
1910	August 29	5.61
1912	December 21	5.68
1913	May 9	5.66
1928	January 22	5.77
1931	June 15	5.49
1947	January 15	5.55
1950	February 17	6.03
1951	November 5	5.97
1962	February 12	5.37
1974	January 31	5.61
1989	February 7	5.07
1990	February 5	5.85
1993	January 17	6.48

provided by Smeaton's Bridge, as is so often the case with observations from before the time of instrumental recordings, is of great value in placing recent events in an historical context.

Whether the recent large Tay floods simply constitute the latest in a series of clusters, or signify some change in the flood regime of the river, perhaps resulting from climate change, poses a question which is difficult to answer. Some favoured climate change scenarios envisage an increase in rainfall along the west of the British mainland, including the headwaters of most of the Tay's tributaries, so an increase in the frequency of flood-producing conditions seems quite plausible. However, the links between climate change studies and any changes in river flow regime are difficult to develop – not least because of the limitations of climate change modelling – and likely changes in flood risk cannot therefore be postulated with any great certainty.

Comparison with other Great UK Floods

At this point it is worth making comparison with other major UK floods, specifically recalling the great Findhorn flood of 17th August 1970, which still holds the UK gauging station peak discharge record. A peak of 2410 m^3s^{-1} was recorded at Forres gauging station, where the catchment area is 781.9 km^2, a mere 17% of the catchment area to Ballathie on the Tay. Considering also that there was no snowmelt contribution to the Findhorn flood, its magnitude seems all the more remarkable.

The rainfall responsible for the 1970 Findhorn flood was intense over a wide area, benefiting from strong orographic enhancement as the northerly winds rose over the Monadhliath Mountains[10]. Such a synoptic situation is characteristic of all the known major floods of this area, always occurring in summer[11], and historical records of the 'Muckle Spate' of 1829[12] demonstrate the occurrence of a larger peak in the more distant past.

Archer's investigation of the 1771 Tyne flood[13] produced a discharge estimate of 3900 m^3s^{-1} for Hexham (catchment area 1970 km^2), exceeding by a large margin any other UK historical flood estimate. Like the Findhorn flood, this seems a remarkable discharge in relation to the corresponding catchment area, and these two extreme historical events together provide a useful context in which to view the recent Tay flood.

Rainfall intensities in the 1993 Tay flood were not exceptional, and it is important to note that at most gauging stations on the Tay's main tributaries, previous events generated with rather less important snowmelt components have achieved peaks comparable with those of January 1993 (e.g. Kenmore, Comrie Bridge, Pitnacree, Port-na-Craig, Wester Cardean). Had heavier rain fallen on the snowpack present on January 16th, an even larger flood peak would have been produced. However, the likelihood of heavier rain falling on such a snowpack, and with a spatial and temporal distribution still capable of producing coincident high peaks from all the major tributaries, is quite remote.

Risk Assessment

With the occurrence of the major floods of 1990 and 1993, the time series data on which risk assessments may be made have changed substantially[14]. While assessments of flood risk should never be made solely on the basis of statistically derived magnitude-frequency curves, changes in the shape of such curves are still likely to have some bearing on the understanding of flood risk at a given site.

On the Tay, the definition of flood series is further complicated by the existence of five years of estimated peaks at Ballathie preceding the full record commencing in 1952. Moreover, the estimated peaks of 1950 and 1951 are both larger than any others recorded until 1993. Up until 1989 the flood series from 1952 contained only one peak above 1500 m^3s^{-1} (1570 m^3s^{-1} on 30th January 1974) and, if considered in isolation, could be interpreted to suggest a very low risk of any major flood, above say 2000 m^3s^{-1}. If all the peak estimates for the preceding five years are accepted, however, the two peaks of 1890 m^3s^{-1} and 1850 m^3s^{-1} for 1950 and 1951 respectively produce a much different picture with a small but discrete group of outliers appearing, and indicating a higher risk of floods exceeding the 2000 m^3s^{-1} threshold. This group is substantially enlarged by the addition of the 1990 and 1993 annual

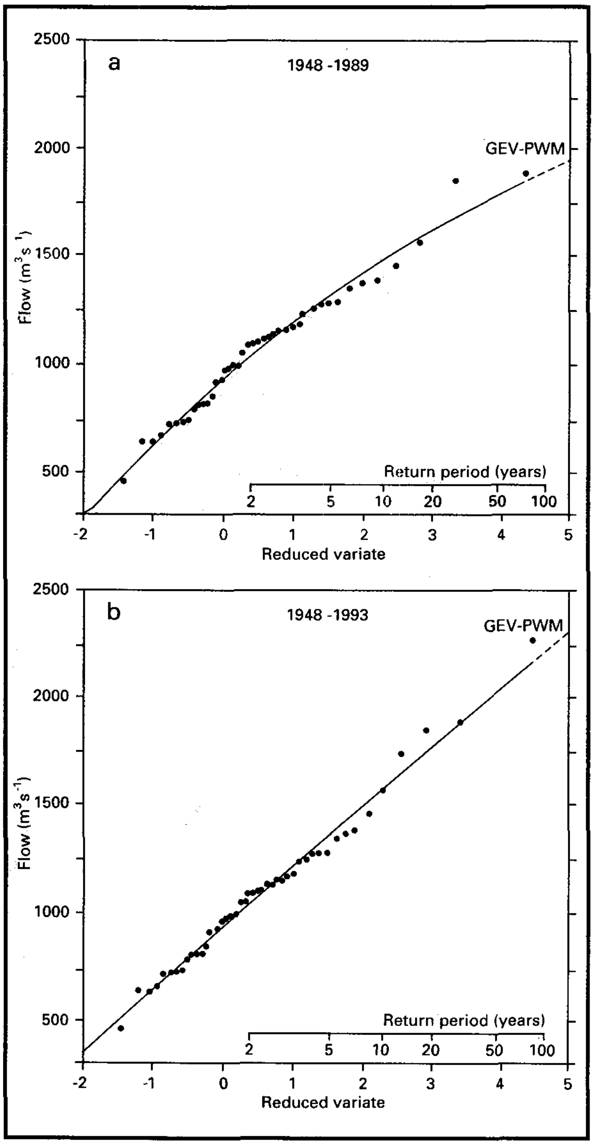


Figure 4 Flood frequency curves for the River Tay at Ballathie

maxima (Figure 4), and it is interesting to note that three of the four largest events (1993, 1950, 1990) were all associated with substantial snow-melt contributions. Such an observation raises the possibility that Tay flood series might best be modelled by use of methods which explicitly recognise different populations within the observed data[15].

The events of the past few years have done much to concentrate attention on the nature of flood risk. The clustered nature of major floods on the Tay, coupled with an important variability in the mechanisms of flood generation, illustrates the complexity of modelling flood frequency distributions.

Long-term Response

In the course of its progress, the flood made considerable demands on the emergency services and local authorities throughout Tayside, as occurred in many surrounding areas which were also affected. With its damaging effects at North Muirton, central Perth and throughout the surrounding area, however, it was acknowledged that some more considered long-term response was also required, to minimise within justifiable resources the risk of similar damage recurring in the future.

The most urgent need to counter the effects of any future peak was at North Muirton. With the floodbank there breached in three places, it was imperative to repair these as soon as possible, as the Tay remained high after its major peak and further frontal systems threatened to bring rain which might cause further inundation of property. Heavy plant was therefore brought in quickly to reduce this vulnerability. On the agricultural floodplain too, farmers were concerned to mend breaches in their defences to prevent any further flooding of their land. Unfortunately, two further peaks at approximately the mean annual flood level occurred on 30 March and 8 April 1993, and in some areas where floodbanks had not been reinstated, further crop loss and sediment deposition occurred. One method of damage limitation not yet introduced in the Tay valley would be a re-positioning of these banks in areas of repeated failure: benefits would accrue from a reduction of damage to banks and fields alike. However, as noted above, the *River Tay Catchment Study*[6] has found the present arrangement of banks to be near-optimal for the purpose of attenuating downstream flooding.

Following the 1993 flood, Tayside Regional Council commissioned two major studies: a catchment study to enhance the understanding of flood-generating processes in the Tay basin and its sensitivity to various changes in land use, climate, snowmelt and hydro-power operations; and a Perth flood study to assess structural options for flood mitigation in the urban area. An initial estimate of the cost of works to protect Perth from a flood similar to that of January 1993 combined with a 100-year extreme tide is £11.1 million, with other design options also having been identified[16]. In the catchment study, the effects of afforestation were considered to be broadly helpful in reducing the rate of snowmelt which might contribute to flood generation, though in rainfall events land use impact would be very limited[6]. Little or no improvement in the operation of the hydro-power schemes is available to help attenuate floods in the Tay: by the time that the value of additional storage capacity becomes apparent, the limited potential rate of draw-down makes such efforts futile against the volume of runoff being produced in upstream areas.

Considering the large size of catchment, and the marginal effects of land use and resource management on its hydrological behaviour in times of extreme flood, it seems unlikely that any formal basin management plan could be justified in response to the flood threat. The control of floodplain development, through planning legislation, appears to offer much greater scope for the future management of the flood hazard. More practically, the flood warning system has shown its worth in reducing damage in the 1993 event, and it is hoped that more recent developments of the system will allow businesses and individuals to more effectively protect their property in any future emergency.

Conclusions

The Tay flood of 17th January 1993 achieved a peak discharge of 2269 m^3s^{-1} at Ballathie gauging station and is the second largest – after the Findhorn flood of 1970 – recorded at any UK gauging station. It resulted from a very deep snowpack across the entire catchment being subject to temperature increases and rainfall, which caused major tributaries of the main river to add to the flood wave as it passed downstream in a way which was to ensure the flooding of hundreds of properties and some 52 km^2 of farmland. The North Muirton housing estate received the most concentrated damage after its flood embankment was breached, but effects were widespread throughout the lower part of the Tay basin.

The presence of several large hydro-electric reservoirs in the catchment reduced the magnitude of the peaks emerging from the Garry, Tummel and Lyon tributaries, and while it was suggested that the presence of agricultural flood embankments might have exacerbated flooding in downstream areas, their widespread failure and the inundation of areas normally protected by them in fact provided greater attenuation than would otherwise have been available. Flood warnings gave early notice of the floods for all areas, but nothing could be done to substantially reduce the major peak which was developing in the river upstream.

Coming only three years after the February 1990 event, this larger flood generated considerable local concern both through the damage and disruption it caused, and by raising awareness of the threat of further flooding in the future. In a broader context such events raise the possibility of a temporally variable model of flood risk being applicable to the Tay and other rivers, while the threat of climate change introduces the possibility of greater flood risk for the future. Detailed studies and discussions are now taking place to assess what means might be employed to afford the maximum protection to Perth in any further major floods.

Recent events have served to remind Perth and other communities in the Tay catchment of their vulnerability to flooding after a substantial period of relatively little threat. However, it is likely that not only the activities of the local authorities, but also the behaviour of the river itself over the next few winters, will play a large part in determining whether or how any efforts to reduce this vulnerability should be attempted. It is certain that the continuing monitoring and documentation of notable flows will play a fundamental role in enhancing our understanding of flooding on the Tay, which must form the basis of any future plans for its management.

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