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Analysis of the effects of beaver dam-building activities on local hydrology

Angela M Gurnell

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1 INTRODUCTION

This study was commissioned by Scottish Natural Heritage in the following context.

Under Article 22 of the EC Habitats Directive (EC/92/43), the UK Government is required to consider the re-introduction of certain species which are threatened in mainland Europe and have become extinct in the UK. The European beaver (*Castor fiber*) is one of these species.

The European beaver became extinct in Scotland approximately 300 years ago. The landscape has altered substantially in the intervening period. A characteristic of beaver ecology is their ability to build dams and, thus, modify the landscape to increase its suitability for their occupation. This ability to modify their habitat has caused them to be classified as 'ecosystem engineers' (Gurney & Lawton, 1996). Their consequent direct and significant control on ecosystem structure and dynamics has also led them to be considered a 'keystone species' (Naiman *et al.*, 1986). It is important to recognise these effects prior to any reintroduction in order to make an informed decision on the feasibility and desirability of restoring this native species to the current landscape.

This report attempts to assess the effects of beaver dam building activities on local hydrology through the combination of two research approaches.

> (i) In section 2, a review of the international literature is undertaken. This summarises published information on the spatial and temporal variability in the distribution of beaver and the characteristics of suitable beaver habitat (2.2); the nature of building activities by beaver (2.3); environmental conditions associated with dam building (2.4); and the physical environmental impact of dam building at local (2.5) and landscape (2.6) scales.
>
> (ii) Section 3 evaluates the hydrological and geomorphological consequences of beaver reintroduction in Scotland through an evaluation of the flow regime and geomorphology of Scottish rivers (3.1); simple modelling of the interaction between beaver dams of differing size, variations in local slope and channel/floodplain dimensions, and low and flood flows (3.2); and the examination of three case study sites located on the River Farrar, Abhainn Deabhag and the River Dee (3.3).

The results of these two pieces of research are combined in section 4 to assess the limitations in the available information (4.1); the major controls on the potential spatial distribution of reintroduced beaver in Scotland and thus on the identification of suitable sites for reintroduction (4.2); and the potential impacts of dam building by beaver in Scotland (4.3).

2 THE EFFECTS OF BEAVER DAM BUILDING ACTIVITIES ON LOCAL HYDROLOGY - A LITERATURE REVIEW

2.1 BACKGROUND

Although this chapter reviews the hydrological influence of the European beaver (*C. fiber*) as a result of dam building activities, reference will be made to the more extensive literature on the North American beaver (*C. canadensis*) where appropriate. There are great similarities in the way the two species have an impact upon the environment. Both species can be considered to be keystone species because of their direct and significant control on ecosystem structure and dynamics (Naiman *et al.*, 1986), although *C. fiber* is believed to undertake more restricted building activity than *C. canadensis* (Collen, 1995). The literature on the influence of accumulations of large woody debris (LWD) on fluvial processes will provide a further insight into the potential hydrological impact of beaver dams. In the absence of beaver, unmanaged woodland streams and rivers accumulate numerous dams of LWD at typical spacings of 40 dams per km in 3rd order streams (Gurnell *et al.*, 1995), and although these dams may be less well-constructed than those produced by beaver, they are likely to have a similar if smaller-scale influence on the fluvial system.

In order to appraise the hydrological effects of beaver dam building activity, a number of topics are reviewed below. A context is placed on the likely distribution and magnitude of beaver activity by considering the spatial and temporal distributions of beaver including the potential densities of beaver and the density of beaver colonies, and the habitat characteristics which might favour the establishment of substantial beaver populations. A description is then given of the nature and potential dimensions of in-stream structures built by beaver and the environmental conditions under which dam building has been observed to occur. The environmental impact of dam building is then appraised both locally and at the landscape scale in relation to the river continuum. From the review of these topics, an assessment is made of the likely hydrological impact to ensue following the introduction of *C. fiber* an area.

Here 'hydrology' is interpreted very broadly to include not only the hydrological processes associated with surface water and near-surface groundwater, but the related processes of sediment transfer and sedimentation, and the impact of changes in these processes on the physical character or geomorphology of the river system.

2.2 SPATIAL AND TEMPORAL DISTRIBUTIONS

2.2.1 Colonisation

C. canadensis can rapidly spread into suitable habitats as the population increases. Johnston & Naiman (1990) estimated that it would be possible for *C. canadensis* to colonise as far as 736km from its initial nucleus over a 46 year period. In the absence of natural predators and competitors, *C. canadensis* have colonised areas of Tierra del Fuego to densities of 0.2-5.8 colonies/km of river in 40 years (Lizarralde, 1993). However, colonisation by *C. fiber* after reintroduction appears to be slower. MacDonald *et al.* (1995) review the success of reintroduction of *C. fiber* into various European countries. Annual population increases from these introductions have ranged from close to 0% (Netherlands) to as high as 34% annually (over 6 years, Peene valley, Germany), but levels of approximately 15-20% appear to be typical. A useful comparison can be made between *C. fiber* and *C. canadensis* in Finland, where both species have been introduced. Nineteen *C. fiber* were introduced from Norway in 1935 and 7 *C. canadensis* were introduced from the United States in 1937 (Lahti & Helminen, 1974). By 1990, the former had increased to about 800 whereas the latter had resulted in an increase to 3300-5200 (MacDonald *et al.*, 1995). In part this may reflect the larger litter size of *C. canadensis* (Lahti & Helminen, 1974). Whatever the cause, *C. canadensis* was found to dominate or displace *C. fiber* at locations where they were both introduced (Ermala *et al.*, 1989, Lahti & Helminen, 1974).

2.2.2 Colony size

Beavers normally live as a family unit or colony, consisting of two parental adults, the yearlings born the previous year, and the young of the year. A beaver colony is defined as 'a group of beaver occupying a pond or stretch of stream, using a common food supply and maintaining a common dam or dams' (Bradt, 1938; cited in Hill, 1982). Various average colony sizes have been reported (Table 2.1), with colonies of *C. fiber* being thought to be a little smaller than those of *C. cadanensis*.

Table 2.1 Beaver colony sizes reported in the literature

Source	Location	Colony size
C. canadensis		
Collen, 1995		
quoting Hodgdon & Hunt, 1953	Maine	4.3 individuals
quoting Payne, 1982	Newfoundland	5.3
quoting Novak, 1977	Ontario	7.6
Hill, 1982	N. America	2.7-6.2 (recorded averages)
Macdonald & Barrett, 1993	Europe	3-9
C. fiber		
Curry-Lindahl, 1967	Sweden	
	Ångermanland	5
	Värmland	3.2
	Jämtland	3.1
Macdonald & Barrett, 1993	Europe	5-6
Collen 1995		
quoting Myrberget 1967	Sweden	4.9
Zurowski & Kasperczyk, 1986	Poland	3.7
quoting Palionene, 1975	Lithuania	4
..quoting Golodusko, 1975	Belyorussia	4.4
quoting Tamuch & Tollkarev, 1976	Polesie	3.4

2.2.3 Colony density

The density of colonies varies with the quality of the habitat and the degree to which colonisation of an area has stabilised (Table 2.2). Semyonoff (1951, cited in Collen, 1995) suggested that in Russia, 1.5, 0.5 and 0.1 colonies per km might be expected in good, quite good and mediocre beaver habitat, respectively. Hartman (1994a) reports on *C. fiber* colonisation of the Värmland and Västernorrland Provinces of Sweden. In two study areas populations built to maximum densities of 0.25 and 0.2 colonies per km^2. The number or density of colonies in an area is an important factor in governing the potential number of dams that may be constructed.

TABLE 2.2 Beaver colony density reported in the literature

Source	Location	Density
C. canadensis		
Boyce, 1983	Alaska	0.63/km (mean nearest neighbour)
Beier & Barrett, 1987	Truckee R., Ca	0.74/km (sites <2% slope)
Howard & Larson, 1985	Massachusetts	0.83/km
quoting Collins, 1976	Wyoming	0.9/km
quoting Nordstrom, 1972	New Brunswick	1.25/km
Johnston & Naiman, 1987	Minnesota	1.0/km^2
Lizarralde, 1993	Tierra del Fuego	0.2-5.8/km
McCall *et al.*, 1996	Maine	0.32/km^2 (no trapping)
Robel & Fox, 1993	Kansas	0.08-1.4/km (rivers) 0.0-0.25/km (reservoirs)
C. fiber		
Hartman, 1996	Sweden R. Sverkestaån	1.0/km
Hartman, 1996b	Sweden Värmland and Västernorrland	0.25/km^2 (peak density)
Macdonald *et al.* 1995		
quoting Heidecke, 1984	Peene Valley, Germany	0.26/km
Sidorovich *et al.* 1996	Belarus - Poland	0.29./km (average) 0.0-0.5/km (range)

Densities are expressed either in km of river or per unit area in km^2

2.2.4 Habitat suitability

Hill (1982, p262) notes that *C. canadensis* “occur commonly in large rivers, impoundments, and large lakes with relatively constant water levels, in protected areas of large lakes that have extensive wave action, streams, tributaries and small seepages that have adequate flow for damming”. Although proximity to a water body is an essential requirement for beaver, the nature of that water body and other properties of the habitat play a role in governing the degree to which beaver might colonise and sustain a population.

River flow and lake level regime

The discharge/water level regime is certainly important to beaver, who will build dams to stabilise water levels when necessary. The introduction of modifications to the water level regime of a river or lake can lead to major impacts on beaver. For example, Wolff *et al.* (1989) show how flow augmentation to improve the quantity and reliability of the flow in an ephemeral stream in Wyoming led to a threefold increase in the number of beaver and a doubling of the total impounded area of beaver ponds within two years. Curry-Lindahl (1967) noted the catastrophic impact of rapidly-varying winter flows associated with hydro-power generation on the local beaver population. Martin (1977) considered a variety of impacts of man-modified streamflows on beaver, including the potential of increased winter flows to wash away food caches, and the potential of low flows in autumn to stimulate dam-building. Smith & Peterson (1991) also noticed alterations in beaver behaviour consequent upon winter draw-down in lake levels. The beaver spent less time in their lodges, were unable to fully use stored food and spent more time foraging than beaver on reservoirs that were not subject to winter drawdown. As a result, Smith & Peterson recommended that total annual water level fluctuation should not exceed 1.5m, whereas winter drawdown should not exceed 0.7m.

River channel characteristics

Streams containing steep, rocky or bedrock bottoms are less favoured by beaver, possibly as a result of the destructiveness of high water conditions in such streams (Hill, 1982, citing Retzen *et al.*, 1956). Hacker & Conblentz (1993) identified soft soils as one of six habitat factors associated with beaver recolonisation of clearcut areas in Oregon. The materials that constitute the bank and bed of the watercourse are important because they affect whether and where beaver can construct burrows and lodges, whether it is possible to construct dams to regulate water levels, and the degree to which dam and canal construction will give access to substantial new areas and sources of food. This is another reason why beaver may not favour streams flowing on bedrock or with a very coarse, rocky bed. Boyce (1983), studying *C. canadensis* in Alaska, found the highest densities of beaver colonies in areas where a high proportion of the area used by the colonies contained sand or gravel bars. He attributed the importance of this to its association with a dynamic fluvial environment where diversity in bed topography and deposited sediment calibre provides deep pools and oxbows, and sources of fine clay sediments for dam and lodge construction, and where the riparian zone is patchy, offering a range of vegetation types reflecting different stages in vegetation colonisation. Boyce (1983) does not indicate precisely where beaver establish colonies or locate dams and lodges in this environment but comments that oxbows are frequent. Beaver colonies have been noted to frequently establish around oxbows and other floodplain water bodies adjacent to large river channels (e.g. Townsend & Butler, 1996).

Food availability

C. canadensis is selective in its choice of woody plants (eg Busher, 1996), often showing a strong preference for aspen over all other species, and also preferentially utilizing willow, alder, maple and ash species. Smaller woody stems (<4cm diameter) are preferred (Barnes & Mallik, 1996; Basey & Jenkins, 1995), and the size of pieces cut decreases with increasing distance from water (Jenkins, 1980).

Similarly, vegetation as a food source for *C. fiber* is suggested by Stocker (1983) to be a crucial issue in attempts at reintroduction. In Finland, *C. fiber* use any of the available hardwood species, but show a clear preference for aspen (*Populus tremula*) and birches (*Betula pubescens* and *B. verrucosa*). Debarking of conifers is rare (Lahti & Helminen, 1974). Beaver diet varies seasonally (Lahti & Helminen, 1974, Roberts & Arner, 1984; Svensden, 1980). Both *C. canadensis* and *C. fiber* consume woody vegetation, grass and forbs, and aquatic vegetation. They depend largely on woody food sources in winter, but can spend up to 90% of feeding time consuming grass, forbs and aquatic vegetation in summer. Barnes & Dibble (1988) illustrate the impact of beaver in west central Wisconsin on forest succession. The beaver greatly reduced tree density and were selective in their choice of woody plants. As a result, a major reduction was predicted in future populations of ash, hickory and hackberry in areas of beaver activity, and a corresponding increase in the density of basswood, elm, and possibly silver maple and prickly ash. Doucet and Fryxell (1993) undertook experimental investigations of food preference by *C. canadenis* for five forage species, and found a clear order of preference as follows: aspen (*Populus tremula*), white water lily (*Nymphaea odorata*), raspberry (*Rubus idaeus*), speckled alder (*Alnus rugosa*), and red maple (*Acer rubrum*). In Sweden, *C. fiber* mainly feed on fresh bark as well as shoots, buds, twigs and leaves, of deciduous trees, particularly aspen (*Populus tremula*), birch (*Betula pubescens*) and salix species (*Salix caprea, S. aurita, S. cinerea, S. glauca, S. lapponum, S. pentandra*). They also eat roots stems and leaves of many grasses and flowering plants (Curry-Lindahl, 1967). Thus availability of preferred vegetation is likely to be an important criterion in habitat selection. Since the maximum distance that beaver will travel from water to obtain food is thought to be approximately 100m and beaver commonly browse within 10 m (Howard & Larson, 1985, Nolet *et al*, 1994), the proximity of preferred food to water courses is particularly important. However, beaver can change such proximity by impounding ponds and constructing canals. The resultant change in the position of the water shoreline can extend considerably the access of beaver to food in areas of low relief.

Important combinations of factors in habitat selection

A number of researchers have undertaken multivariate analyses of habitat characteristics in order to identify those which best discriminate areas that are likely to be colonised or used by beaver.

Howard & Larson (1985) used principal components regression to assess the relationship of habitat variables to beaver colony site longevity (revealed from air photograph analysis), and linear discriminant analysis to assess the relationship of 14 habitat variables to colony site longevity. Of these 14 variables, 7 appeared to significantly affect colony site longevity: watershed size, stream width, stream gradient, soil drainage class, percentage hardwood vegetation within 100m and 200m, and percentage abandoned fields within 100m. Within the restrictions of the sampled range of habitat characteristics which included only relatively narrow streams (< 8m wide) and relatively small watersheds (< 750 ha), these analyses were interpreted to reveal that the best beaver habitat was associated with relatively wider streams with low gradient and poor soil drainage.

Beier & Barrett (1987) used stepwise logistic regression in a series of pairwise contrasts to identify variables influencing habitat use by beaver (*C. canadensis*). They classified 214 stream reaches of approximately 700m length into four groups: (1) at least one active colony present; (2) sign of at least one abandoned colony; (3) sign of past/present beaver usage but not a colony; (4) no sign of past/present beaver usage. 6 physical and 11 vegetation variables were estimated for each reach. Three physical variables; stream gradient, stream depth and stream width; were found to be the most important factors. Low stream gradients were thought to be important because they allow beaver to greatly increase their safe foraging area by dam-building, to establish a food transportation system and, as a result of the lower energy environment, to reduce the potential for damage to dams, lodges and food caches. Deeper and wider streams offer a higher volume of river channel and so were thought to offer more cover, sites for food caches and a more reliable source of water for impoundments. Mean values of river channel gradient (s, in %), width (w, in m), depth (d, in m) and the associated sample size (n) of reaches according to beaver occupancy class were as follows: class (1) s=1.16, w=8.1, d=2.44, n=53; class (2) s=4.22, w=5.9, d=2.13, n=45; class (3) s=5.75, w=4.9, d=1.85, n=44; (4) s=12.53, w=1.4, d=0.85, n=72. Sites abandoned by beaver were related to two types of reach. The first type consisted of reaches that were similar to those with active colonies but with relatively low food availability. These may be re-occupied when the vegetation recovers. The second type were similar to the uncolonised reaches and were probably only occupied for a short period prior to abandonment.

Hartman (1996) evaluated habitat selection by *C. fiber* along a 30km stretch of the R. Sverkestaånin, south-central Sweden. The tortuosity of the shoreline and a dominant cover of grasses and forbs provided the strongest discrimination of beaver occupancy (although tortuosity may be directly influenced by beaver and ground cover is also very likely to be a reflection of beaver impact). Thereafter, beaver showed a habitat preference for softer soils, higher cover of deciduous tree species and narrower sections of river. In the study area the river had little variability in gradient or depth, and so these did not have an impact on habitat selection. Furthermore, river width was generally large (mean = 114m) because it was affected by lake formations. Thus the preference for narrower sections still implied widths of the order of 40 m.

The results from these studies may appear to conflict to some degree, but this is indicative of the different fluvial environments in which the studies were undertaken, and some general but quite broad conclusions can be drawn about the characteristics of suitable beaver habitat.

(i) *Food availability.* Easy access to grasses, forbs and hardwood vegetation.

(ii) *Channel dimensions.* Where streams are small and shallow, the larger channels are preferentially selected by beaver, whereas in areas of wide channels, the narrower locations are selected. A preference for channel widths of the order of 8-40m are identified by the quoted sources.

(iii) *Channel/floodplain gradient.* Lower gradients are preferred (e.g. <2% slope)

MacDonald *et al.* (1995) present criteria for gauging the quality of release sites for *C. fiber*, which further illustrate the broad range of habitat characteristics that suit colonisation by beaver. They suggest that the physical - vegetational characteristics of a *good* site are as follows: 2-4m water depth, 10-100m river width, <0.3 $m.s^{-1}$ flow velocity, bank materials of peat-loam soil, bank height > 1.5 m, bank slope < 60°, woody species predominantly aspen and willow and <8cm diameter, and a good herb cover. Even within this *good* category, the range of suitable physical conditions is quite wide, but if conditions from the *fair* category are added, the range becomes enormous (e.g. river depths of 1-6 m, widths of 2-300m, banks >0.5m height and <80° slope). Only the requirement for fine bank material seems to be a relatively restrictive requirement. However, beaver do not always construct dams. The following two sections consider the building activities of beaver and the environmental conditions under which dam building has been observed to occur.

2.3 BUILDING ACTIVITIES

Beavers can greatly affect their environment by constructing dams, canals and other structures. For example, where *C. canadensis* remain unexploited, their activities can influence as much as 20-40% of the total length of 2nd to 5th order streams (Naiman *et al.*, 1986), and can involve impressive scales of constructional activity (eg Morgan, 1868). Under exploitation, the impact of *C. canadensis* is more restricted, whereas *C. fiber* appears to undertake dam building less frequently. In addition to cutting wood to construct dams, wood is also used by both species in lodge construction as well as being a major food source that is often stored under water in caches. Cutting operations are mostly made close to the water course but in some cases they may extend as far as 100m away (Curry-Lindahl, 1967). However, the construction of dams raises the local water level, so changing the position of the waters edge, which is further modified by the excavation of canals out from the pond margin Hodgdon & Lancia (1983).

2.3.1 Dams

Dams consist of tree trunks, branches, twigs, earth, mud and sometimes stones. Beaver require their shelter (lodge or burrow) to have access points which are under water, and so dams are constructed where necessary to achieve this, with building activity being timed according to necessary adjustments in the water level (Richard, 1983). Several dams can be built by the same colony to control the ponded water level in relation to the lodge or burrow entrances. The length and height of dams varies with the topography. Early descriptions of the number and dimensions of dams built by *C. canadensis* in relatively undisturbed conditions in North America (eg Dugmore (1914), Morgan (1868), Warren (1927)) indicate some enormous structures several hundred metres long and several meters high. However, the large majority were suggested by Dugmore (1914) to be less than 1.5 m high, which is not dissimilar to the heights achieved by accumulations of fluvially-transported woody debris in river channels. This typical height of beaver dam is supported by Townsend's (1953) observations in Montana, where dams varied in size from small canal dams approximately 0.5 m long up to dams of 13m in length and reaching heights of up to 1.5m. Recently, Butler (1995) has suggested typical dam sizes of 15-70m long and 1-2m wide, although he does not indicate whether the longer dams are constructed to span channels of that width. These North American sources also illustrate that although many of the dams are watertight structures, if not well-maintained they become leaky, and on some larger rivers, they only extended part-way across the channel. Thus, further parallels can be drawn between these three types of beaver dam structure and the 'active', 'complete' and 'partial' dams of large woody debris that occur in river systems (Gregory *et al.*, 1985).

It is thought that *C. fiber* build dams less frequently than *C. canadensis* and that usually they build rather smaller structures. For example, dams built by *C. fiber* in Sweden rarely exceed 15m in length, are typically 1m in height (Curry-Lindahl, 1967), and are usually only built in shallow waters less than 10m wide (Hartman, 1994a). In Poland, Zurowski & Kasperzyk (1986) found that of 257 beaver sites in the Suwalki Lakeland, only 50 had dams. Medwecka-Kornas & Hawro (1993) describe 12 dams in the Saspowka brook, Poland, ranging from 2.5-24m in length (average 8.5m) and 0.4-1.7m in height (average 0.8m). Zurowski (1992) found that of 62 sites of beaver colonies in the Masurian and Brodnica Lakelands, 17 had dams, with more than one dam occurring in many sites. Furthermore, all of the dams were located on small rivers or drainage ditches and appeared to be constructed primarily to provide access to new food areas. Zurowski (1992) tried to evaluate the stimuli which are supposed to trigger dam building. Although the sound of running water has been suggested to be an important stimulus for dam building by both *C. canadensis* (e.g. Hodgdon & Lancia, 1983) and *C. fiber* (eg Richard, 1983), Zurowski (1992) concluded that this was of secondary importance to the stimulus of improving safety and access to food at particular sites.

Figure 3.1 depicts a typical dam (in this case constructed by *C. fiber*, from Richard, 1955). The dam is constructed of pieces of wood, typically 1-2m long. It sometimes incorporates stones and is sealed with mud on the upstream face.

Woo & Waddington (1990) classified beaver dams in sub-arctic northern Ontario according to their construction materials.

> (i) They identified two types of construction materials for active dams: stones, new branches, fresh mud; and no stones, fresh branches and mud.
>
> (ii) Four types of construction material for old dams: stones, old branches, mud and debris; no stones, old branches, mud and debris; no stones, old branches, some remaining mud and debris; only branches remain.
>
> (iii) Two types of construction materials for relict dams: only branches remain; most of branches gone, only half of original structure remains.

They also identified four types of dam according to their flow control: overflow, gapflow, throughflow and underflow, which are essentially correlated with increasing age and state of repair of the dam (Figure 2.2).

Richard (1955) classified dams constructed by *C. fiber* on the upper course of the River Tave, France, according to their structure. Here dams attained 8-10m in length and were constructed of wood pieces that were aligned across the river, parallel to the banks or near vertically. The near-vertical pieces and those parallel to the bank form the key pieces of the structure, which is then filled out upstream with transverse pieces. Three basic types of structure were identified (Figure 2.3):

> Type 1 uses a fallen or inclined tree to give support to the structure, although other vertical pieces of wood may be introduced by the beaver (Figure 2.3, upper diagram).
>
> Type 2 is based upon a structure of vertical key pieces which have been driven into the stream bed (Figure 2.3, middle diagram).
>
> Type 3 is counterbalanced by longitudinally-oriented props which support the dam against the upstream water pressure. This type of structure is combined with type 2 in constructing the largest dams (Figure 2.3, lower diagram).

Beaver dams adopt a variety of planforms, but upstream-oriented arc-forms are common (Figure 2.4). Dams may simply occupy the active river channel, they may extend across low-gradient banks (e.g. upper diagram, Figure 2.4) or they may extend across floodplains and/or side channels to create wide ponds. Figure 2.5 (from Richard, 1967) illustrates how a dam was progressively widened from a small within-channel dam to a long channel-floodplain dam in four stages. This illustrates the way in which beaver may develop long dams and large ponds on floodplains, even though the width of dammed channel is relatively small.

Once a dam is constructed and a pond is created in a low-gradient area, the zone of floodplain accessible to beaver can be further extended by canal construction. Canals constructed by *C. canadensis* can vary in length from <1m to >100m, in width from 0.35m to 1m, and are typically over 0.5m deep. Canals are used as routeways and also to transport timber to the beaver pond.

2.3.2 Burrows, lodges and caches

Figure 2.6 illustrates a typical arrangement of dam, burrow and below-water burrow entrance. However, local physical conditions do not always permit such an arrangement and, as a result, beaver can construct a wide variety of shelters. Erome (1984) produced a typology of beaver shelters constructed in the Rhône basin by *C. fiber* (Figure 2.7). The typology relates to different combinations of bank slope and profile, suitability for burrowing, bank material cohesiveness, and the potential for the entire burrow entrance to be maintained at or below the water level. Natural holes in the bank are often utilised. When natural holes are not available, beavers excavate their burrows where the bank is high enough and the bank material is sufficiently firm. When these conditions are not met, intermediate structures between burrows and lodges, called bank lodges, are found. Varying amounts of woody material are incorporated either to conceal the burrow entrance, to compensate for the lack of soil cohesiveness or for lack of soil depth. The level of the nest chamber is typically 0.3-0.7m above the upper edge of the burrow entrance. This difference in level defines an upper limit to desirable water level fluctuations, particularly to rapid water level fluctuations that might drown the kits. Nest chambers are typically 0.4-0.5m in height and so, allowing for sufficient clearance of the top of the river bank above the ceiling of the nest chamber, bank heights of 1.5-2.0m above the roof of the burrow entrance are required for successful burrow construction. Where the banks are lower, various forms of bank lodge can be constructed which combine a bank burrow with a woody construction on the bank top. True lodges, made entirely from wood pieces, were found by Erome (1984) to be very rare in the Rhône basin, where they are built only when it is not possible to create the alternative structures. Although beavers will normally construct burrows in preference to lodges where the river banks are sufficiently high, Zurowski (1992) found that *C. fiber* built many lodges in the Masurian and Brodnica Lakeland of Poland. On average, each colony built more than one lodge. Additional lodges were used in different ways according to local topography. For example, secondary lodges were sometimes occupied when the water level was low near the main lodge, or when human recreation disturbed the beavers. Most lodges were conical in profile and circular or oval in plan.

Food is accumulated for later consumption in caches. The caches can be a significant size where the winter is long. In Sweden branches and twigs collected during the late summer and autumn are stored inside and outside the lodge and, in the latter case, are anchored to the dam, river or lake bed (Curry-Lindahl, 1967).

TABLE 2.3 **Beaver (*C. canadensis*) dam density reported in the literature**

Source	Location	Density
Butler & Malanson, 1995 quoting McComb *et al.*, 1990	eastern Oregon	0.14/km
Leidholtbruner *et al.*, 1992	coastal Oregon	1.1/km 1.2/km
Naiman *et al.*, 1986, 1988	Quebec	10.6/km (average) 8.6-10.6/km (range)
	Minnesota	2.5/km (average) 2.0-2.9/km (range)
Woo & Waddington, 1990	north Ontario	14.3/km (average) 5-19/km (range)

FIGURE 2.1: A classic beaver dam (from Richard, 1955)

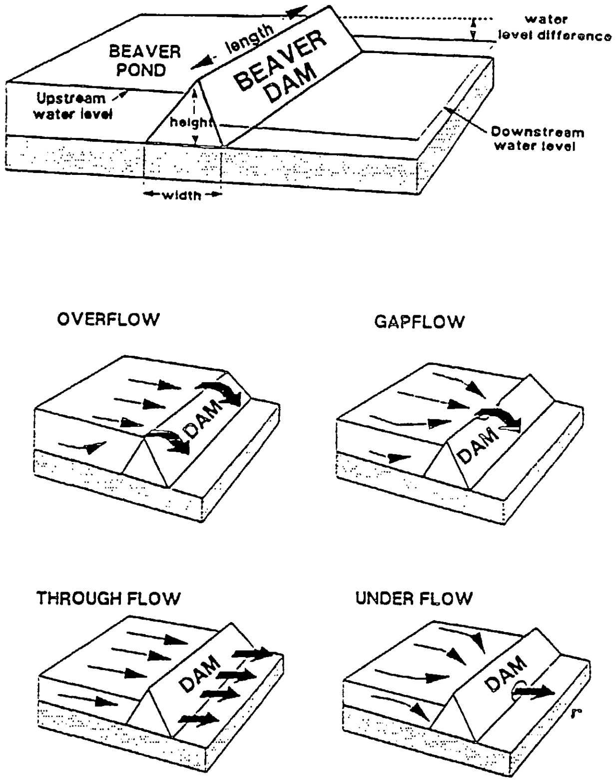
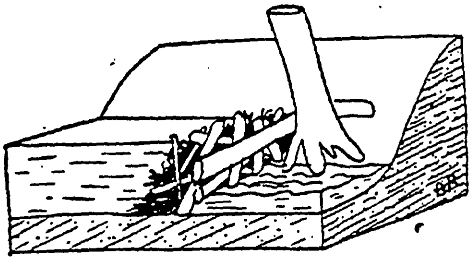
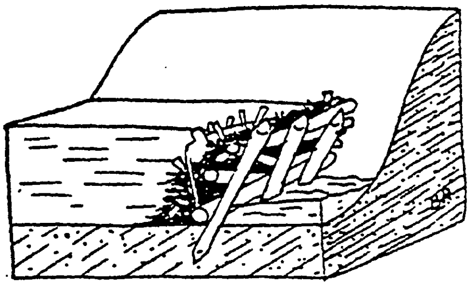


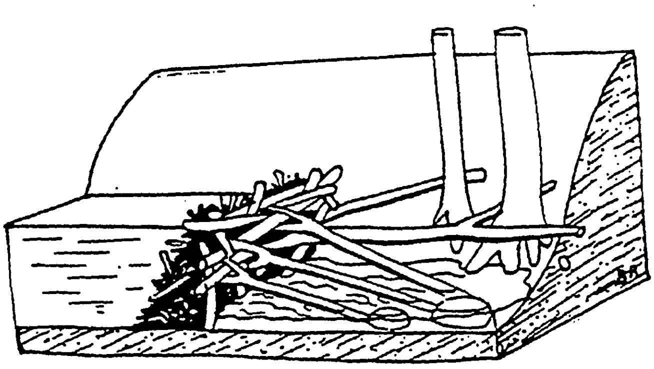
FIGURE 2.2: Types of flow across beaver dams (from Woo & Waddington, 1990)



Type 1



Type 2



Type 3

FIGURE 2.3: Three types of dam structure (from Richard, 1955)

FIGURE 2.4: A common beaver dam plan form is based on one or more arcs (from Richard, 1967)

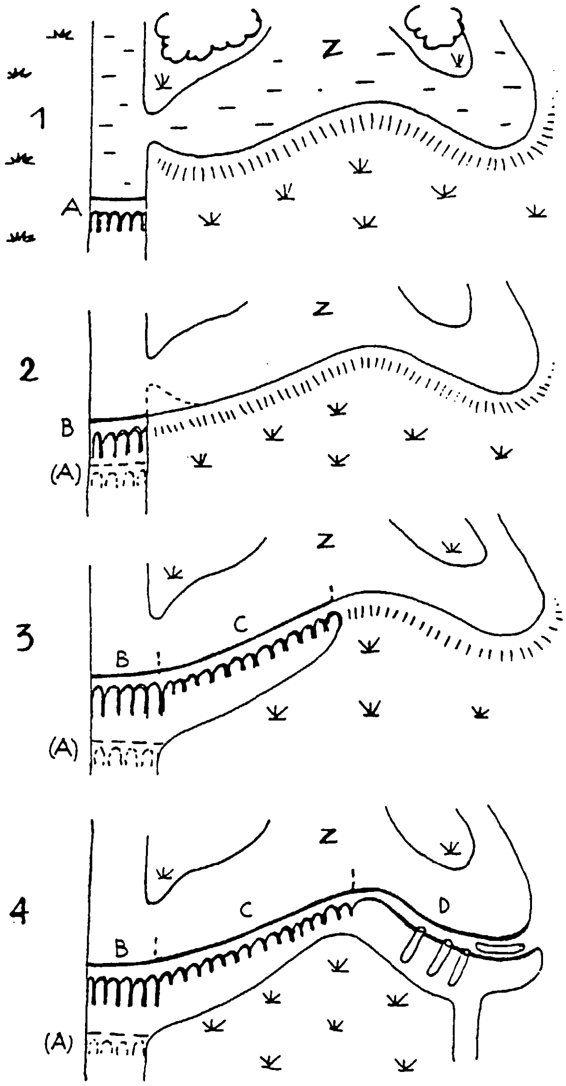


FIGURE 2.5: The lateral extension of a beaver dam (from Richard, 1967)

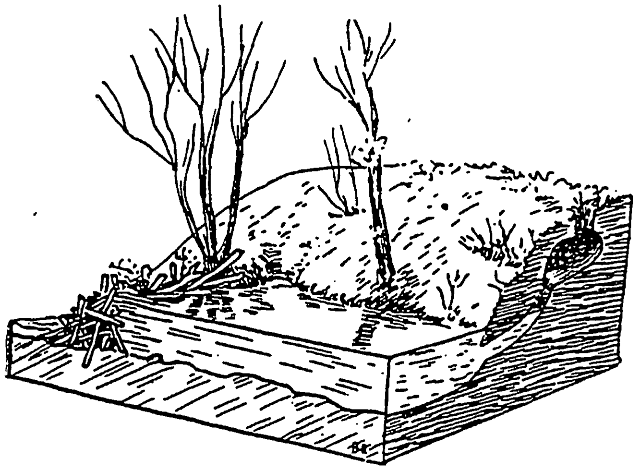


FIGURE 2.6: A typical configuration of dam, burrow and below-water entrance (from Richard, 1955)

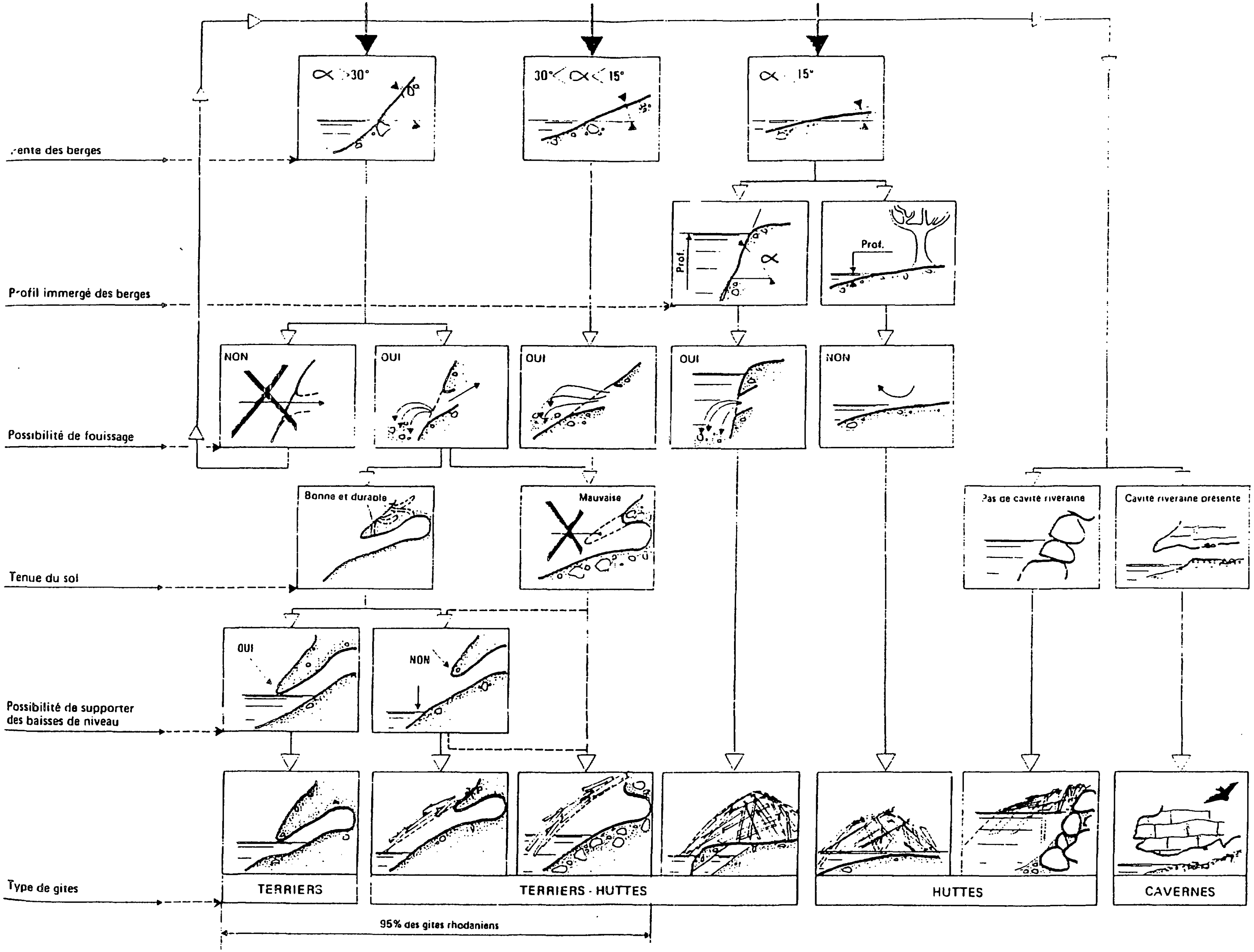


FIGURE 2.7: A classification of beaver burrows, burrow-lodges and bank lodges (from Erome, 1984).

2.4 ENVIRONMENTAL CONDITIONS ASSOCIATED WITH DAM BUILDING

The presence/absence and density of beaver dams is highly variable (Table 2.3) depending upon the number of beaver colonies and the degree to which environmental conditions encourage dam building. Only reference to environmental conditions associated with dam building by *C. canadensis* were found in the literature consulted for this review. McComb *et al.* (1990, cited in Collen, 1995) found that reaches with dams were shallower, had a lower gradient, a greater tree canopy cover and gentler bank slopes than reaches without dams, and that dams were not built at sites with a rock substrate. Naiman *et al.* (1986) noted that most dams were built on 1st to 4th order streams in their study area in Quebec, Canada. This corresponds to the range of stream orders in which accumulations of LWD have the greatest tendency to form dams (Gurnell *et al.*, 1995).

Although beaver dams may be maintained in the same location for long periods of time (several centuries in some cases), dams may become abandoned and fall into decay, or they may pass through cycles where they fall into decline and then are later re-established (e.g. Warren, 1932; Sinitsyn, 1992). The circumstances governing dam abandonment, failure, and reoccupation are all hydrologically important, but little information was found concerning these circumstances in the literature. Beier & Barrett (1987) identify river reaches abandoned by beaver and allocated them to two groups. The first group comprised reaches that were similar to those with active colonies but with relatively low food availability. These may be re-occupied when the vegetation recovers and then dam building and maintenance may recommence. The second group comprised reaches that were more similar to uncolonised than to colonised reaches and were probably only occupied for a short period of time prior to abandonment. The extent to which beaver dams might fail during major flooding (e.g. as a result of rapid snowmelt), is illustrated by Leidholtbruner *et al.* (1992), who found only one complete dam during a spring survey of 19km of stream in coastal Oregon, but the density had risen to over 1 dam per km of stream by the following autumn.

2.5 PHYSICAL ENVIRONMENTAL IMPACT OF DAM BUILDING

Beaver, through their dam-building and feeding activities, act as a keystone species which affects ecosystem structure and dynamics far beyond its immediate requirements for food and space (Naiman *et al.*, 1986). Johnston & Naiman (1987) illustrate the way in which beaver ponds and canals affect local hydrological processes to create a series of disturbance patches within the forest landscape. The patches include (i) the pond, (ii) the surrounding riparian zone with its raised water table and browsed vegetation, exhibiting both waterlogged areas and areas of enhanced soil moisture content, (iii) often a marginal floating mat of peat and vegetation along parts of the pond boundary, and (iv) a zone of anaerobic sediments beneath the pond bed. All of these patches are a direct effect of the changed hydrological conditions which are a consequence of beaver dam construction. Each colony of beaver may build several dams and thus create more than one pond. For example, Johnston & Naiman (1990) found that in the Kabetogama Peninsula, Minnesota, each beaver colony was associated with an average of approximately two dams, the ponds inundating an average area of 4 ha. They also observed that the largest ponds, presumably representing the optimum sites for damming water, were constructed earliest in a 46 year period of beaver population expansion. Because beaver impoundments are restricted to sites where a low dam can retard the flow of water sufficiently to create a pond, there is a limit to the area that can potentially be affected by beaver' (Johnston & Naiman, 1990).

It is scarcely surprising, that beaver dam construction can have far-reaching environmental impacts. Indeed, Hammerson (1994) reviews 21 environmental changes that occur when a section of stream is replaced by a beaver pond constructed by *C. canadensis*.

1. Storage of precipitation, which is gradually released through dry periods, and reduced variability in discharge regime.
2. Decreased current velocity.
3. A several-hundred-fold increase in the wetted surface area of the channel (in areas of gentle topography).
4. Increased water depth.
5. Elevation of the water table.
6. In forested areas, an increase in the amount of open canopy.
7. Loss of wildlife species that depend on living riparian deciduous trees.
8. Enhancement or degradation of conditions for fish.
9. Creation of conditions favourable to wildlife that depend upon ponds, pond edges, dead trees, or other habitats not present or in limited supply in stream systems not modified by beaver.
10. Replacement of running-water invertebrate taxa by pond taxa, and an increase in the absolute importance of collectors and predators and a decrease in the relative importance of shredders and scrapers in impounded sites.
11. A several-fold increase in the mass of insects emerging from the water surface per metre of stream length.
12. Increased plankton productivity.
13. Increased trapping of sediment and a decrease in turbidity downstream.
14. More favourable conditions for the growth of plants such as willow and alder.
15. A great increase in the amount of organic carbon, nitrogen (and its availability), and other nutrients in the channel; an increase in carbon turnover time; and an increase in nitrogen fixation by sediment microbes.
16. Amelioration of stream acidity.
17. An increase in aerobic respiration, the amount in a pond being 16 times that in a riffle).
18. In low order streams a substantial shift to anaerobic biogeochemical cycles in sediments beneath the aerobic pond sediments.

19. An increase in the amount of organic matter suitable for methane-producing microorganisms and increased carbon output by methanogenesis.

20. Reduced oxygen levels in the water in spring and early summer due to decomposition of the augmented organic matter.

21. Increased resistance of the ecosystem to perturbation.

The present review focuses on the physical environmental effects of dam construction on fluvial systems, including where possible impacts between dams and ponds. These effects are considered below in relation to surface water storage and river flow regime, bank hydrology and riparian water table dynamics, sedimentation and fluvial geomorphology.

2.5.1 Surface water storage and flow regime

The amount of water stored within a beaver pond is a function of the dam dimensions and the local valley geomorphology, particularly down-valley slope, and cross-valley profile (Johnston & Naiman, 1987). As a result, beaver dams located on streams in constricted, steep, upland valleys pond back less water, are more restricted in area, and vary little in their spatial extent with changing water levels. Furthermore, the topography of upland river corridors does not favour the construction of beaver canals. In contrasts, the wider, lower gradient valleys favoured by beaver for dam construction support spatially-extensive, complex pond and canal systems. The volume of water stored is also a function of the degree to which the beaver dam is water tight. Devito & Dillon (1993) monitored water levels and outflows from a 3.8 ha beaver pond in central Ontario. These data illustrate how the pond controlled downstream discharge as a result of overtopping of the dam when the pond was full, and as a result of some limited seepage through or under the dam, when water levels fell below the dam crest. However, once the water dropped more than 5cm below the dam crest, the downstream river flows became very small, indicating how watertight the dam was. Thus, hydrologically, a well-constructed beaver dam acts like a low weir, causing water storage which impacts on both high and low flows in the river system. Although the effect of a single beaver pond on river flows will be small, a sequence of ponds may have a significant effect. Ehrman & Lamberti (1992) found that reaches of third order streams with woody debris dams retained water 1.5 to 1.7 times longer than those with minimal LWD. The impact of a sequence of well-constructed beaver dams on water retention within a river reach will be much greater. Effects on the transmission of river flows will include an increase in the time of rise of the flood hydrograph and a decrease in the magnitude of the flood peak discharge, whereas gradual seepage from the ponds during dry periods may sustain low river flows, seepage to the riparian zone, and areas of water storage within the channel network far longer than would occur in river channels without beaver dams. The extent of such impacts upon both high and low flows depends upon the storage capacity of the ponds and the degree to which the dams are watertight. Storage capacity is greatly affected by local topography and whether the dam is entirely in-channel or extends across the floodplain (e.g.. see section 3.2). As dams are constructed, maintained or fall into decay, their effect on the river flow regime will vary considerably.

2.5.2 Bank hydrology and riparian water table dynamics

Water levels in beaver ponds are a function of the difference between the volume of water entering (river flow, precipitation, groundwater seepage), flowing out of the pond (river flow, groundwater seepage), and evaporating from the pond surface. Thus, the water level varies seasonally and during flood events (Naiman *et al.*, 1994). Variability in the relative levels of water upstream and downstream of beaver dams and within the adjacent riparian zone can give rise to complex surface water - groundwater interactions. For example, White (1990) described longitudinal (i.e. downstream) convective flow patterns beneath beaver dams, whereas Lowry (1993) noted a correlation between seasonal and flow-event controlled water levels in a beaver pond in central Oregon and the lateral riparian groundwater levels. Larger fluctuations occurred in groundwater levels in the riparian zone surrounding the pond than in those adjacent to an unponded section of river. In addition, local hydraulic gradients suggested enhanced recharge of the riparian aquifer adjacent to the pond in comparison with the unponded reach. A similar effect has been noticed in relation to accumulations of LWD in river channels, where bankside wetland areas may be produced as a result of the locally high water table which is maintained by seepage from the ponded water behind the debris dams into the channel banks during low flow (Gurnell & Gregory, 1987).

2.5.3 Sedimentation

In-channel sediment storage provides a buffer between episodic inputs of sediment to the river system and their regulated transmission downstream. The ability of a river channel to store sediment depends on its overall dimensions and slope, and on the presence of features such as bends and obstructions, including beaver dams. Although the role of beaver ponds in trapping sediment has been recognised in North America, there is little information on the volumes of sediment and their rates of accumulation (Butler & Malanson, 1995). Nevertheless, the role of LWD accumulations in sediment storage and their impact on sediment transfer rates has been illustrated by a number of studies. Keller & Tally (1979) estimated that up to 40% channel area in their study creeks in California were zones of sediment storage controlled by woody debris accumulations. Annual sediment yields from small forested watersheds are frequently less than 10% of the sediment stored (Sullivan *et al.*, 1987). If debris accumulations are removed, sediment rapidly comes out of storage, leading to major increases in sediment transport and yield (Beschta, 1979, Klein *et al.*, 1987, MacDonald & Keller, 1987, Smith *et al.*, 1993).

A major study of sedimentation in beaver ponds was undertaken by Naiman *et al.* (1986). This research estimated retention of 3.2 x 10^6 m^3 sediment within beaver ponds on 2nd to 4th order streams in their Quebec study area. If sediment were evenly distributed over the total area of stream bed it would reach a depth of 42 cm. The gradual infilling of beaver ponds ultimately results in the development of beaver meadows, which are organically-rich, gently sloping, alluvial plains (Ruedemann & Schoonmaker, 1938).

Sediment deposited in beaver ponds can be both mineral and organic in nature. At the point where the river system enters the pond, deposits of mainly mineral sediment may settle out of the flow, but within the major body of the pond, sediments are a mixture of mineral and organic material derived from the inflowing stream, bank failure, excavations of canals and burrows, input of organic matter from riparian vegetation, import of organic matter by beaver and primary production within the pond. The material accumulates on the bed and rates of sedimentation can be very high. For example, Butler & Malanson (1995) estimated rates of sedimentation ranging from 2.1 to 27.9 cm.yr^{-1} for eight locations on four beaver ponds in Glacier National Park, Montana. The trapping of sediment in beaver ponds has resulted in the deliberate introduction of beaver to inhibit sediment transfer, stabilise stream banks and restore riparian habitat in many areas of North America (eg. Apple, 1982; Bergstrom, 1985, Brayton, 1984; Farrar, 1971; Johnson, 1984; Ruedemann & Schoonmaker, 1938). Furthermore, recent erosional downcutting in low-order streams in North America has been attributed to the removal of beaver (Parker *et al.*, 1985). However, Butler & Malanson (1995) point out that the provenance of the sediment is unclear. In particular, it is important to separate sedimentation of fluvially-transported sediment from that introduced into the ponds by beaver activity such as the excavation of canals and burrows. Such a separation would allow the accumulation rates of fluvially-transported sediment to be estimated, so that the role of beaver dam building activity in attenuating the transfer of sediment within drainage basins can be quantified.

The fate of the organic component of the accumulated sediment also has important and long-term environmental consequences. Naiman *et al.* (1994) combine observations from several study sites in Minnesota to evaluate the long term biogeochemical characteristics of boreal forest drainage networks affected by beaver, so providing a useful summary of this aspect of the impact of beaver ponds. They show that

> "beaver influence the distribution, standing stocks, and availability of chemical elements by hydrologically-induced alteration of biogeochemical pathways and by shifting element storage from forest vegetation to sediments and soils. As the upland vegetation dies and decays after dam construction, only a portion of the chemical elements are exported downstream (except for calcium and magnesium) or returned to the atmosphere (C and N only). Consequently the organic horizons of pond sediments accumulate substantial standing stocks of chemical elements that are available for vegetative growth when dams fail, the ponds drain, and meadows are formed. These influences are spatially extensive and long-lasting, affecting fundamental environmental characteristics of boreal forest drainage networks for decades to centuries" (p912).

2.5.4 Fluvial geomorphology

The geomorphological consequences of beaver dams have not been widely considered in the literature, but inferences can be made by combining the above summary of impacts on individual fluvial processes with observations of the geomorphological effects of accumulations of LWD. Thus, both sources of information are combined here to assess the geomorphological impact of beaver dam construction in relation to channel morphology, channel stability and drainage network development.

The discharge regime, sediment load and structural elements within the channel determine the shape of the river channel. Beaver dams represent very important structural elements within the channel. The construction of beaver dams impedes flow in river channels producing steps in the river's long profile. This impact on the river's long profile has hydrological consequences, through the ponding and diversion of water, which affect river bank hydrology, flood peak attenuation for flood events up to and slightly above bankfull, and hydraulic consequences through complex changes in the downstream pattern of energy dissipation. Large obstructions such as beaver dams partly or completely block the flow, creating areas of high or low flow velocity and thus shear stress on the channel bed and banks, and so regulating the scour and deposition of sediment. The exact configuration of the resulting channel morphology and the interaction with moving bedload depends on the shape and size of the roughness element and its position and configuration within the stream channel (Lisle, 1981). The presence of beaver dams is likely to produce the increased diversity in channel width and depth (Keller & Tally, 1979; Hogan, 1986), in-channel morphological features (Keller & Swanson, 1979) and patchiness of bed sediment of differing calibre (Sullivan *et al.*, 1987) that have been identified as characteristics of streams containing accumulations of LWD. Contrasts in the downstream morphological effects of both beaver dams and LWD accumulations are related to the leakiness of the structures and the degree to which over-, through- or under-flows occur in high-velocity localised threads. The patchier the flow and the greater the fall of the water, the greater the sediment sorting and morphological diversity that may result. For example, concentrated flow over the crest of well-sealed, active LWD accumulations usually results in the excavation of plunge pools and, in gravel-bed streams, to the downstream deposition of well-sorted gravel bars. Where the beaver dams extend out across the floodplain, its downstream consequences may differ from LWD accumulations. For example, diffuse seepage through the floodplain part of the dam may lead to the development of areas of floodplain wetland, whereas concentrated flow may result in the excavation stream channels.

LWD accumulations have been shown to play a major role in controlling the stability of low order streams. This role is particularly well illustrated by observations of the consequences of debris removal. Bilby (1984) observed large changes in channel structure in the first storm after debris clearance from a small western Washington stream. Channel cross sections were substantially altered by the removal of stored sediment and the number, volume and area of pools decreased. Heede (1985) tested the hypothesis that log steps take the place of gravel bars by observing the formation of gravel bars in a forest stream that was kept clear of LWD accumulations. After five years all removed log steps had been replaced by gravel bars, supporting the hypothesis that increased bedload movement was required to offset the loss of log steps. Similar results are presented by Smith *et al.* (1993), who observed a four-fold increase in bedload transport at bankfull discharge in a second-order gravel-bed stream during the first six months after experimental debris removal. Given their similar sediment-storing role, beaver dams can be expected to have a similar effect in enhancing the stability of streams.

Dam building by beaver can have an impact on the drainage network in a complex manner, particularly in locations where floodplains are wide and channel gradients are low. For example, Woo & Waddington (1990, p226) describe drainage patterns on subdued topography in subarctic northern Ontario:

> "In most cases water spilled from the beaver pond returns to the channel at a short distance below the dam. In other situations, new flow diversion channels may be created that act as spillways when the ponds are full... Then water may not get back to the original channel until it has travelled tens or hundreds of metres downstream. When these diversion channels are reoccupied over a period of time, they may be sufficiently downcut to become permanent routes along which water will flow".

Townsend (1953) mapped beaver dams and channel networks associated with rivers 3 - 15 m wide with floodplains 1-2 km wide in Montana. Here dam building had caused extensive changes to the drainage network, with river channels subdividing into several distributaries at dam and pond locations where the water level had been raised sufficiently for flow diversions to occur across the relatively flat landscape.

In summary, the impact of dam construction on sediment storage and flow diversion in areas of low relief will have implications for channel planform and dynamics. The sedimentation effects of beaver dams reduce any tendency towards the development of a braided channel consisting of mobile bars of sediment separating active threads of the river flow, although it must be stressed that the establishment of dams in an active braided environment is extremely unlikely. Nevertheless, the flow diversion effects of beaver dams can encourage the establishment of more stable multi-thread channel systems. At a local level, a series of interconnected, ephemerally-, intermittently- and perennially-occupied channels may be created to accommodate flood flows, seasonally higher flows and baseflows (as identified by Gurnell *et al.*, 1995, in association with LWD accumulations). Over larger areas of very low relief, the presence of beaver dams may encourage the development of an anastomosing channel pattern with stable vegetated land occupying the areas between the multiple river channels.

Beaver dam failure may also have geomorphological consequences. There is little information in the literature on this topic, and that which exists relates entirely to the failure of large dams constructed by *C. canadensis* in North America. When high flows and water levels threaten to seriously damage beaver dams, the beaver often open a small channel on the dam crest to lower the water level (Butler, 1995). Even so, beaver dams can fail catastrophically with severe consequences when large volumes of water are impounded. Butler (1995) suggests that excessive, high-intensity precipitation, rapid snowmelt, animal burrowing through the dam (and presumably anthropogenic interference), and collapse of upstream dams may cause catastrophic dam failure. The last cause is similar to that of debris torrents associated with LWD that have been reported in steep mountain streams in North America. 'Catastrophic' failure can only occur if the dammed water volumes are large enough and, given the typical dimensions of dams, such large volumes will be relatively rare and will occur on low gradient streams. Butler (1995) describes a number of catastrophic failures of beaver dams resulting in, for example, transport of clasts >1m in diameter, incision of 0.5-0.6m of a channel bed, and severe sediment deposition downstream. However, the very limited literature on this subject suggests that such failures are extremely rare.

2.6 BEAVER IMPACTS AND THE RIVER CONTINUUM

The far-reaching impact of beaver on river systems caused Naiman *et al.* (1986) to consider their influence on the River Continuum Concept (RCC, Vannote *et al.*, 1980). The RCC views river systems as longitudinally interconnected channels where hydrological, geomorphological and biological processes operate along a continuum. The concept does not fully allow for interruptions to the continuum such as ponds and lakes (major water bodies were subsequently addressed by the Serial Discontinuity Concept, Ward & Stanford, 1983) or for major lateral interactions, although this was considered by Sedell *et al.* (1989) for large rivers. Interruptions and lateral interactions characterise the impact of beaver, particularly on small streams, where they are most likely to construct dams. Naiman *et al.* (1986)

specifically suggest that where beaver are present, the implied characterisation of small streams (approximate orders 1-3) by the RCC needs to be redefined to include numerous zones of open canopy, large accumulations of fine detritus, increased wetland area, increased biogeochemical interactions with riparian plants and soils, reduced allochthonous inputs per unit area, and concomitant adjustments in the functional attributes of the invertebrate community' (Naiman *et al.*, 1986, p1267). The view of Sedell *et al.* (1989, p 53) that 'the large river system is a sequence of patches of varying lengths and widths, and not a simple continuum' seems also to apply to small streams subject to extensive beaver activity.

The fairly restrictive environmental requirements for dam construction suggest that significant lengths of channel will remain free of dams, even in headwater streams where the channel is sufficiently narrow for damming. Furthermore, in zones of dam construction, there will be between-dam patches which are unaffected by the backwaters from the dams. Dams regulate the range of river flows so reducing the range in discharge and flow velocities between dams in comparison with the pre-dam situation. They also cause much of the river's energy to be dissipated at the dam locations rather than gradually along the stream's long profile. Both of these effects are likely to increase the stability of river channels between dams and beaver ponds. More significantly, sediment movement is heavily regulated by the presence of beaver ponds, resulting in a reduced sediment supply to intervening sections of river channel, with all size ranges of sediment (including fine suspended sediment) being trapped by large ponds. The result of sediment retention, is the potential for local erosion of the channel immediately below dams and for the enhanced transport and sorting of sediments in river stretches that are free of dams and are downstream of dam locations.

Further downstream, where the main river systems are too wide for damming, beaver occupy sloughs, backswamps, backwaters, lakes and minor channels on the floodplain (Butler, 1995; Naiman *et al.*, 1988; Townsend & Butler, 1996). In these locations, they construct dams and canals from which they cut wood and open up the floodplain forest. Wood cut by beaver or delivered by other means to the channel in upstream reaches can accumulate in the main channel even where it is too wide for dam construction. In large single-thread channels, wood may accumulate as marginal ribbons of debris at the edge of the active channel or in the riparian vegetation. In braided systems, it may be deposited within the active channel forming a focus for enhanced sedimentation and possibly bar development (Piégay & Gurnell, in press).

2.7 SUMMARY AND CONCLUSIONS

In assessing the potential hydrological influence of beaver dam construction, three groups of issues are important: (i) the suitability of the habitat for colonisation by beaver; (ii) the potential of the habitat to encourage dam construction; (iii) the likely hydrological impact of dam construction under the range of environmental conditions within which dam construction may occur.

2.7.1 Habitat suitability for colonisation

This review has illustrated the extensive literature on this topic, and, in the absence of significant anthropogenic interference, the very wide range of physical conditions under which beaver colonies exist. The only relatively restrictive physical requirements seem to be a preference for finer river bank materials on relatively low gradient streams (indicated either explicitly, or through the requirement for medium to low flow velocities). This reflects the ability of beaver to modify the habitat to suit their requirements through dam, burrow and lodge construction. For example, wide fluctuations in water level can be regulated, although extremely low flows (e.g. intermittent streams) and widely and rapidly fluctuating flow levels (e.g. >1.5 m) can cause difficulties for beaver. In contrast to the wide range of physical conditions under which beaver colonies may exist, the riparian vegetation cover is extremely important and requirements are quite restrictive. Hardwoods and a good herb layer are minimum requirements, and the presence of willow and aspen is ideal.

2.7.2 The potential of the habitat to encourage dam construction

Although the literature on this aspect is more limited, a number of inferences can be drawn, which are outlined here in relation to different characteristics of the fluvial system:

Stream order

Dam building occurs mainly on streams of 1st to 4th order. Such streams typically have widths up to 10-15 m. Since these are also the orders of streams in which LWD accumulations frequently dam the stream (both active and complete dam types), the range in stream order must reflect the capability of well-constructed woody structures to dam river systems. Furthermore, the flow regime in lower order streams is often less reliable than in larger rivers. Dams can maintain water levels during summer low flows and can reduce the seasonal and storm event range in water levels by attenuating discharges through a sequence of ponded water stores, and by spreading the flows across a dam crest that is wider than the original river channel.

Stream gradient

Although low order, narrower stream channels permit dam building, steep headwater streams present a number of other difficulties. An increase in slope increases the power of the stream and so increases the likelihood that high flows will precipitate dam failure. Steep gradient channels provide a reduction in the potential ponded area resulting from dam building. Since beaver dams are usually < 1.5 m high, increasing gradient can rapidly reduce the pond area to a level where it provides insufficient protection for the animals and insufficient extension of the potential foraging area for the beaver colony. As a result construction on gradients that are greater than 4% is very unlikely.

Substrate, sediment transport and channel dynamics

Although beaver have been observed to construct dams on a wide range of calibres of substrate, bedrock streams are not favoured, presumably because of the poor anchorage for the dam structure. Furthermore, dams and their associated ponds are unlikely to survive for long where there is high sediment transport and where the channel banks are highly mobile. Lower bedload transport and channel mobility are most likely to be features of low gradient (i.e. low power) streams, with a relatively stable flow regime. Such conditions will also lend themselves to the deposition of fine alluvial bank materials that are suitable for burrow construction. From these requirements, beaver are highly unlikely to attempt to dam braided rivers and steep rock-bed channels, and are most likely to dam single-thread, low bedload, wandering channels.

Within a suitable stream system, beaver select the optimum sites for dam construction first. Thus zones of locally low gradient channel with a wide river corridor of subdued topography and suitable bank materials will be selected, resulting in the largest area of water inundation and access to foraging sites in response to the minimum building effort by the beaver colony.

2.7.3 The likely hydrological impact of dam construction

The effects of dam construction within a suitable catchment are as follows:

(i) Introduction of a stepped long profile to the stream channel, where stream energy is mainly dissipated at the locations of the beaver dams which form the major steps in the system. Plunge pools may develop below well-sealed dams. The ponds above the dams will act to sustain low flows and to attenuate flood peaks.

(ii) An increased complexity in the hydrology of the riparian zone with alternating patches of high and low water table, spatially varying soil water regimes, and complex stream-riparian aquifer flow paths.

(iii) Increased sediment storage within the channel system, decreased and attenuated sediment yield from the catchment.

(iv) Sorting of bed sediments, where a variety of particle sizes are present. Sorting will occur within the beaver ponds, where coarser sediments will be deposited in the pond heads and finer sediments within the main pond body. Sorting will occur downstream of the dams within dam-free channel sections where sediment supply is limited by upstream storage within beaver ponds.

(v) Storage, decomposition and processing of organic matter closer to its source area within the beaver ponds.

(vi) Development of a more complex local channel network to accommodate high flows and the potential in extensive areas of low relief for an anastomosing type of river planform to develop.

(vii) As a result of (i) to (vi) an overall increase in both lotic and riparian habitat diversity and an increase in channel stability.

3. AN EVALUATION OF THE HYDROLOGICAL AND GEOMORPHOLOGICAL IMPLICATIONS OF BEAVER REINTRODUCTION IN SCOTLAND

This chapter explores the hydrological and geomorphological implications of beaver reintroduction in Scotland. Section 3.1 considers the habitat requirements highlighted in the preceding chapter in relation to some characteristics of Scottish river systems. Section 3.2 develops simple modelling approaches to assess some of the hydrological impacts of beaver dam construction under different topographic and river flow conditions. Finally, section 3.3 presents case studies where the potential impacts of beaver dam building activities have been evaluated.

3.1. THE SIGNIFICANCE OF FLOW REGIME AND GEOMORPHOLOGY OF SCOTTISH RIVERS FOR THE REINTRODUCTION OF BEAVER

3.1.1 Habitat requirements

The literature review presented in Chapter 2 identified the following broad habitat requirements for beaver:

(i) *Food availability.* Easy access to grasses, forbs and hardwood vegetation, particularly aspen and willow.

(ii) *Channel dimensions.* Where streams are small and shallow, the larger channels are preferentially selected by beaver, whereas in areas of wide channels, the narrower locations are selected. MacDonald *et al.* (1995) suggest 2-4m water depth, 10-100m river width, bank height > 1.5 m and bank slope < 60° are required of a good site for beaver. Of these requirements, bank height is the most restrictive since bank slope can be manipulated by excavation and water depth can be manipulated by dam building.

(iii) *Channel/floodplain gradient.* Lower gradients are preferred (e.g. <2% slope - approximately 1.2 degrees). Lower gradients are also more likely to be associated with the lower flow velocities ($<0.3\ m.s^{-1}$) and finer, more organic bank materials (peat-loam soil) suggested to represent good beaver habitat by MacDonald *et al.* (1995).

The degree to which beaver may attempt to modify the habitat through dam construction is reflected in the following criteria:

(i) *Stream order.* Dam building occurs mainly on streams of 1st to 4th order. Such streams typically have widths less than 10-15 m. This reflects the degree to which woody structures are capable of successfully damming streams and the fact that water depths are shallower and the flow regime is less reliable in lower order streams in comparison with larger rivers, so rendering water level regulation by beaver necessary. Dams which extend beyond the channel margins and so spread the discharge across a greater width, can have a very strong regulatory effect on water levels.

(ii) *Flow regime* Flow regime to some extent varies with stream order, since smaller catchments tend to exhibit more extreme flows per unit catchment area than large ones. Also headwater streams are normally located within the high elevation zone of the catchment, which is usually associated with the highest amounts of precipitation, the steepest slopes, and thus, potentially, the highest peak discharge per unit catchment area. However, there are other factors which may be important in influencing flow variability and thus the likelihood of beaver dam construction. Of particular importance is the impact of artificial manipulation of flows. Flow regulation may impact on beaver in three ways. First, a decrease in the range of flows may encourage beaver colonisation without encouraging beaver dam construction. Second, a reduced range in flows may encourage beaver colonisation accompanied by dam construction to further regulate water levels, where water level fluctuations or velocities are still too high. In either of these cases, a flow regime which includes sudden releases of high flows forms a third category of artificial regime which may be extremely destructive, resulting in the washing out dams and the rapid inundation of nests and burrows.

(ii) *Stream gradient.* Narrower channels, typical of low-order headwater streams, permit dam building but steep headwater streams present a number of other difficulties for beaver as a result of the magnitude of stream power and the reduction in the potential ponded area resulting from dam building. As a result, although dam building is usually confined to narrower channels, construction on gradients that are greater than 4% (i.e. approximately 2 degrees) is very unlikely.

(iii) *Substrate, sediment transport and channel dynamics.* Bedrock streams are not favoured by beaver. Dams are unlikely to survive for long where there is high sediment transport and where the channel banks are highly mobile. Lower bedload transport and channel mobility are most likely to be features of low gradient (i.e. low power) streams, with a relatively stable flow regime. The bed material is not a major problem for dam construction as long as it is relatively stable. Indeed, beaver often build dams which make use of the strengthening effect of large boulders. Thus rivers where the flow is regulated to reduce periods of bedload transport, or where coarse bed material is naturally stable, may be attractive to beaver. Beaver are highly unlikely to attempt to dam actively braiding, gravel-bed rivers and steep rock-bed channels, and are most likely to dam single-thread, low bedload, wandering channels and stable multi-thread anastomosing channels.

3.1.2 Flow regime and geomorphology of Scottish rivers

Werritty *et al.* (1994) note that the "geomorphological freshwater resources in Scotland afford a richer diversity of processes, forms and patterns than any other part of the UK ... because of the highly resistant underlying bedrock, deeply dissected relief (particularly in the Highlands), the juxtaposition of highland and lowland environments in the piedmont zone, and the marked climatic gradients (especially in terms of precipitation) from west to east across the country". A number of these properties of Scottish rivers may prove problematic for beaver colonisation.

(i) Mountainous terrain is associated with **steep gradients** which may restrict the habitat suitability for beaver.

(ii) Steep slopes and high rainfall result in the relatively high total and unit **stream power** of Scottish rivers (Ferguson, 1981). High discharges and steep slopes may yield flow velocities and bedload transport rates which are unsuitable for beaver, and in particular may make dam construction difficult and dam failure common.

(iii) The **rapidly varying discharges** induced by high-intensity precipitation over mountain catchment headwaters and by sudden spring snowmelt may cause flow level variability to be too great and may result in the failure of beaver dam structures built to reduce flow level fluctuations. Many streams throughout the steep mountainous zones of Scotland may exhibit such rapidly-varying discharges, but this is a particular feature of the steep-gradient rivers along the Scottish west coast. In such streams, if colonisation by beaver were successful it would be likely to result in annual cycles of dam construction and failure similar to those observed in the north-west United States (e.g. Liedholtbruner *et al.*, 1992).

The influences of flow regulation may reduce or increase flow variability. Gilvear (1994) discusses the extremely varied impacts of river regulation schemes on Scottish rivers, including hydro-power, water supply and flood alleviation schemes. Rivers directly affected by hydro-power reservoirs experience reduced magnitude flood flows, compensation flows which vary from 3.4% to 38.7% of mean daily flow with an average of 13.7% (Gustard, 1991; cited in Gilvear, 1994), generally representing an increase on unregulated dry weather flows. Compensation flows may be released at a constant or seasonally-varying rate and may incorporate freshets or block grants. Alternatively, flow may be released to maintain a specified flow regime at a particular point downstream (Gilvear, 1994). Downstream of hydropower stations, large and rapid changes in river level can occur.

Table 3.1 presents information on the flow regime of five sites, two of which are affected by hydropower generation and three have unregulated flow regimes. The two regulated sites are both on the River Farrar. One site is immediately below a dam, so that its flow regime is entirely controlled by dam releases of compensating flow, freshet flow and occasional larger releases. The second site is further downstream where the discharge is influenced by flows from a number of small unregulated tributary streams and where flows from hydro-power releases have been reintroduced into the river. In the upstream, compensating flow site, the flow range between the mean annual flood and the mean flow is higher than the unregulated sites (although the mean flow is undoubtedly higher than the estimate in Table 3.1, where it is based only on the compensating flow). The ratio of longer return period floods (e.g. Q_{10}) to the mean annual flood is also larger than in the unregulated sites. This suggests that this site has a greater range in flows at the annual and larger timescales than at the unregulated sites. However, day to day flow variability is less, being largely dependent on a fixed compensating flow ($2.38\ m^3.s^{-1}$) with additional freshet flow in summer ($6.93\ m^3.s^{-1}$). This variation in flow would be associated with quite small changes in water depth. For example, in the River Farrar near detailed study site A (section 3.3.1), such a range in discharge would result in less than a 0.3m change in water depth. In contrast, the downstream site which receives the additional flow from power generation has a similar ratio between longer return period floods and the mean annual flood to the unregulated sites but the ratio of the mean annual flood to the mean flow is smaller. Therefore, at this site, flow variability at the annual and slightly longer timescales is smaller than at the unregulated sites but short-term variability in flow in response to hydro-power generation may be substantial and may be associated with significant and abrupt changes in water levels which could be problematic for beavers.

(iv) The prevalence of erosion-resistant parent material results in the predominantly **coarse bed material** that is a characteristic of many Scottish rivers (Werritty *et al.*, 1994). If mobile, this coarse bed material will mitigate against the construction of stable beaver dams even where the channel is sufficiently narrow. Furthermore, coarse bed material is often associated with relatively coarse bank material, rendering some river banks incohesive and unstable and restricting the potential locations for burrow construction.

(v) A combination of high stream power, and widely varying flows is normally associated with active river channel systems which are unsuitable for beaver.

The above observations imply that many Scottish rivers may be unsuitable for successful beaver colonisation and particularly for dam building. However, this is a gross simplification of the situation. Suitable beaver habitat is likely to occur patchily along individual river systems in response to subtle changes in river gradient, flow regime, and bank and bed materials. Many sites may offer suitable conditions for the construction of burrows, even if dams are difficult to construct or are prone to failure. More tranquil flow locations in low-gradient tributary and distributary channels, and within old channel systems on low-gradient floodplains, offer potential for dam and canal construction and for the development of significant ponded areas. Furthermore, these lower gradient areas are usually at relatively low altitude, where suitable food is likely to be more plentiful and vigorous in its growth rate. Many of the above factors are explored in relation to the case studies presented in section 3.3.

Table 3.1 Flow characteristics at five sites
(estimates are derived from data provided by Scottish Hydro-electric and the Scottish Environment Protection Agency)

	Farrar at Beannachran Dam	Farrar at Struy	Meig at Glenmeannie	Enrick at Mill of Tore	Oykel at Easter Turnaig
Mean annual Flood ($m^3.s^{-1}$)	67.52	141.40	126.71	52.1	397.24
Mean flow ($m^3.s^{-1}$)	2.38[2]	19.42	6.88	3.22	16.44
Flows ($m^3.s^{-1}$) at different return periods[1]					
2 yrs	61.18	132.44	118.09	49.37	372.87
5 yrs	95.23	180.65	164.47	64.08	503.98
10 yrs	117.77	212.58	198.18	73.83	590.79
25 yrs	146.25	252.91	233.98	86.14	700.48
50 yrs	167.38	282.83	262.76	95.27	781.85
$Q10/Q_{ma}$[3]	1.74[2]	1.5	1.54	1.42	1.49
Q_{ma}/Q_{mf}[4]	28.36	7.28	18.42	16.18	24.24

[1] Estimates derived using the annual maximum series of instantaneous peak flows, and the EV1 frequency distribution.

[2] The mean flow is represented by the compensating flow ($2.38m^3.s^{-1}$). Mean flow would be slightly higher because of the release of freshet flows ($6.29\ m^3.s^{-1}$) during July-October and because of occasional flood flows.

[3] Q_{10}/Q_{ma} is the ratio of the flood with a return period of 10 years to the mean annual flood.

[4] Q_{ma}/Q_{mf} is the ratio of the mean annual flood to the mean flow.

3.2. ESTIMATION OF THE IMPACT OF BEAVER DAM CONSTRUCTION ON THE EXTENT OF IN-CHANNEL BACKWATERS AND FLOODPLAIN INUNDATION

This section includes some simple modelling to explore the impact of local topography and river flows on the water depths and the extent of backwaters that might be created by beaver dams. The magnitude of the mean annual flood is estimated for river channels of 5-15m width. The impact of dams of differing height on water levels and backwater development are then assessed both for within-channel and for channel-floodplain dams.

3.2.1 Estimation of the mean annual flood magnitude

Wharton (1995) presents a method for estimating the magnitude of the mean annual flood from the widths of British river channels based on the following equation:

$$Q_{maf} = 0.34\ W^{1.68} \qquad (1)$$

where

Q_{maf} = the mean annual flood ($m^3.s^{-1}$)

W = channel width (m) at the overtopping level.

Application of this equation to the two sites previously discussed on the Farrar (Table 3.1) and to the river Dee at Ballater provides estimates of 52.14, 134 and 243 $m^3.s^{-1}$ in comparison with monitored values of 67.52, 141.4 and 410.5 $m^3.s^{-1}$. The match is good given that the estimated flows are based on channel width measurements from 1:10000 scale Ordnance Survey maps and that the 'monitored' flow for the Dee is certainly an overestimate because it is calculated from the sum of instantaneous maximum flows (which would not have occurred synchronously) at three different gauging stations. Table 3.2 provides estimates of the mean annual flood for channels 5, 10 and 15m wide (theoretically small enough to be bridged by a beaver dam) using equation (1).

3.2.2. Estimation of the head of water created by ponding at low flows and by a steady discharge of the magnitude of the mean annual flood

Beaver dams adopt a range of forms, but in general they are constructed with a relatively level (perpendicular to flow) and fairly sharp (parallel to flow) crest. By assuming a horizontal water surface gradient and by combining the dam height with the river channel gradient, it is possible to estimate the extent of the ponded backwater created at low flows on land surfaces of varying gradient (Table 3.3).

Because beaver dams can adopt a wide variety of forms, some simplifying assumptions are required for modelling. Therefore, a simple modelling approach is adopted here. This uses an equation developed for relating ponded vertical head to discharge over sharp crested rectangular weirs to estimate the upstream head created by dams spanning (a) channels of various widths and (b) channels and floodplains of various widths under a continuous discharge of the magnitude of the mean annual flood (Table 3.2).

$$Q = 1.86\ BH^{1.5} \tag{2}$$

where:

Q = discharge ($m^3.s^{-1}$)

H = head of water (m)

B = width of weir crest (m)

If the estimated head is added to the dam height, simple geometry allows the estimation of the upstream extent of the in-channel or floodplain backwater for dams of varying height and for river channel / floodplains of varying gradient (Table 3.4).

Although the literature suggests that a 4% (approx. 2 degree) gradient is likely to be an upper limit for dam building activity, the estimates in Tables 3.3 and 3.4 suggest that ponds become very small with gradients in excess of 1 degree.

Table 3.2 **Estimates of the mean annual flood and the associated head upstream of a rectangular sharp-crested weir that is (1) confined to the channel width or (2) extends to span channel and floodplain**

Channel width (m)	Mean annual flood ($m^3.s^{-1}$)	In-channel head (m)	Floodplain width (m)	Floodplain head (m)
5	5.08	0.668	15	0.321
10	16.27	0.915	30	0.440
15	32.16	1.099	45	0.528

Table 3.3 **Extent of upstream ponding at low flow (approximately horizontal water surface) associated with variations in dam height and topographic gradient**

Gradient	upstream ponding extent (m) associated with the following dam heights (m)			
	0.5	1.0	1.5	2.0
0.1	286	572	860	1146
0.5	57	115	172	229
1.0	29	57	86	115
1.5	19	38	57	76
2.0	14	29	43	57

* the upstream extent assumes a smooth planar topographic surface. Therefore, the actual extent of floodplain inundation is likely to be associated with the lower dam heights quoted because otherwise the higher in-channel structures necessary to maintain a level crest across the floodplain would be difficult to construct.

Table 3.4 Estimates of the length of backwater created in rivers of cross different width and by in-channel and cross-floodplain dams under a steady discharge of mean annual flood magnitude

Channel and floodplain gradient (degrees)	Channel width (m)	Backwater length (m) for dam height in channel		Floodplain width (m) (including channel)	Backwater length (m) for dam height on floodplain*	
		1.5m	2.0m		0.5m	1.0m
0.1	5	1242	1529	15	470	757
	10	1384	1670	30	539	825
	15	1489	1776	45	589	875
0.5	5	248	306	15	94	151
	10	277	334	30	108	165
	15	298	355	45	118	175
1.0	5	124	152	15	47	76
	10	138	167	30	54	82
	15	149	178	45	59	88
1.5	5	83	101	15	31	50
	10	92	111	30	36	55
	15	99	118	45	39	58
2.0	5	62	76	15	24	38
	10	69	83	30	27	41
	15	74	89	45	29	44

* assumes a mean annual flood for channels 5, 10 and 15m spread across a dam crest of 15, 30 and 45m.

3.3 THREE CASE STUDIES

The following case studies represent conditions which may be predicted on three river systems, following the release of beavers. The areas were selected at random, taking into account issues of ownership and access, and do not infer any plans for future releases. The areas selected presented typical conditions for (1) a river system where water flow is regulated by a hydro-electric dam (River Farrar), (2) a river which is important for angling (River Dee) and (3) a river in which the water is, as far as possible, unregulated by human activities (Abhainn Deabhag). The following presents case studies to assess potential beaver activity under each of these conditions.

3.3.1 River Farrar

Figure 3.1 illustrates the long profile of the study section of the River Farrar, which extends approximately 8km from Beannachran Dam downstream to the main Farrar gauging station (Grid Reference: NH390405). The entire length of channel has a gradient of <2 degrees. The river channel is over 20m wide throughout most of its length and so is too wide for beaver dam construction. The channel is mainly single-thread, although there are occasional vegetated islands. Perennial vegetation, including a fringe of deciduous trees, extends close to the channel along most of the study section, indicating a stable planform. Furthermore, in the upstream part of the study section, algal growth on some of the coarse bed material indicates a stable bed. However, several areas of recently active gravels with an immature vegetation cover indicate some recent channel mobility, probably associated with one or more major flood events within the last few years. A particular problem of the site is the apparent lack of vigour of the deciduous trees, which were mainly birch. The health of the mature trees did not appear to be good and there were very few young trees. This poor woody food supply for beaver would probably prevent successful colonisation of the area by beaver.

Geomorphologically, the study section can be divided into five zones (Figure 3.2). Within the two gorge zones, the channel has a rock bed and banks and is unsuitable for beaver. Within the incised section, the high banks (>3m in places) consist of boulders and cobbles within a finer matrix. It would be possible for beaver to construct burrows but the water level at the time of survey, which presumably represents the compensating flow, was too low to easily maintain a burrow entrance below the water surface. Channel incision has left an extensive terrace close to the active channel, with little intervening space to support dam building and backwater development on the floodplain. If suitable food were available, beaver might be able to construct ponds on the terrace areas adjacent to the river channel. At present a number of seepages and small streams exist on the terraces but there are no trees for food. The two unconfined zones provide floodplain areas where beaver could develop dams and ponds. The upstream unconfined zone is particularly suitable because some old channel remnants are present on the floodplain. Within this zone, Figure 3.2 locates detailed survey sites A, B and C, where the potential impact of dam construction was assessed.

Site A (Figure 3.3) is located within an old channel (Photograph 1). The cross profile illustrates the relative levels of the old channel and the main river water level at the time of survey (i.e. compensating flow). A pool already exists within the old channel (Photograph 2) and there is great potential for the depth and horizontal extent of this pool to be enlarged by trapping water from precipitation and during freshet and high flows behind a dam located close to the junction of the old channel and the main river. A dam approximately 5m wide and less than 0.5m high could increase the water depth by approximately 0.35m and increase the horizontal extent of the pool from the current c. 30m to c. 70m.

Site B (Figure 3.4) is located within another old channel. Here a pond is maintained by a small stream draining the adjacent river terrace. The cross profile illustrates that a dam 1.5m high extending 4m across the old channel with a shallow extension for 5m across the right bank (B2) slope would pond water back to the highest point on the bed of this old channel segment (point x on the sketch location map, Figure 3.4). This would double the length of the pond (from c. 100 to c. 200m), increase its depth from 0.5m to c 1.5m and approximately double its width.

Although many small tributary streams enter the Farrar, most are too steep for beaver dam construction, and the depositional fans of bed material at their junction with the regulated Farrar suggest that transport of coarse bed material is high. However, site C (Figure 3.5, photograph 5 - looking upstream from the bridge, photograph 6 - looking downstream from the bridge) has a slope of 1.6 degrees, which is lower than most of the tributary streams and so was selected for modelling the impact of dam construction. The surveyed cross profile (Figure 3.5) gives a channel overtopping width of approximately 3m, suggesting a mean annual flood magnitude of approximately 2.2 $m^3.s^{-1}$. Assuming the construction of a dam 2m high within the channel and extending the horizontal crest across the entire 13m floodplain, the mean annual flood would create a 0.20m head of water which would create a backwater 61m in length across the upstream floodplain. At low flows the length of the backwater would reduce to 54m.

In general, if the food supply were better, the Farrar could support a beaver population. It might be possible for burrows to be located within the main river banks, but dam construction would only be feasible within abandoned channels on the floodplain and across low gradient seepages and tributary streams. Suitable sites are quite widely spaced and in all cases the extent of the ponded areas are likely to be relatively small. Larger ponds could be created on the terrace areas, but no woody food is available there.

3.3.2 Abhainn Deabhag

The long profile of the Abhainn Deabhag is presented in Figure 3.1. The entire channel downstream of Garve Bridge has a slope >2 degrees and there are extensive areas of bedrock exposure in the channel bed. Thus this downstream section is unsuitable for beaver. Although channel gradients remain steep upstream of Garve bridge, there are locations which could support beaver if the food supply were sufficient. The channel is fringed in many stretches by deciduous trees (mainly birch) and the trees appear more vigorous than along the Farrar.

Figure 3.6 maps the section of the Abhainn Deabhag between Cougie and Garve Bridge. Within this section the river is approximately 12m wide and so is theoretically sufficiently narrow for dam construction. However the river has a very active gravel bed (eg. photograph 10), which would soon fill in the relatively short beaver ponds that could be created on the c 1.3 degree gradient. Although extensive point bars exist within the channel (photograph 10) in the upstream half of the section depicted in Figure 3.6, the absence of significant bank erosion suggests that the channel planform is quite stable. The banks are up to 1.5m high and consist of gravels interspersed with finer particles and some organic material. These features of the bank could support the development of burrows, particularly where riparian tree roots offer additional bank stability. Figure 3.6 locates sites D, E and F where a more detailed assessment of potential beaver dam building activity was undertaken.

Site D (Figure 3.7) is a meandering section within a narrow floodplain with narrow, neck cutoff flood channels (i.e. draining across the meander neck; photographs 7 and 8), which are quite stable in position as indicated by riparian tree growth (photograph 8). Damming of these cutoff channels could create up to 1m depth of ponding and, in the case of the channel spanned by section C3-C4, could extend the water depth for some distance across the adjacent vegetated bar (photograph 8). Although damming of the main channel is unlikely to be successful in the medium term, because of the high bedload transport and frequently high flow velocities, in the short term an extensive beaver pond could be created. If a 2m high dam were constructed across the channel and extended at a horizontal level across the floodplain, this would create a pond at low flows with a width of up to 70m and extending 50m upstream across the floodplain. The channel width of c. 12m suggests a mean annual flood magnitude of 22 $m^3.s^{-1}$. With a 2m dam within the channel and extending across the floodplain, this mean annual flood discharge translates into an additional head of ponded water of c. 0.3m and a floodplain backwater of 62m.

Site E (Figure 3.8) is a floodplain site where the combination of water seepage and topographic depressions related to old channel locations would permit the development of a floodplain beaver pond. The area of floodplain that would be inundated is to the left of the river (i.e. the river's right bank) on photograph 10. Seepage water drains into the river on the extreme left of photograph 10. The junction is depicted more clearly in photograph 9. Figure 3.8 shows the horizontal extent of a level water surface that would result from the construction of a dam approximately 1.5m high and 4m wide at section E1-E2. Although there is no suitable woody food supply for beaver at this site, topographically, it is ideal for the development of a beaver pond.

Site F (Figure 3.9, photograph 11) is a slightly more confined section of the main channel lined by riparian trees. Again, the bedload transport and flashy flow regime would probably not allow the medium-term survival of a beaver dam, but some estimates were made of the likely extent of the ponded backwater. At this site the channel is approximately 12m wide giving an estimated mean annual flood magnitude of 22 $m^3.s^{-1}$. The floodplain is c. 30m wide with a gradient of 1.3 degrees. If a dam were constructed to a height of 2m above the channel bed and extending horizontally across the floodplain, the upstream floodplain backwater at low flows would be 44m. A steady flow of mean annual flood magnitude would develop a head of 0.54m and would extend the floodplain backwater to 68m.

If the food supply were better, there are locations along the section of the Abhainn Deabhag between Cougie and Garve Bridge which could support beaver. Dam construction is most likely on the floodplain where seepages, tributary flows, old channels and active side channels could be utilised. In theory the main river is sufficiently narrow to be dammed. However, the likely flow regime and associated high bedload transport would mitigate against successful dam building.

3.3.3 River Dee

The study section of the River Dee from Ballater Bridge to Dinnet Bridge, consists of a 50-55m wide, mainly single-thread, gravel-bed river, which contains some major vegetated islands. This is set within a floodplain that is up to 1km wide, has a gradient of less than 0.3 degrees, and which supports a significant deciduous woodland cover in places. The river is far too large for damming by beaver, but it is sufficiently incised within its floodplain to provide high banks suitable for beaver burrows. The bank material varies along the section, but it generally consists of very coarse material with a finer matrix. A number of small tributary streams which join the main river along this section could be dammed by beaver. Most of these tributaries are too steep to support more than very small beaver ponds and, indeed, probably transport too much bedload for dams to survive long. However, where these streams cross the low-gradient floodplain, and where distributary channels (i.e. draining from the main river) or old channels exist on the floodplain, there are suitable conditions for dam and canal construction. Two areas were identified from maps and air photographs as being potentially promising areas for beaver colonisation (Figure 3.10). The field visit showed that the area depicted in the lower map of Figure 3.10 could support beaver but was not suitable for dam construction. Here, as along much of this section of the Dee, the main channel was slightly incised and the floodplain was too well drained for the old channel system to support beaver ponds. However, the high incised banks would be suitable in some places for beaver burrows. A second area, depicted in the upper map in Figure 3.10, was found to be very suitable for the construction of beaver burrows, dams and canals. This area is bounded by the existing course of the Dee, and an old course of the river (Photograph 16). Along much of this old course there is a low terrace marking its outer limit (the terrace can be seen to the right side of the channel in Photograph 14). Much of this area is covered by deciduous trees and it includes a network of active channels and partially-flooded, old channels. Although the upstream lengths of distributary are extremely mobile (ie. on the western section of the upper map in Figure 3.10), showing evidence of major bank erosion and gravel deposition, the remaining channels in the area are far more stable. For example, Photograph 12 illustrates a relatively inactive section that could be easily dammed, with steep alluvial banks that are suitable for burrow construction. A tributary stream occupies part of the old Dee course (Photograph 15) in crossing the floodplain to join the main channel. This is another site where damming could create very significant beaver ponds. Surveys were undertaken at sites G and H (Figure 3.11) to assess the potential impact of dam construction.

At site G (Figure 3.11, Photograph 13) the 2m deep, 9m wide channel could easily be dammed to bank full level. A 1.5m dam would cause flooding along a number of currently dry channels to form an extensive pond, whereas a 2m dam (with smaller dams at other topographic low points) would inundate the entire area including the old course of the Dee as far as the low terrace. At site H (Figure 3.12, Photograph 15) a 1m high dam would fill the channel and a dam extension above the channel banks could flood a large area across the low gradient (0.04 degrees) of the nearby floodplain.

3.3 CONCLUSIONS

The above discussions of the hydrological and geomorphological character of Scottish rivers coupled with the detailed case studies illustrate a number of key factors that would have an impact on beaver.

First, food supply is a critical element. With the possible exception of some parts of the Dee site, none of the study sites supported large quantities of ideal woody food for beaver. Whilst travelling between the field sites a number of small streams lined by deciduous trees were noted. These were generally in sheltered, lower gradient sites along valley bottoms.

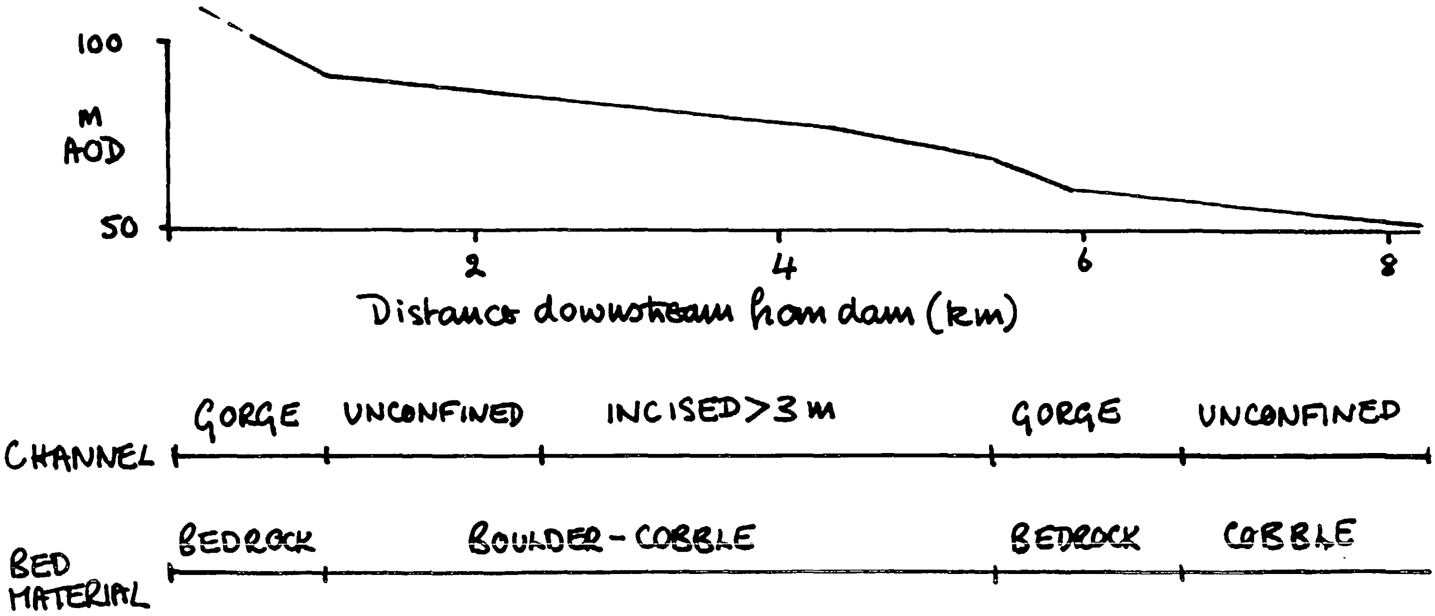
Furthermore, although burrows, with or without additional lodges, could be constructed in most of the sites visited, the conditions were not ideal. River banks mainly consisted of quite coarse material. The finer sediments of the side channels on the Dee floodplain were an exception.

Many of the rivers appeared to be dynamic, with evidence of a flashy flow regime and high bedload transport. As a result, the best sites for damming to produce ponds were in side channels where sediments were locally finer, where flows were gentle or where the water was still, and where the topography would support the development of substantial beaver ponds with minimal damming effort. Even though some streams were found which were sufficiently small to be dammed, they were often on steep gradients where the resultant pond would be very small and where bedload transport would probably soon fill in the pond or destroy the dam. Small rivers receiving compensating and freshet flows regulated by hydro-power dams may also be suitable for beaver dam building, as a result of the reduced range in water levels and decreased flow velocities, but rivers affected by releases from power stations are likely to be subject to short-timescale increases in variability in water depth and velocity which would render them unsuitable for beaver colonisation.

The predicted preference for floodplain and minor tributary areas for dam construction within the study sites visited, suggests that the hydrological and fluvial geomorphological impact of beaver colonisation on the main river channels would be minimal. The most significant environmental impacts would be an increase in the area of open water and wetland on floodplains, and a change in species composition and reduction in deciduous tree cover as a result of soil waterlogging and tree harvesting.

FIGURE 3.1

RIVER FARRAR - LONG PROFILE



ABHAINN DEABHAG - LONG PROFILE

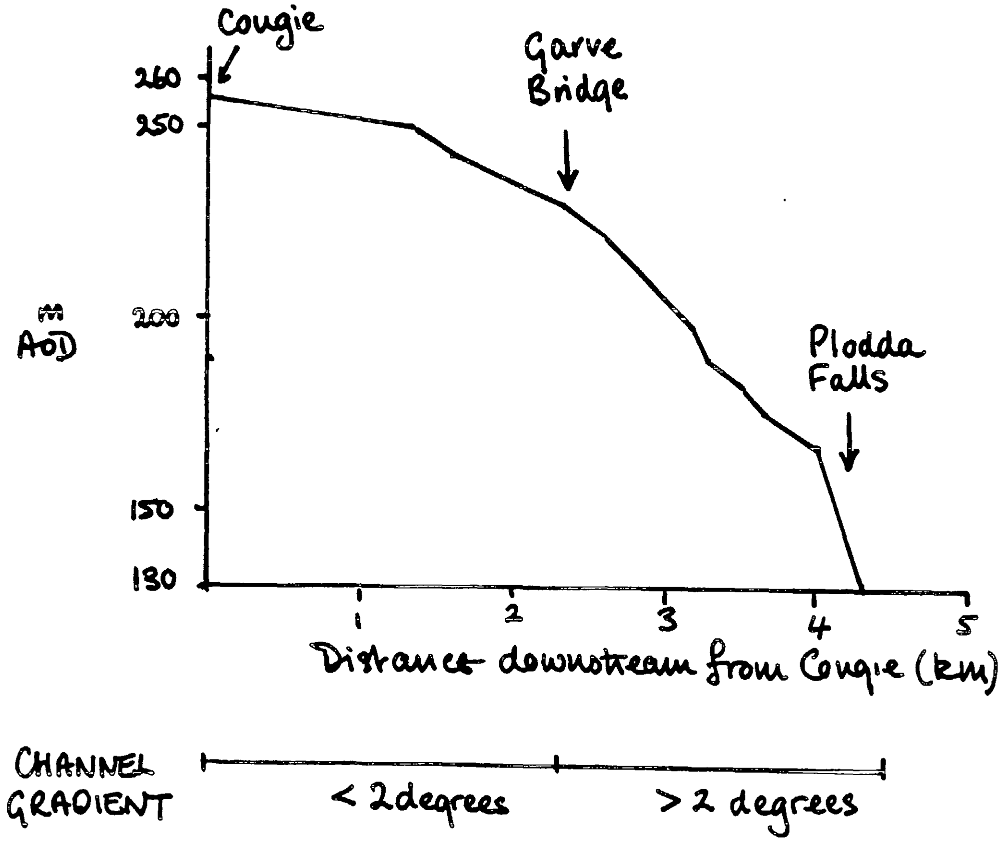


FIGURE 3.2

RIVER FARRAR - STUDY SITES A, B AND C

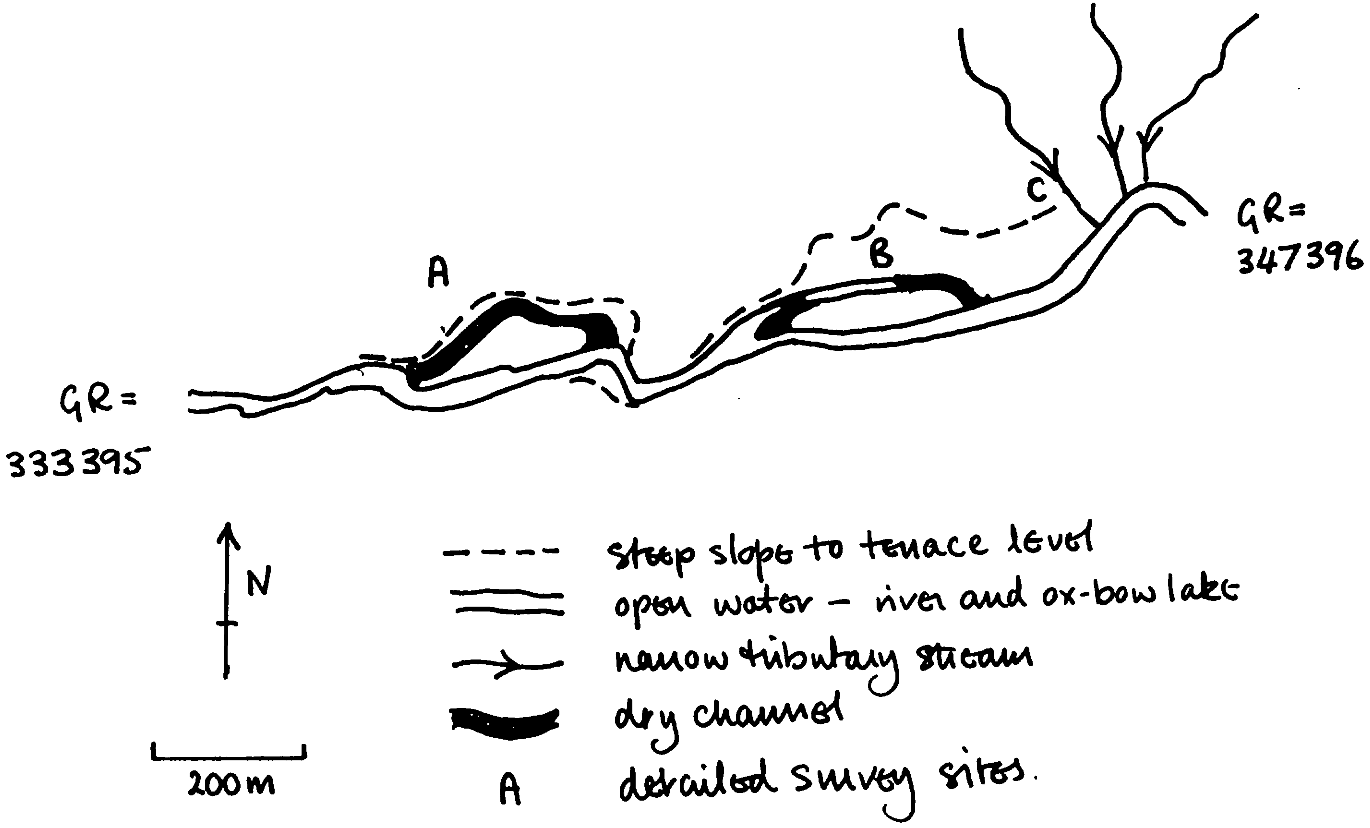


FIGURE 3.3: SITE A - RIVER FARRAR

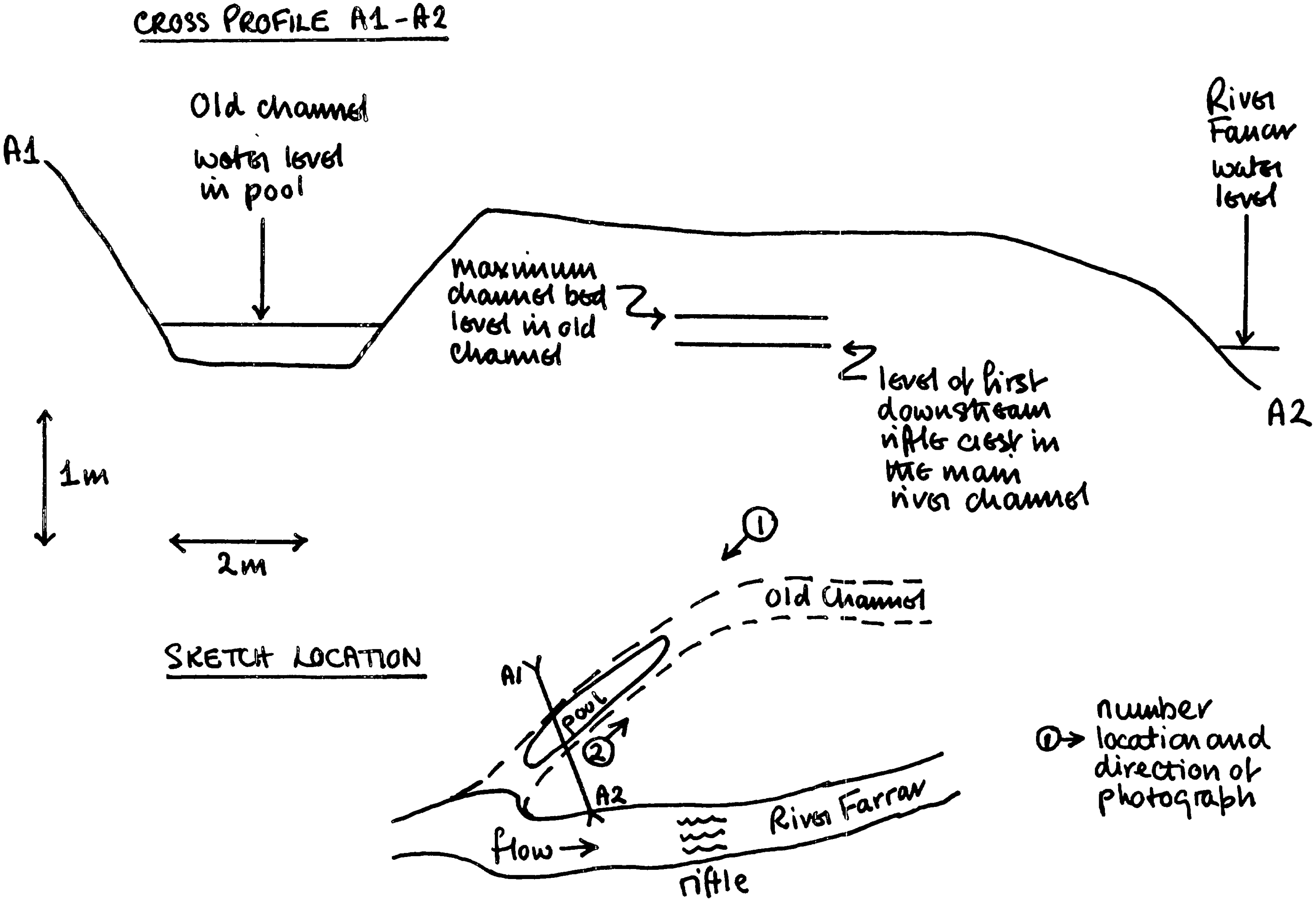
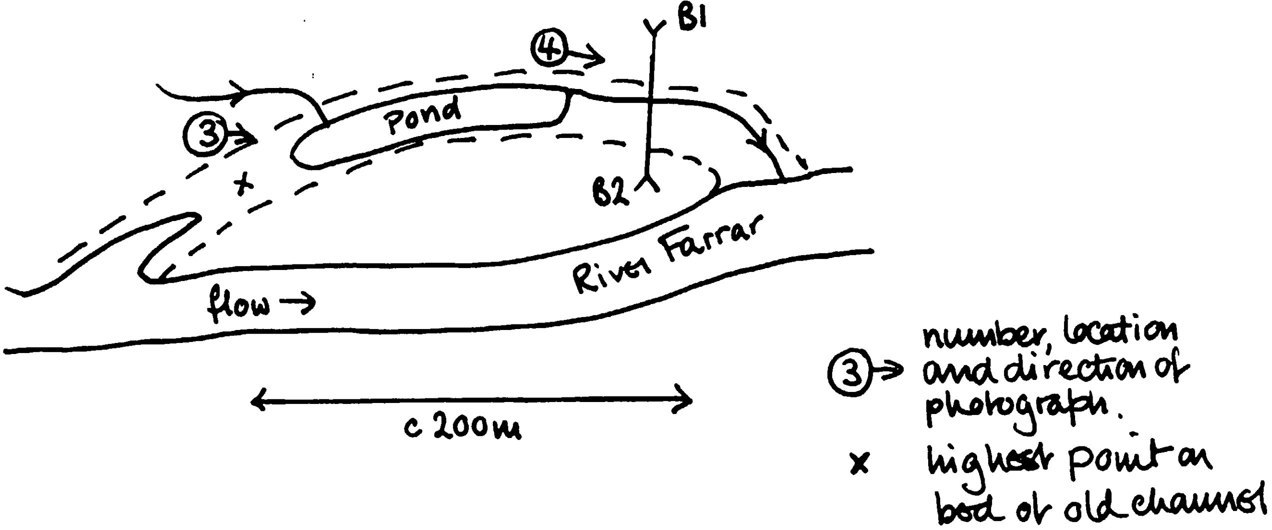


FIGURE 3.4: SITE B - RIVER FARRAR

SKETCH LOCATION



CROSS PROFILE B1-B2

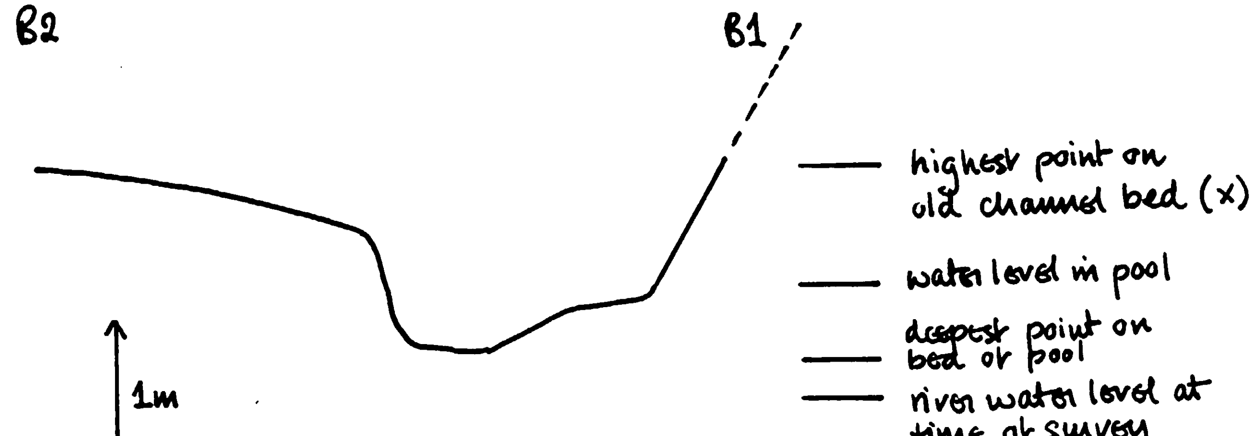
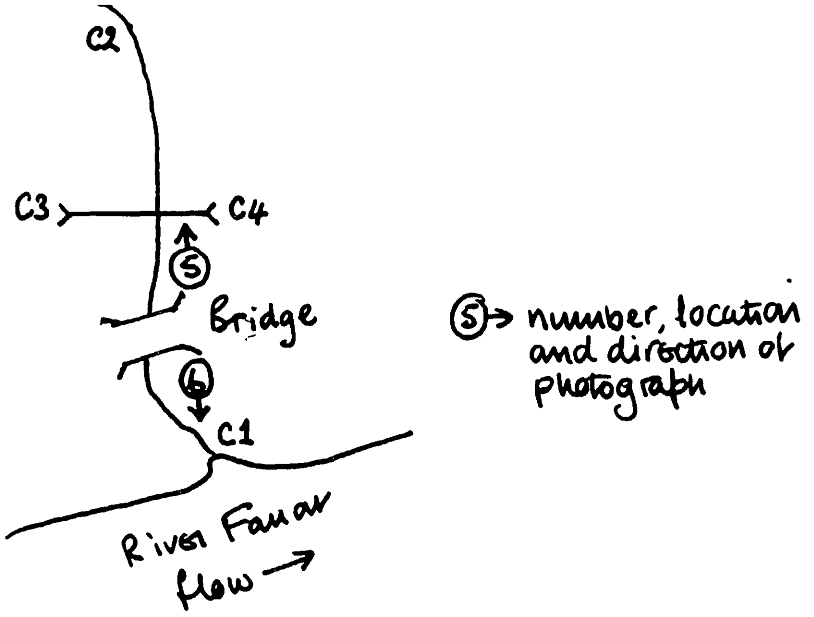
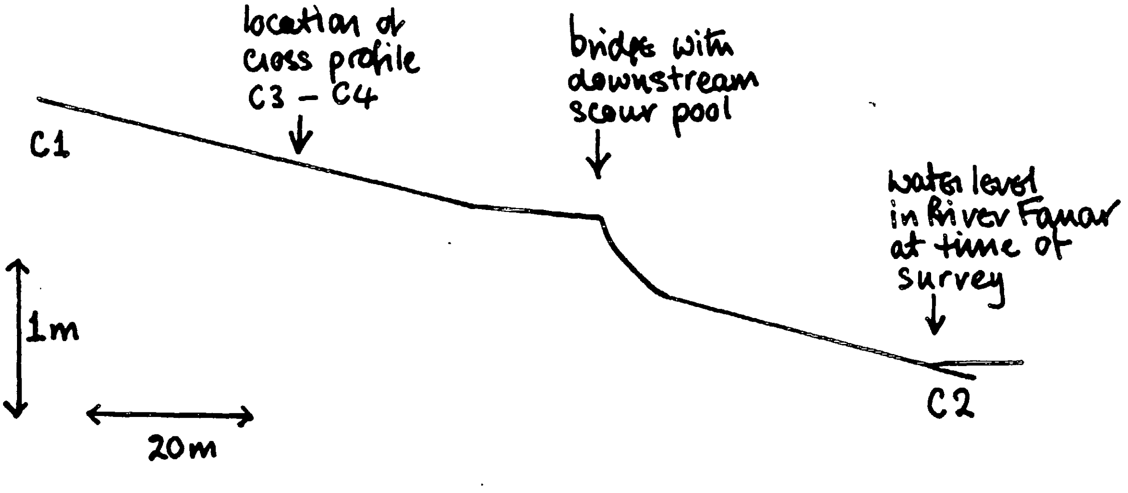


FIGURE 3.5: SITE C - RIVER FARRAR

SKETCH LOCATION



LONG PROFILE C1-C2



CROSS PROFILE C3-C4

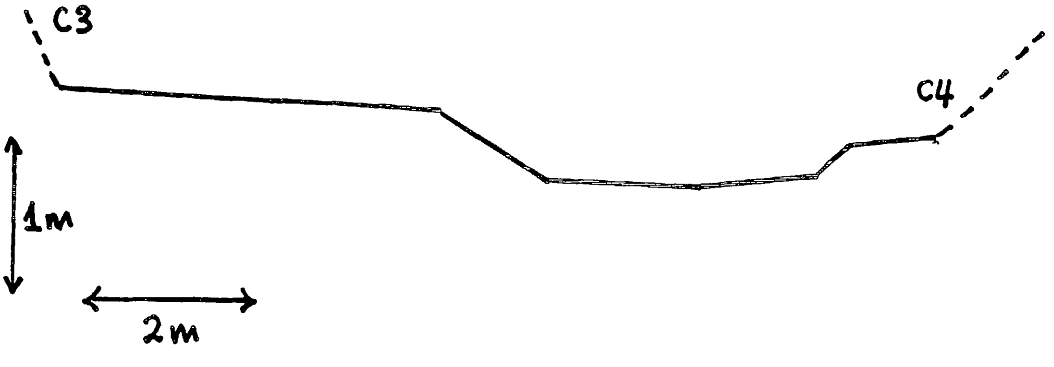


FIGURE 3.6:

ABHAINN DEABHAG - STUDY SITES D, E AND F

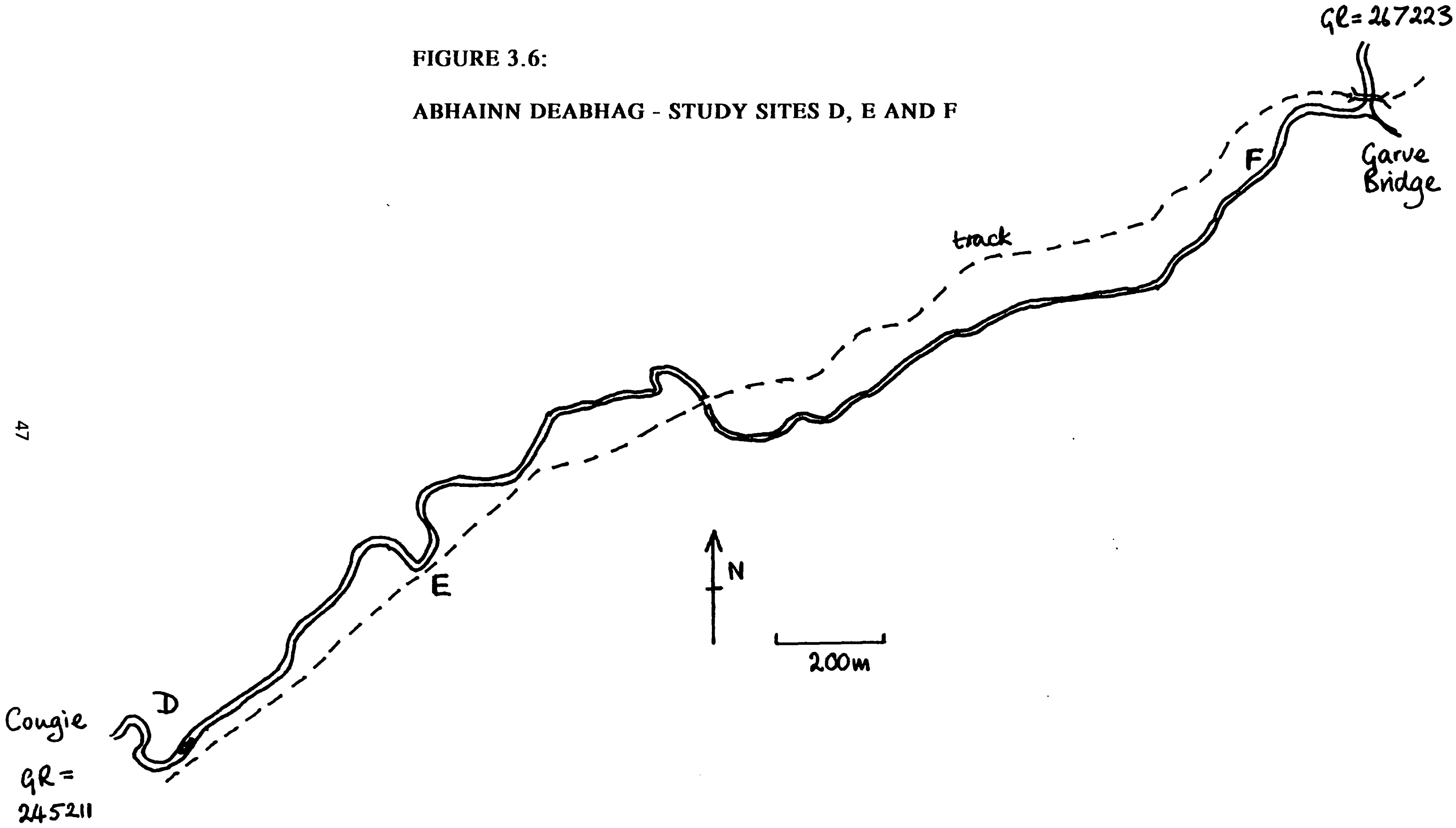


FIGURE 3.7

SITE D - ABHAINN DEABHAG

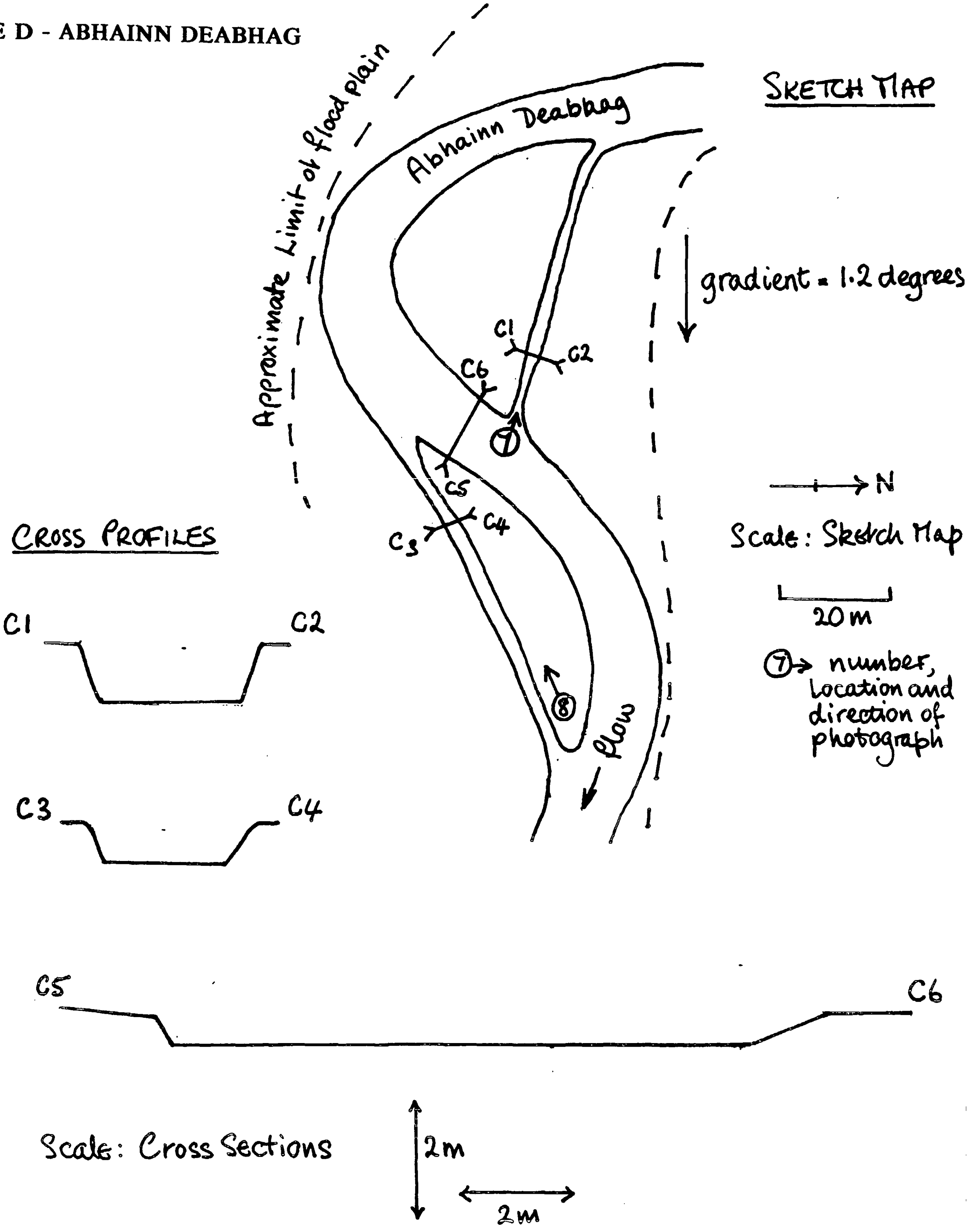


FIGURE 3.8: SITE E - ABHAINN DEABHAG

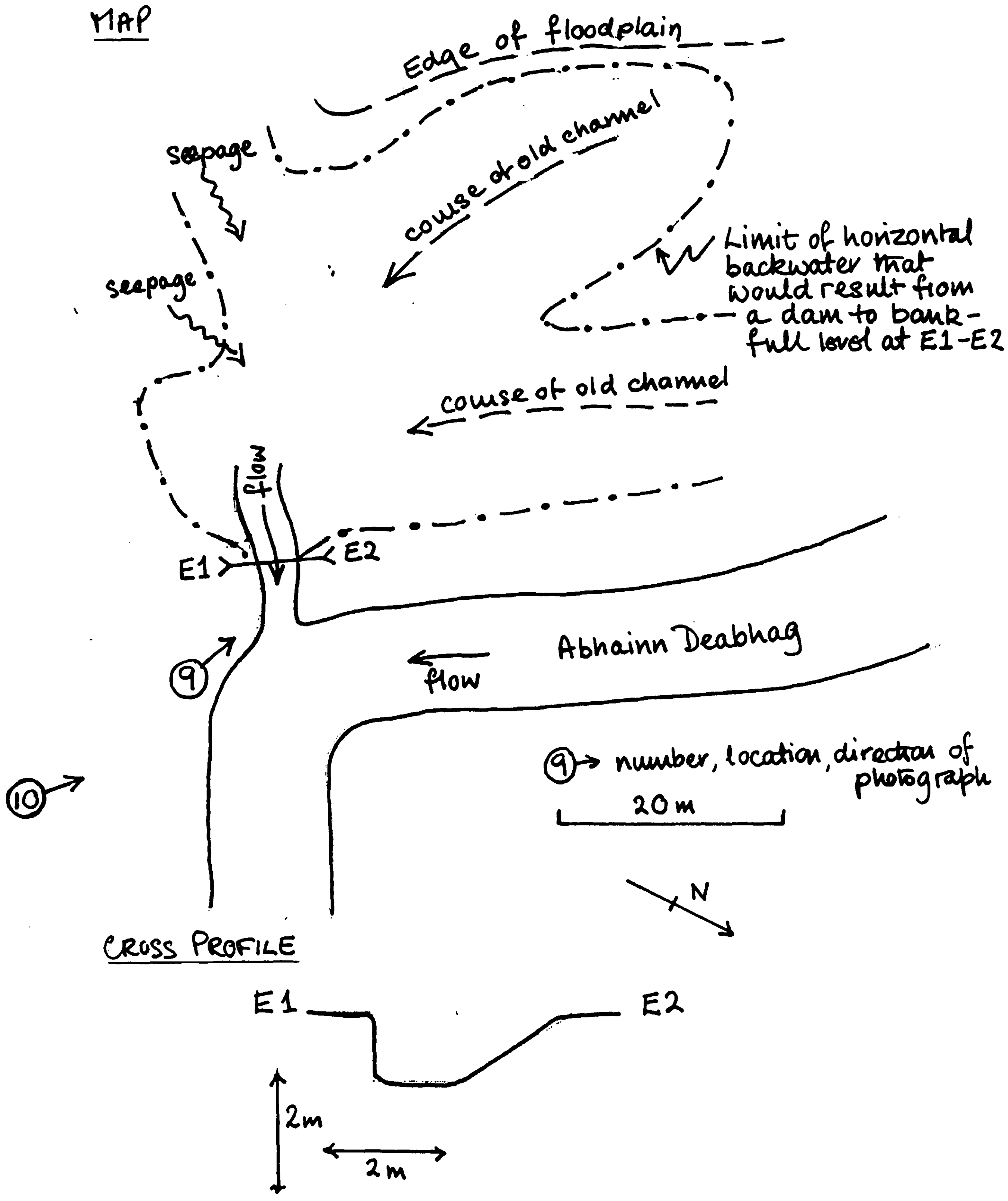
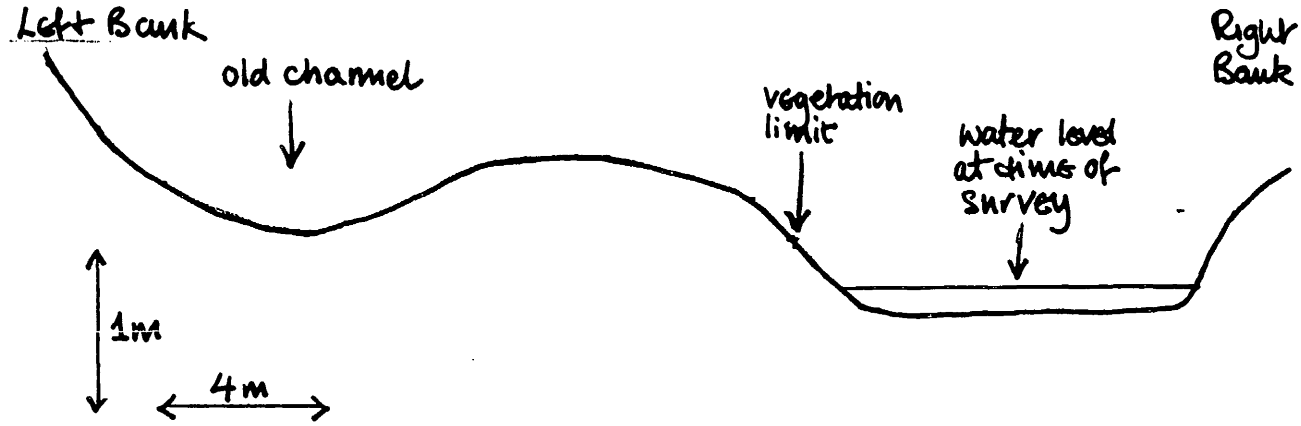


FIGURE 3.9: SITE F - ABHAINN DEABHAG

CROSS PROFILE OF MAIN CHANNEL AND FLOODPLAIN



slope of river = 1·3 degrees

photograph ⑪ taken from the left bank floodplain looking upstream towards this surveyed cross-profile

FIGURE 3.10: RIVER DEE

UPPER MAP - STUDY SITES G, H
LOWER MAP - STRETCH WITH OLD FLOODPLAIN CHANNELS BUT MAIN CHANNEL INCISED

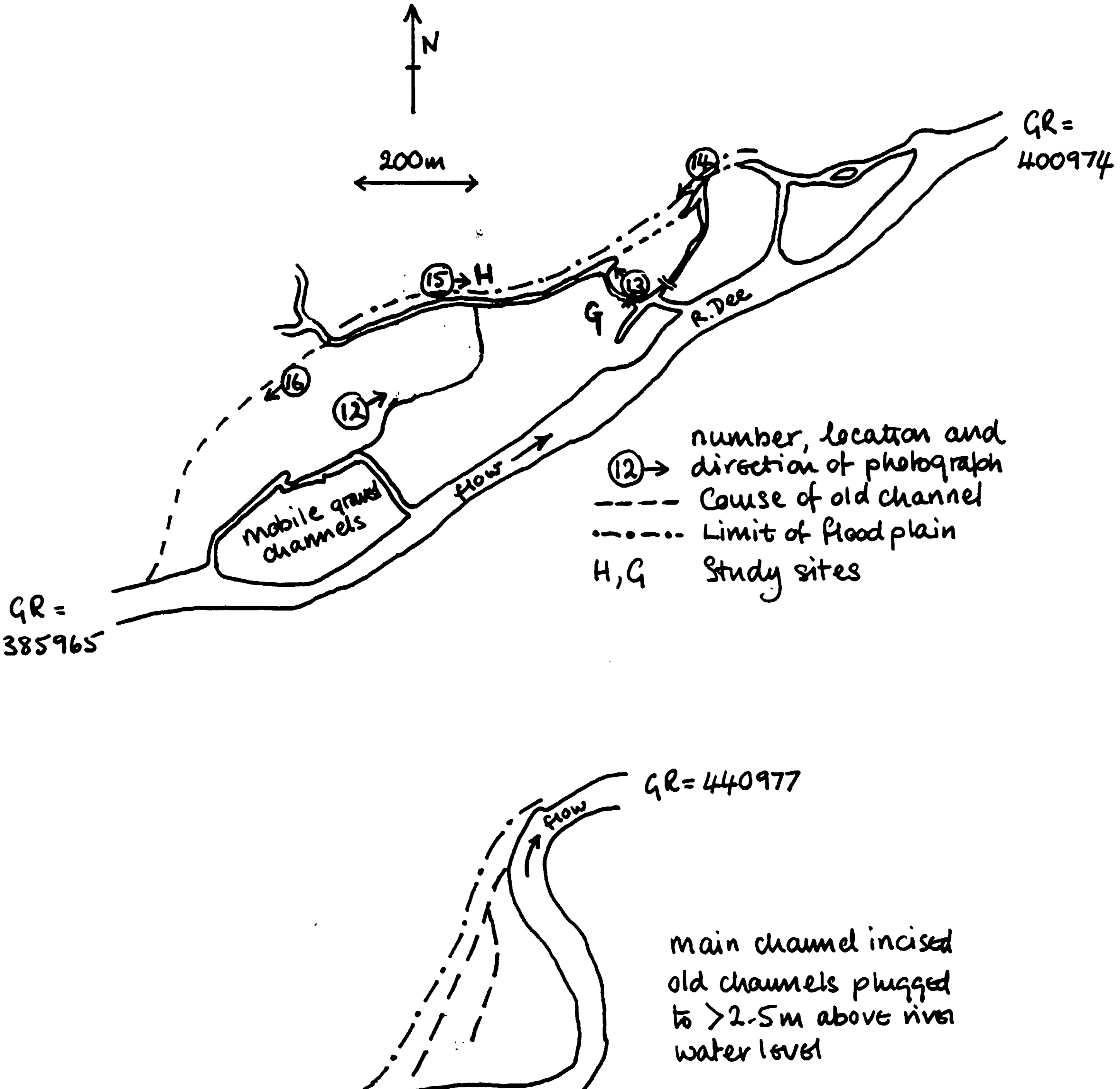


FIGURE 3.11: SITE G - RIVER DEE

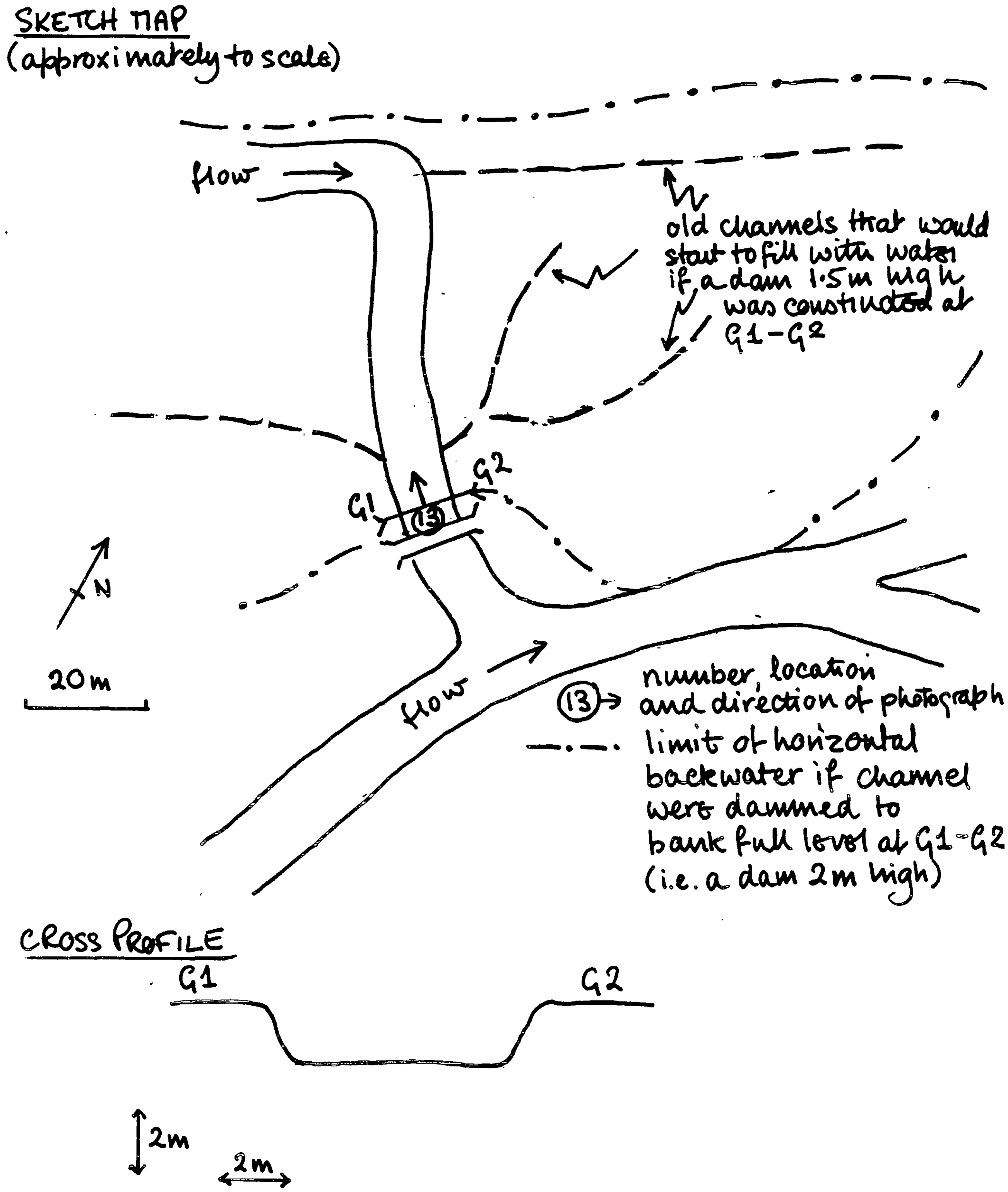
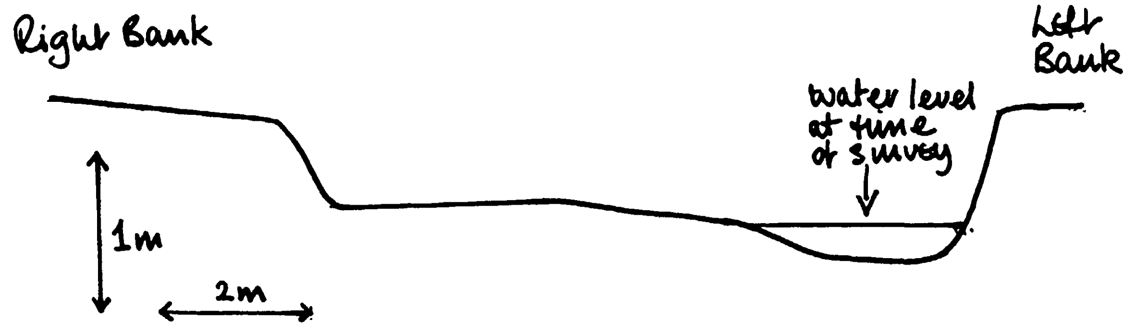


FIGURE 3.12: SITE H - RIVER DEE

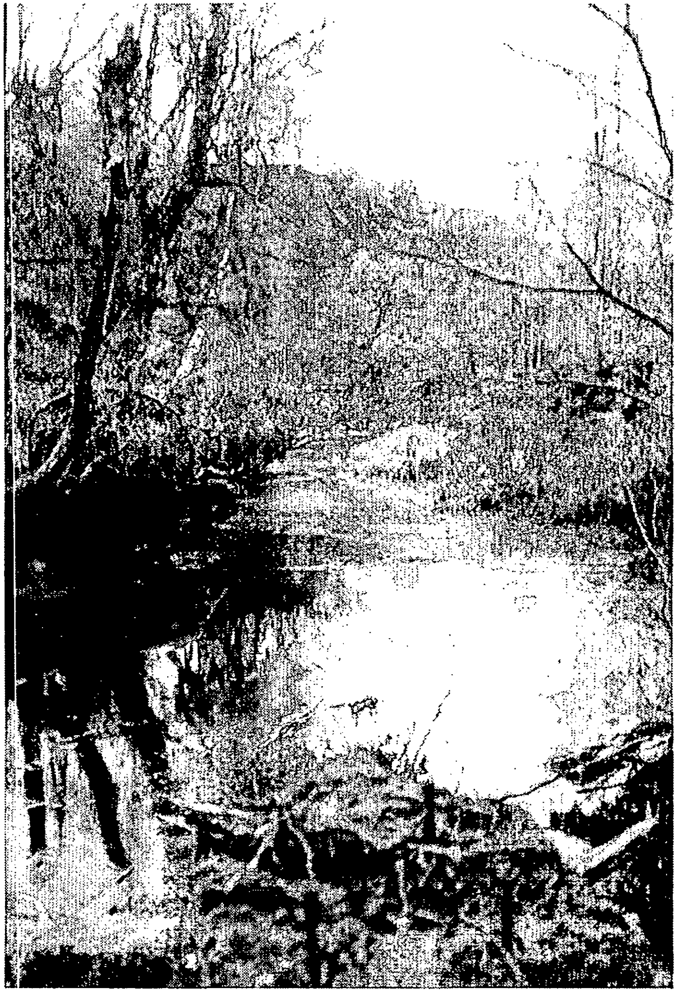
CROSS PROFILE OF TRIBUTARY TO THE R.DEE AT SITE H



flood plain slope in direction of flow = 0.04 degrees

Photograph ⑮ was taken at this cross profile looking in a downstream direction

Photograph 1



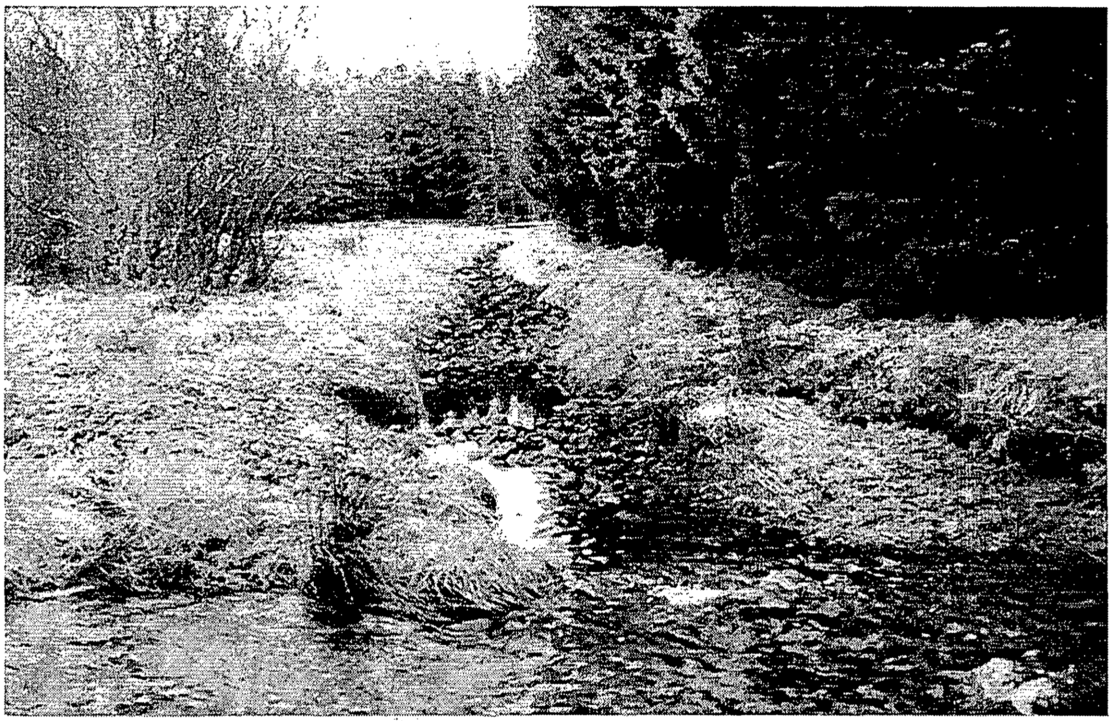
Photograph 2

Photograph 3

Photograph 4

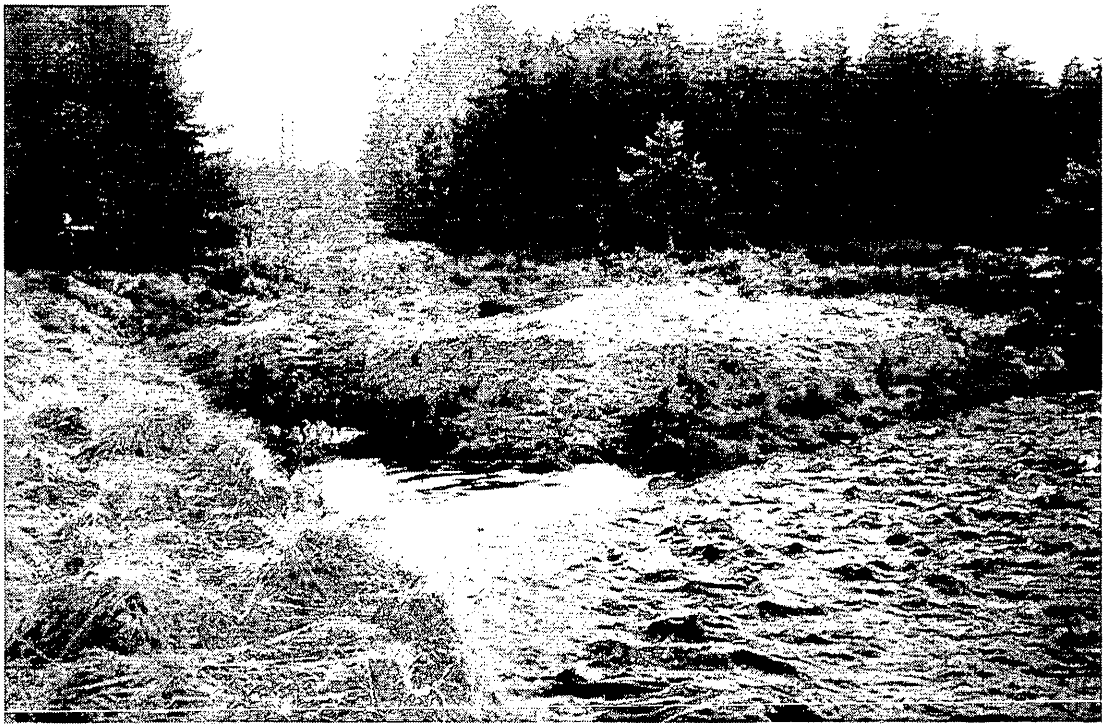
Photograph 5

Photograph 6



Photgraph 7

Photograph 8



Photograph 9

Photograph 10

Photograph 11

Photograph 12

Photograph 13

Photograph 14

Photograph 15

Photograph 16

4. CONCLUSIONS

4.1 LIMITATIONS IN THE AVAILABLE INFORMATION

The literature review (Chapter 2) reveals a number of limitations in the available information in the context of estimating the likely impact of colonisation and dam building by *C. fiber*.

(i) Most of the literature describes aspects of the environmental impact of *C. canadensis* rather than *C. fiber*. Whilst there are likely to be major similarities in the impact of the two species, their impact cannot be assumed to be identical. The review attempts to identify contrasts between the two species using the information that is available.

(ii) Most of the literature cited was written by biologists, so that many of the important characteristics of beaver from a hydrological and geomorphological perspective are not described in sufficient detail. As a result, parallels have been drawn with observations of the physical role of LWD accumulations and conclusions have been extended by applying hydrological and geomorphological logic to the frequently thin evidence.

(iii) Important factors that govern the hydrological and geomorphological influences of beaver dams that are poorly covered in the literature include the following:

- beaver do not always build dams, but when they do are the dams grouped in particular areas and what is their size distribution? How does their character and distribution change with changing population density? What are the specific associations between physical environmental characteristics such as channel dimensions, gradient, flow regime and velocity, bank and bed materials and the presence/absence, dimensions and permanence of dams? In particular, what are the dimensions and gradients of the river channels that are dammed, rather than simply the dimensions of the dams?

- what is the typical spacing of dams, including the degree to which dams are evenly spaced or clustered and the degree to which that relates to dam and river dimensions?

- what are the characteristics of the way that water drains from dams - is it predominantly diffuse seepage, dispersed overtopping, or is it funnelled into high-velocity threads?

- what is the length of channel unaffected by ponding between dams? To what extent is the minimum 60-80% channel length free of backwater cited by Naiman *et al.* (1986) for unexploited *C. canadensis*, transferable to *C. fiber*?

(iv) Although an analogy can be drawn between the physical role of LWD accumulations and beaver dams in estimating the hydrological and geomorphological impact of the latter, it must be recognised that there are contrasts between the two types of woody structure which may limit the validity of the comparisons that can be drawn:

- LWD dams are less-well engineered than beaver dams. The latter are constructed of more evenly sized wood pieces that are carefully emplaced and then sealed with mud. LWD dams are more leaky than actively-maintained beaver dams.

- although both types of dam predominantly occur on streams of order 1 to 4, LWD dams occur on a wider range of river gradients, and are probably best formed on steeper gradients than beaver dams because of their dependence on the power of the stream to move the debris and construct the dams.

- LWD dams are usually in-channel structures, whereas beaver dams can extend out across the floodplain. Although LWD accumulations occur on floodplains, they tend to occur patchily within ephemeral channels or to be aligned in ribbon-shaped structures parallel to the direction of flow (Piégay & Gurnell, 1997) rather than damming water flow down the floodplain.

4.2. MAJOR CONTROLS ON THE POTENTIAL SPATIAL DISTRIBUTION OF REINTRODUCED BEAVER AND BEAVER DAMS IN SCOTLAND

The appraisal of the flow regime and geomorphology of Scottish rivers, and the three case studies presented in Chapter 3, reveals a number of important factors which will significantly affect the potential spatial distribution of re-introduced beaver and beaver dams in Scotland.

(I) *A plentiful and suitable food supply* is probably the greatest constraint on the successful re-introduction of beaver. With the possible exception of some parts of the Dee site, none of the study sites supported large quantities of ideal woody food for beaver. It is likely that the best sites will occur at lower altitude locations within the piedmont zone, where environmental conditions may support vigorous growth of woody deciduous trees.

(ii) *A relatively subdued flow regime and stable river bed.* In the study sites visited, the rivers appeared to be dynamic, with evidence of a flashy flow regime and high bedload transport. None of the rivers appeared to be ideal for beaver dam construction. Even though some tributary streams were found which were sufficiently small to be dammed, they were often on steep gradients where the resultant pond would be very small and where bedload transport would probably soon fill in the pond or destroy the dam. As a result, the best sites for damming to produce beaver ponds were found in side channels where sediments were locally finer, where flows were gentle or where the water was still, and where the topography would support the development of substantial beaver ponds with minimal damming effort. Small rivers receiving compensating and freshet flows regulated by hydro-power dams may also be suitable for beaver dam building, as a result of the reduced range in water levels and decreased flow velocities, but rivers affected by releases from hydro-power stations are likely to be subject to short-timescale increases in the variability of water depth and velocity which would render them unsuitable for beaver colonisation and dam building.

(iii) *Bank materials suited to burrow construction.* Although burrows, with or without additional lodges, could be constructed in most of the sites visited, the conditions were not ideal. River banks mainly consisted of coarse material. The finer sediments of the side channels on the Dee floodplain were an exception. Again, lower-gradient piedmont locations are likely to exhibit the most suitable bank materials.

In order to identify suitable sites for beaver re-introduction, more detailed information is required on all of the above factors. Querying of an existing GIS, which contains simple topographic, river network and vegetation cover information for Scotland, has produced a first level of identification of potential beaver release sites. But it is now necessary to examine the identified areas in more detail to separate out a second classification of the most suitable sites. Application of survey methodologies similar to the River Corridor and River Habitat Surveys that are undertaken in England and Wales, would give information on bed and bank materials, channel morphology, flow type and naturalness, in-channel, riparian and near-channel floodplain vegetation type and structure. Such information would be ideal for identifying good reintroduction sites. In the absence of such surveys, careful analysis of high-quality air photographs should help to screen sites for the suitability of the vegetation cover and for floodplain morphological features such as old channel remnants, whereas detailed analysis of topographic maps would reveal local variability in channel planform, width and gradient, and could provide a wealth of additional information on floodplain extent and morphological complexity.

4.3 POTENTIAL IMPACTS OF DAM BUILDING BY BEAVER IN SCOTLAND

The predicted preference of beaver for floodplain and minor tributary areas for dam construction within the study sites visited (Chapter 3), suggests that the hydrological and fluvial geomorphological impact of beaver colonisation on main Scottish river channels would be relatively small. The most significant environmental impacts would be an increase in the area of open water and wetland on floodplains, and a change in species composition and reduction in deciduous tree cover as a result of soil waterlogging and tree harvesting by beaver. Damming of small rivers would also result in an increase in open water and wetland habitat and in local modification of the vegetation.

Other potential impacts which need careful consideration include the following.

(i) *Sediment storage and regulation of sediment transport.* Where beaver construct dams across streams and small rivers, the expected changes in the transfer of sediment are likely to have beneficial effects for aquatic organisms and for river management as a result of reductions in the load of moving sediment, including suspended sediment; creation of a diversity of sediment storage areas; and sorting of sediment into patches of differing calibre within and between beaver ponds. Catastrophic dam failures are likely to be extremely rare, and so the release of large quantities of stored sediment is extremely unlikely. The local failure of a single dam will only result in the sediment being trapped in storage areas immediately downstream, including the next beaver pond.

(ii) *Changes in the bed material and bed forms of undammed stretches of river.* The likely consequence of the sediment storage and energy-dissipation impacts of beaver dams, is that undammed stretches of river are likely to become morphologically more complex

(iii) Harvesting of wood by beaver and the rare occurrence of dam failure could lead to release of woody debris and the downstream *blockage of structures such as bridges.* However, the relatively small wood piece sizes cut by beaver (typically <2m lengths), and the likelihood that all wood would be trapped by the next downstream dam, render such blockage unlikely. Clearly, dams constructed near narrow-arched bridges and other elements of infrastructure might require removal or management to reduce the likelihood of blockage and flooding, but other dams are likely to the have the beneficial effects of stable LWD dams in reducing the downstream movement of woody debris and enhancing decomposition of wood near its point of entry to the fluvial system.

(iv) *Impacts on fish* will depend on the fish species considered. The species-specific impacts of the following factors require consideration:

- regulation of sediment transport, reduced turbidity and the sorting of fluvial sediments.

- the development of ponded areas on river systems in addition to free-flowing sections of river, which lead to greater diversity of in-channel physical habitat with respect to flow velocity and depth, substrate calibre, water temperature and quality.

- beaver ponds provide an important control on river flows and on the availability of deeper water areas during low flow conditions (Wolff *et al*, 1989).

- the development of in-channel and floodplain ponds and distributary channels results in better surface and subsurface connectivity between floodplain and river.

- although beaver dams may appear to be impenetrable, they appear to act as semi-permeable barriers to fish movement, allowing significant fish movement during periods of elevated discharge (e.g. Schlosser, 1995).

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REFERENCES

Apple, L. (1982). The use of beavers in riparian / aquatic habitat restoration in a cold desert, gully-cut stream: a case history. In: *Proceedings 18th annual meeting Colorado-Wyoming Chapter, American Fisheries Society* (Whaley, R. ed), 29-35, Laramie, Wyoming.

Barnes, D.M. & Mallik, A.U. (1996). Use of woody-plants in construction of beaver dams in northern Ontario. *Canadian Journal of Zoology* **74(9)**: 1781-1786.

Barnes, W.J. & Dibble, E. (1988). The effects of beaver in riverbank forest succession. *Canadian Journal of Botany* **66**: 40-44.

Basey, J.M. & Jenkins, S.H. (1995). Influences of predation risk and energy maximization on food selection by beavers (castor canadensis). *Canadian Journal of Zoology* **73(12)**: 2197-2208.

Beier, P. & Barrett, R.H. (1987). Beaver habitat use and impact in Truckee River Basin, California. *Journal of Wildlife Management* **51(4)**: 794-799.

Bergstrom, D. (1985). Beavers: ecologists "rediscover" a natural resource. United States Department of Agriculture, Forest Service, Oct 1-5.

Beschta, R.L. (1979). Debris removal and its effects on sedimentation in an Oregon coast range stream. *Northwest Science* **53**: 71-77.

Bilby, R.E. (1984). Removal of woody debris may affect stream channel stability. *Journal of Forestry* **82**: 609-613.

Boyce, M.S. (1983). Habitat ecology of an unexploited population of beavers in interior Alaska. In: *Worldwide Furbearer Conference Proceedings* (J.A. Chapman & D. Pursley eds). 155-186, Donnelly, Falls Chard, Virginia.

Brayton, D.S. (1984). The beaver and the stream. *Journal of Soil and Water Conservation* **39**:108-109.

Busher, P.E. (1996). Food caching behavior of beavers (castor canadensis) - selection and use of woody species. *American Midland Naturalist* **135(2)**: 343-348.

Butler, D.R. (1995). *Zoogeomorphology: animals as geomorphic agents.* Cambridge University Press, Cambridge.

Butler, D.R. & Malanson, G.P. (1995). Sedimentation rates and patterns in beaver ponds in a mountain environment. *Geomorphology* **13(1-4)**: 255-269.

Collen, P. (1995). The reintroduction of beaver (*Castor fiber* L.) to Scotland: an opportunity to promote the development of suitable habitat. *Scottish Forestry* **49(4)**: 206-217.

Curry-Lindahl, K. (1967). The Beaver, *Castor fiber* Linnaeus, 1758 in Sweden - Extermination and Reappearance. *Acta Theriologica* **12**: 1-15.

Devito, K.J. & Dillon, P.J. (1993). Importance of runoff and winter anoxia to the p and n dynamics of a beaver pond. *Canadian Journal of Fisheries and Aquatic Sciences* **50**: 2222-2234.

Doucet, D.M. & Fryxell, J.M. (1993). The effect of nutritional quality on forage preference by beavers. *Oikos* **67(2)**: 201-208.

Dugmore, A.R. (1914). *The Romance of the Beaver: being the history of the beaver in the western hemisphere*. William Heinneman, London, 225p.

Ehrman, T.P. & Lamberti, G.A. (1992). Hydraulic and particulate matter retention in a 3rd-order Indiana stream. *Journal of the North American Benthological Society* **11**: 341-349.

Ermala, A., Helminen, M. & Lahti, S. (1989). Some aspects of the occurrence, abundance and future of the Finnish beaver population. *Suomen Riista* **35**: 108-118.

Erome, G. (1984). La typologie des gites du castor rhodanien, *Castor fiber. La Terre et la Vie* **39**: 55-76.

Farrar, G.B. (1971). The beaver: the conservationist! *Defenders of Wildlife News*, **46**: 205-206.

Ferguson, R.I. (1981). Channel form and channel changes. In: *British Rivers* (Lewin, J. ed.). George Allen and Un win, London, 90-125.

Gilvear, D.J. (1994). River flow regulation. In: *The fresh waters of Scotland: a national resource of international significance* (Maitland, P.S., Boon, P.J. & McLusky, D.S. eds.). Wiley, Chichester, 463-487.

Gregory, K.J., Gurnell, A.M. & Hill, C.T. (1985). The permanence of debris dams related to river channel processes. *Hydrological Sciences Journal* **30**: 371-381.

Gurnell, A.M. & Gregory, K.J. (1987). Vegetation characteristics and the prediction of runoff: analysis of an experiment in the New Forest, Hampshire. *Hydrological Processes* **1**: 125-142.

Gurnell, A.M., Gregory, K.J. & Petts, G.E. (1995). The role of coarse woody debris in forest aquatic habitats: implications for management. *Aquatic Conservation* **5**: 143-166.

Gurney, W.S.C. & Lawton, J.H. (1996). The population dynamics of ecosystem engineers. *Oikos* **76**: 273-283.

Hacker, A.L. & Coblentz, B.E. (1993). Habitat selection by mountain beavers recolonizing Oregon coast range clearcuts. *Journal of Wildlife Management* **57(4)**: 847-853.

Hammerson, G.A. (1994). Beaver (*Castor canadensis*) ecosystem alterations, management and monitoring. *Natural Areas Journal* **14**: 44-57.

Hartman, G. (1994a). *Ecological studies of a reintroduced beaver (Castor fiber) population.* Dissertation, Swedish University of Agricultural Sciences, Department of Agricultural Sciences.

Hartman, G. (1994b). Long-term population development of a reintroduced beaver (*Castor fiber*) population in Sweden. *Conservation Biology* **8(3)**: 713-717.

Hartman, G. (1996). Habitat selection by European beaver (*Castor fiber*) colonizing a boreal landscape. *Journal of Zoology*, 240, 317-325.

Heede, B.H. (1985). Channel adjustments to the removal of log steps: an experiment in a mountain stream. *Environmental Management* **9**: 427-432.

Hill, E.H. (1982). Beaver. In: *Wild Mammals of North America* (Chapman, J.A. and Feldhammer, G.A. eds.). 256-281.

Hodgdon, H.E. & Lancia, R.A. (1983). Behavior of the North American beaver, *Castor canadensis. Acta Zoologica Fennica* **174**: 99-103.

Hogan, D.L. (1986). *Channel morphology of unlogged, logged and debris-torrented streams in the Queen Charlotte Islands*, British Columbia Ministry of Forests and Lands, Land Management Report No. 49, 94pp.

Howard, R.J. & Larson, J.S. (1985). A stream habitat classification system for beaver. *Journal of Wildlife Management* **49(1)**: 19-25.

Jenkins, S.H. (1980). A size-distance relation in food selection by beavers. *Ecology*, 61(4), 740-746.

Johnson, P. (1984). The dam builder is at it again! *National Wildlife* **22**: 8-15.

Johnston, C.A. & Naiman, R.J. (1987). Boundary dynamics of the aquatic-terrestrial interface: the influence of beaver and geomorphology. *Landscape Ecology* **1**: 47-57.

Johnston, C.A.. & Naiman, R.J. (1990). Aquatic patch creation in relation to beaver population trends. *Ecology* **71**: 1617-1621.

Keller, E.A. & Swanson, F.J. (1979). Effects of large organic debris on channel form and fluvial process. *Earth Surface Processes* **4**: 361-380.

Keller, E.A. & Tally, T. (1979). Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment. In: *Adjustments of the Fluvial System* (Rhodes, D.D. and Williams, G.P. eds.). Proceedings of the 10th Annual Geomorphology Symposium, SUNY, Binghampton, New York, Kendell/Hunt Publ. Co., 169-197.

Klein, R., Sonnevil, R. & Short, D. (1987). Effects of woody debris removal on sediment stirage in a northwest California stream. *International Association of Hydrological Sciences Publication* **165**: 403-404.

Lahti, S. & Helminen, M. (1974). The beaver *Castor fiber* (L.) and *Castor canadensis* (Kuhl) in Finland. *Acta Theriologica* **19(13)**: 177-189.

Leidholtbruner, K., Hibbs, D.E. & McComb, W.C. (1992). Beaver dam locations and their effects on distribution and abundance of Coho Salmon fry in 2 coastal Oregon streams. *Northwest Science* **66(4)**: 218-223.

Lisle, T.E. (1981). Roughness elements: a key resource to improve anadromous fish habitat In: *Proceedings of the propagation, enhancement and rehabilitation of anadromous salmonid populations and habitat in the Pacific Northwest Symposium* (Hassler, T.J. ed.) Humboldt State University, Arcata, California, 93-98.

Lizarralde, M.S. (1993). Current status of the introduced beaver (*Castor-canadensis*) population in Tierra-del-Fuego, Argentina. *Ambio* **22(6)**: 351-358.

Lowry, M.M. (1993). *Groundwater elevations and temperature adjacent to a beaver pond in Central Oregon.* Unpublished M.Sc. thesis, University of Oregon.

McCall, T.C., Hodgman, .P., Diefenbach, D.R. & Owen, R.B. (1996). Beaver populations and their relation to wetland habitat and breeding waterfowl in Maine. *Wetlands* **16(2)**: 163-172.

Macdonald, A. & Keller, E.A. (1987). Stream channel response to the removal of large woody debris, Larry Damm Creek, northwestern California. *International Association of Hydrological Sciences Publication* **165**: 405-406.

Macdonald, D.W. & Barrett, P. (1993). *Mammals of Britain and Europe.* Harper Collins, London.

Macdonald, D.W., Tattersall, F.H., Brown, E.D. & Balharry, D. (1995). Reintroducing the European beaver to Britain - nostalgic meddling or restoring biodiversity. *Mammal Review* **25(4)**: 161-200.

Martin, P.R. (1977). *The effect of altered streamflow on furbearing mammals of the Yellowstone River Basin, Montana.* Technical Report 6, Helena, MT:Water Resources Division, Montana Department of Natural Resources and Conservation, 79p.

Medwecka-Kornas, A. & Hawro, R. (1993). Vegetation on beaver dams in the Ojcow National Park (Southern Poland). *Phytocoenologia* **23**: 611-618.

Morgan, L.H. (1868). *The American beaver and his works.* J.B. Lippincott and Co., Philadelphia, 330p.

Naiman, R.J., Melillo, J.M. & Hobbie, J.E. (1986). Ecosystem alteration of boreal forest streams by beaver (*Castor canadensis*). *Ecology* **67(5)**: 1254-1269.

Naiman, R.J., Johnston, C.A. & Kelley, J.C. (1988). Alteration of North American Streams by Beaver. *Bioscience* **38(11)**: 753-762.

Naiman, R.J., Pinay, G., Johnston, C.A. & Pastor, J. (1994). Beaver influences on the long-term biogeochemical characteristics of boreal forest drainage networks. *Ecology* **75(4)**: 905-921.

Nolet, B.A., Hoekstra, A. & Ottenheim, M.M. (1994). Selective foraging on woody species by the beaver (*Castor fiber*), and its impact on a riparian willow forest. *Biological Conservation* **70(2)**: 117-128.

Parker, M., Wood, F.J., Smith, B.H. & Elder, R.G. (1985). Erosional downcutting in lower order riparian ecosystems: have historical changes been caused by removal of beaver? In: *Riparian ecosystems and their management: reconciling conflicting uses* (R.R. Johnston ed). US Forest Service General Technical report **RM-120**: 35-38.

Piegay, H. & Gurnell, A.M. (in press) Large woody debris and river geomorphological pattern: examples from S.E. France and S. England. *Geomorphology.*

Richard, P.B. (1955).. Bièvres constructeurs de barrages. *Mammalia* **19**: 293-301.

Richard, P.B. (1967). Le déterminisme de la construction des barrages chez le castor du Rhône. *La Terre et la Vie* **4**: 339-470.

Richard, P.B. (1983). Bièvres constructeurs de barrages. *Mammalia* **19(2)**: 293-301.

Robel, R.J. & Fox, L.B. (1993). Comparison of aerial and ground survey techniques to determine beaver colony densities in Kansas. *Southwestern Naturalist* **38(4)**: 357-361.

Roberts, T.H. & Arner, D.H. (1984). Food habits of beaver in East-Central Mississippi. *Journal of Wildlife Management* **48(4)**: 1414-1419.

Ruedemann, R. & Schoonmaker, W.J. (1938). Beaver-dams as geologic agents. *Science* **88**: 523-525.

Schlosser, I.J. (1995). Dispersal, boundary processes, and trophic level interactions in streams adjacent to beaver ponds. *Ecology* **76**: 908-925.

Sedell, J.R., Richey, J.E. & Swanson, F.J. (1989). The river continuum concept: a basis for the expected behaviour of very large rivers? In: *Proceedings of the International Large River Symposium* (Dodge, D.P. ed.) Can. Spec. Publ. Fish. Aquat. Sci. **106**: 49-55.

Sidorovich, V.E., Jedrzejewska, B. & Jedrzejewski, W. (1996). Winter distribution and abundance of mustelids and beavers in the river valleys of bialowieza-primeval-forest. *Acta Theriologica* **41(2)**: 155-170.

Sinitsyn, M.G. (1992). Use of very large scale aerial photographs in the study of beaver colonies (*Castor fiber*). *Zoologicheskii Zhurnal* **71(7)**: 130-139.

Smith, D.W. & Peterson, R.O. (1991). Behavior of beaver in lakes with varying water levels in Northern Minnesota. *Environmental Management* **15(3)**: 395-401.

Smith, R.D., Sidle, R.C. & Porter, P.E. (1993). Effects of bedload transport of experimental removal of woody debris from a forest gravel bed stream. *Earth Surface Processes and Landforms* **18**: 455-468.

Stocker, G. (1983). Problems in utilization of plant food resources by the beaver. *Revue Suisse de Zoologie* **90**: 487-496.

Sullivan, K., Lisle, T.E., Dolloff, C.A., Grant, G.E. & Reid, L.M. (1987). Stream channels: the link between forests and fishes. In: *Streamside Management: Forestry and Fishery Interactions* (Salo, E.O. and Cundy, T.W. eds.). Proc. Symp., 12-14 February 1986, Seattle, Washington, College of Forest Resources, University of Washington, 39-97.

Svendsen, G.E. (1980). Seasonal change in feeding patterns of beaver in Southeastern Ohio. *Journal of Wildlife Management* **44(1)**: 285-290.

Townsend, J.E. (1953). Beaver ecology in Western Montana with special reference to movements. *Journal of Mammalogy* **34**: 459-479.

Townsend, P.A. & Butler, D.R. (1996). Patterns of landscape use by beaver on the lower Roanoke river floodplain, North-Carolina. *Physical Geography* **17(3)**: 253-269.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R. & Cushing, C.E. (1980). The river continuum concept. *Can. J. Fish. Aquat. Sci.* **37**: 130-137.

Ward, J.V. and Stanford, J.A. (1983). The serial discontinuity concept of lotic ecosystems. In: *Dynamics of lotic ecosystems* (T.D. Fontaine and S.M. Bartell eds) 29-42, Ann Arbor Science, Ann Arbor, Michigan.

Warren, E.R. (1927). *The Beaver: its works and ways*. Bailliere, Tindall and Cox, London, 177p.

Warren, E.R. (1932). The abandonment and reoccupation of pond sites by beavers. *Journal of Mammalogy* **13**: 343-346.

Werritty, A., Brazier, V., Gordon, J.E. & McManus, J. (1994). Geomorphology. In: *The fresh waters of Scotland: a national resource of international significance* (Maitland, P.S., Boon, P.J. and McLusky, D.S. eds.). Wiley, Chichester, 65-88.

Wharton, G. (1995). Information from channel geometry - discharge relationships. In:. *Changing river channels* (Gurnell, A.M. & Petts, G.E eds.) Wiley, Chichester, 325-346.

White, D.S. (1990). Biological relationships to convective flow patterns within stream beds. *Hydrobiologia* **196(2)**: 149-158.

Wolff, S.W., Wesch, T.A. & Hubert, W.A. (1989). Stream channel and habitat changes due to flow augmentation. *Regulated Rivers, Research and Management*, **4(3)**: 225-233.

Woo, M.K. & Waddington, J.M. (1990). Effects of beaver dams on sub-arctic wetland hydrology. *Arctic* **43(3)**: 223-230.

Zurowski, W. (1992). Building activity of beavers. *Acta theriologica* **37(4)**: 403-411.

Zurowski, W. & Kasperczyk, B. (1986). Characteristics of a European Beaver Population in the Suwalki Lakeland. *Acta Theriologica* **34**: 311-321.

Zurowski, W. & Kasperczyk, B. (1988). Effects of reintroduction of European Beaver in the lowlands of the Vistula Basin. *Acta Theriologica* **33**: 325-338.

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Scottish Natural Heritage is an independent body established by Parliament in 1992, responsible to the Secretary of State for Scotland.

Our task is to secure the conservation and enhancement of Scotland's unique and precious natural heritage - the wildlife, the habitats, the landscapes and the seascapes - which has evolved through the long partnership between people and nature.

We advise on policies and promote projects that aim to improve the natural heritage and support its sustainable use.

Our aim is to help people to enjoy Scotland's natural heritage responsibly, understand it more fully and use it wisely so that it can be sustained for future generations.