Restoration of Riverine Trout Habitats - A Guidance Manual

The Game Conservany Trust Fisheries Technical Manual 1

Technical Report W18

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Statement of use
This Manual provides guidance on the restoration of riverine trout habitats and presents a project management approach which should be adopted to promote the effectiveness of such work. The Manual is for use by Environment Agency Fisheries Staff and external Fishery Managers involved in promoting and implementing this area of work.

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GLOSSARY

Aggradation	-	Accumulation of depositing sediment
Alevin	-	Newly hatched trout, still living on a yolk sac
Alluvial	-	Pertains to a channel composed of sediments previously deposited by the stream
Anadromous		Fish which spawn in freshwater but migrate to sea to feed
Armour	-	Coarse sediments protecting a stream bed
Brown trout	-	Trout which is resident in freshwater throughout its life and does not migrate to sea
Buffer strip	-	Strip of land adjacent to a stream removed from cultivation to reduce agricultural inputs
Carrying-capacity	-	The maximum number of trout a stream can accommodate
Channelization	-	The practice of straightening of meandering streams to improve land drainage
Coppicing	-	Trimming trees back to the base to encourage low growth
Denitrification	-	A process by which nitrates are removed from groundwater in waterlogged, organic rich soil
Density-dependent mortality	-	The mortality rate of a population is dependent on the size of the population
Discharge	-	The volume of water flowing down a stream in a given time
Froude number	-	A measure of stream flow parameters which is related to the specific energy of flowing water
Fry	-	A trout which has just absorbed its yolk sac and has commenced to feed
Gabion baskets	-	Wire mesh baskets which, if filled with stones, are used in bank protection

Groundwater	-	Water within an aquifer which is flowing to or from a stream
Habitat bottleneck	-	The habitat for whichever life-stage of trout has the greatest constraining influence on the population
HABSCORE	-	Habitat Score - A computer based model which predicts trout numbers from stream habitat parameters
Hyper-habitat	-	A habitat in which particular habitat features are given more emphasis than would occur naturally
Interstices	-	Free space between gravel particles through which water can flow
Intra-gravel flow	-	Flow of water through river bed gravels
Overshading	-	Shading by bankside trees which severe enough to suppress in-stream and emergent plant growth
Parr	-	A juvenile trout
Permeability	-	A measure of the ease by which water flows through gravel
PHABSIM	-	Physical Habitat Simulation System. A computer based model which predicts the quality of habitat for trout of different life-stages according to measured habitat parameters
Plunge pool	-	A pool formed by water cascading over a waterfall and physically eroding the bed
Pool	-	An area of deep water in a stream created by scouring currents during high flows
Re-bar	-	Steel bars used in reinforcing concrete which have wide application in anchoring instream structures
Revetment	-	Artificial strengthening of a stream bank to prevent erosion
Riffle	-	An area of shallow water over gravel deposits on a stream bed

Sea trout	-	A trout which spends some of its life at sea
Secondary circulation	-	A spiralling effect on stream flow within a channel which causes periodic scour and deposition produced a diversity of pools and riffles
Sinuosity	-	A measure of the degree to which the plan form of a stream deviates from a straight line
Smolt	-	A juvenile trout which has developed saltwater tolerance and is actively migrating to sea to become a sea trout
Spiling	-	A technique of stabilizing eroding streambanks using growing willows
Thalweg	-	The axis within a stream where the current is concentrated

EXECUTIVE SUMMARY

The overall aim of this manual is to provide advice and guidelines on the restoration of riverine habitats for brown trout. The manual is aimed at Environment Agency fisheries staff and external fisheries managers who have responsibility for managing and implementing such restoration work. The manual is also of benefit to other professionals who's work is associated with managing riverine habitats (e.g. flood defence, conservation).

The information used for the manual was based on a major literature review. Most information was obtained from published work but significant use was made of unpublished material from the Environment Agency and other organisations.

The manual is structured in a logical sequence covering essential aspects of brown trout habitat restoration. Focus is initially placed on the trout stream environment to provide an essential insight into basic stream processes which form and influence riverine habitats. Current knowledge of brown trout habitat requirements is then reviewed in relation to the requirements of the different life stages and potential limiting factors which may influence population status. An assessment of factors causing habitat degradation and the need for restoration is also discussed.

A major section of the manual is the description of a project structure which is required to promote effective and efficient management of habitat restoration initiatives. The approach has been identified following an assessment of best practice from the literature. Critical aspects of the project approach including scheme appraisal and limiting factor analysis are covered.

A large variety of habitat restoration techniques have been identified and reviewed to provide information of benefits, drawbacks, design considerations, appropriate use, effectiveness, etc.

Limitations on effective trout habitat restoration have been identified. Current understanding of detailed habitat requirements and particularly the accurate identification of limiting factors are constraints on effective implementation. Information on the effectiveness of many techniques is available but robust appraisal of applications in UK streams remains limited. The key to further development of this field in the UK is improved management of these initiatives in order to improve our information base.

Key recommendations include;

- Management of fisheries habitat restoration should be within the project model identified in order to improve effectiveness and efficiency.

- Fisheries habitat restoration should be promoted within the framework of strategic catchment management planning.

- Fisheries habitat restoration should be progressed via a multi-disciplinary approach involving appropriate input from a range of professionals.

- Development of riverine fisheries habitat restoration as a specialized field within the Environment Agency and promotion of internal communication and knowledge transfer.

- Promotion of co-ordination, integration and collaboration with other government and external agencies including the production of a common R&D plan.

- Promotion of R&D to continue to improve strategic understanding of brown trout habitat requirements and limiting factors.

KEY WORDS

Trout, *Salmo trutta*, Habitat, Restoration, Methods, Management, Guidance

1. INTRODUCTION

1.1 Aims

1.1.1 Overall aim

The overall aim of this manual is to provide stream managers with up-to-date information on how to most effectively restore degraded stream habitats for the species *Salmo trutta* (hereafter referred to as “trout”) in both its “brown trout” and “sea trout” forms. Habitat restoration, as described in this manual, largely concerns aspects of the physical habitat which are particularly amenable to direct management. These include both abiotic features (e.g. the bed and banks) and the physical effects of vegetation. In addition to the information provided, the manual also seeks to be a source of further information on what is a complex subject and over 350 supporting references are included.

This manual is not concerned with the improvement of water quality or the alteration of the general stream ecology, except insofar as the latter can be influenced by the physical habitat. Water flow requirements and fish passage are not specifically covered in detail but are referred to along with sources of further information.

1.1.2 Subsidiary aims

Successful trout stream restoration involves different elements whose description are the subsidiary aims of the manual. The first is a description of what habitat restoration is intended to re-create; that is, the preferred habitats of trout and how these are created and maintained naturally. The major aim which then follows, is a review of the various techniques which are available to restore trout habitat in terms of their application and effectiveness.

Mann and Winfield (1992) found that, in Britain, a general lack of a disciplined approach to habitat restoration has been a major obstacle to the advancement of the subject, in terms of both knowledge and practice. Another aim has, therefore, been to describe and stress the implementation of a project management approach to habitat restoration to improve both the quality of restoration work and to generate further knowledge. This approach involves pre-scheme appraisals to correctly identify problems, scheme design considerations and post-scheme appraisals.

1.1.3 Intended users

The manual is specifically aimed at Environment Agency (EA) fisheries staff and independent fisheries interests who are involved in restoration work. However, it is also intended for other specialisms within the EA, including conservation, flood defence and geomorphology. It is hoped that non-fisheries staff will be introduced to what trout stream restoration involves, so that it can be incorporated within the broader functions of the EA.

1.2 How To Use This Manual

1.2.1 The approach

This manual is not intended to be a recipe book whereby problems can be diagnosed from standard examples and standard solutions recommended. This approach to stream restoration has been widely tried, and although the end product can be a successful restoration, it frequently is not. This manual promotes a different approach. To perform a successful restoration, it is firstly necessary to understand how to identify habitat deficiencies and their causes. The causes frequently are processes operating at the catchment scale, so the need to consider habitat on a wide scale is emphasised. Then, before appropriate habitats can be restored, it is fundamentally important that the habitats to be created are understood in terms of how they are formed and maintained in natural streams. By understanding the processes which create habitat, schemes can be designed specifically to address the requirements of any particular situation. The need to appraise restoration projects and learn from them is emphasised. Given the varied elements of stream restoration, the need for project management is also stressed.

In following this approach, this manual is not intended to provide an exhaustive list of different techniques which may be used to restore stream habitats. Instead, representative techniques are described in terms of how and why they influence the processes which create habitat. By understanding why a technique works, it will be possible to design a restoration scheme in accordance with local needs. If further details are required on alternative designs of the various techniques, these can be found in the references supplied.

1.2.2 Content of the manual

It is intended that this manual be read in its entirety if the necessary understanding of trout habitat restoration is to be obtained. The structure of the manual follows a logical sequence, moving through from the initial description of trout stream processes and habitat requirements through ultimately to habitat improvement techniques. This is shown in Box 1.1.

Box 1.1

Chapter	Title	Subject
2	The Trout Stream Environment	Describes the processes which form riverine habitats
3	Brown trout habitat requirements	Describes brown trout habitat requirements and places them within the context of the overall stream environment. It also introduces the concept of how habitat can limit numbers

Box 1.1, continued

4	Habitat degradation and the need for restoration	Describes common problems and why restoration is necessary
5	Habitat restoration project management	Introduces the steps required to conduct effective restoration schemes.
6	Pre-scheme assessments	Describes methods of appraising habitat quality and trout populations to identify habitat limitations
7	Post-scheme appraisal	Describes the design of appraisal schemes to assess effectiveness
8	Restoration methods	Describes the techniques available to restore habitats.
9	Current limitations	Describes ways in which habitat restoration is limited as a technique
10	Conclusions	Concludes on the state of habitat restoration as a discipline in terms of where it is currently and how it should develop in future
11	Recommendations	Provides recommendations for the improvement of habitat restoration, both as a discipline and in implementation

1.3 Trout - A Valuable Resource Requiring Conservation

1.3.1 The importance of trout

Indicator of a healthy ecosystem
In Britain, today, the trout has a high ecological significance. As a species, it requires clean water and a healthy physical habitat. It is also perhaps the most widely distributed of all freshwater fish species in the British Isles, being present in rivers, streams and lakes from the south of England to the Northern Isles (Maitland and Campbell 1992). As a consequence of these two factors the presence of trout is universally considered to be an indicator of the quality of the freshwater ecosystem.

Variable species
Another very important feature which attracts ecological interest in the trout is that it is a very variable species. As described by Elliott (1994), the trout adopts a practically limitless variety of life history strategies. Some may be born in a small stream and never stray from it during their entire lives. Others may drop downstream from spawning streams into larger rivers or

lakes to feed, to return later to spawn. Some even migrate to sea to feed and make the full transition into salt water tolerant "sea trout". In large measure, these different strategies are likely to represent genetic adaptations to particular environments, and the differences have arisen through the ability which trout possess in "homing" back to their native stream to spawn. Conservation of the genetic diversity of wild trout populations is now considered to be of great importance (Winstone *et al.* 1993, Giles 1994) and this can only be achieved by preserving the diversity of habitats in which trout are found.

Trout fisheries

In addition to its ecological importance, the trout is extremely important in fisheries terms. Its wide distribution means it is probably the most widely fished for freshwater species in Britain, and in many areas where cyprinid species or salmon (*Salmo salar* L.) are not common, it is the most sought after species. It is primarily fished for by recreational anglers, but sea trout are also fished for commercially in many areas. Whilst accurate figures are not easy to come by, trout angling is of considerable economic importance. For example, Elliott (1989) notes that sea trout fisheries alone in England and Wales had a minimum capital value of £55 million in 1989. In many areas natural production of brown trout is insufficient to satisfy fishing pressure. As a result farm reared trout are widely stocked. In 1995, some 344 tonnes of brown trout were produced for stocking in England and Wales (Gandhi 1996) which equates to a value of probably just under £2 million.

1.3.2 Trout under threat

Although the trout has adapted to a wide spectrum of freshwater types, it is under threat in many areas and, consequently, many populations are in decline or have even been eliminated altogether (Giles 1992). The reasons behind these declines are varied and complex.

Pollution

An obvious problem affecting trout are reductions in water quality through direct polluting discharges where these occur. Fortunately, the pollution historically generated in many industrial areas is slowly being tackled. Another, less direct, form of pollution is that of acidification through "acid rain" which has occurred in upland areas of Wales, Cumbria and south west Scotland. However, there are many insidious problems which are more widespread and have less obvious effects.

Habitat degradation

A major problem has been degradation of the freshwater habitat as a result of recent land use practices. These include dredging to improve land drainage, overgrazing and physical destruction of streambanks by livestock, erosion of sediment from cultivated land, overshading of streams by forestry plantations, increasing nutrient levels as a consequence of increased use of inorganic fertilizers and many more (Giles 1992).

In many areas where stream degradation has affected the ability of trout populations to effectively reproduce, fisheries are maintained through the stocking of farm reared trout. This is, in fact, a very widespread practice in rivers and lakes in most of England (Giles 1989, 1992).

1.3.3 Reversal of decline

As habitat degradation is a widespread problem and can often be tackled by practical means at a local level, the successful reversal of the decline in wild trout stocks is most likely to be achieved through habitat restoration and management. If a culture of habitat restoration is not adopted amongst fishery managers, freshwater ecosystems will continue to degrade, valuable populations of wild trout will continue to be lost or be genetically altered through interbreeding with stocked trout, and valuable wild trout fisheries will continue to decline. Habitat restoration is, therefore, an imperative.

In addition to producing self-sustaining trout fisheries as opposed to the need for perpetual stocking, habitat restoration for brown trout also has much wider benefits for conservation generally. It is, therefore, an integral part of the widespread need to restore riverine ecosystems.

1.4 Trout Stream Restoration

1.4.1 Trout habitat management in the past

Trout have some fairly specific physical habitat requirements which will be described in detail in Chapter 3. Briefly, these include shallow gravelly areas in which to spawn and deeper pools with permanent protective cover under the banks for older trout. It has long been recognized that to maintain good fisheries, such elements of the habitat must be maintained or even increased in number. In the past, many rivers, especially in southern England, had river-keepers on them. Amongst other things, their duties included improving spawning areas and holding pools. A good description of the state of the art at the time is provided by Carter-Platts (1930). Unfortunately many of the procedures undertaken by Victorian and Edwardian river-keepers were never appraised to see if they really worked or not. Like fly fishing, river keeping was seen as something of an art which could border on mysticism. As a consequence, with the decline in numbers of river-keepers which occurred after the Second World War much of their knowledge and experience which was never properly documented has been lost or become accessible to only a very few.

1.4.2 North American experiences

In North America, trout fishery management has taken a somewhat different course to that in Britain. In the USA, problems were perceived with trout habitat as early as 60 years ago and methods of overcoming these were sought by arms of both the Federal and State governments. As a consequence "trout stream restoration" was born. From an early period, the value of scientific appraisal was appreciated and streams were altered by the addition of cover and structures which scoured deeper pools. Some projects were appraised in terms of their impacts on trout numbers, invertebrate populations, stream morphology and comparisons with unaltered streams and the results duly published in scientific publications (e.g. Tarzwell 1938, Shetter *et al.* 1946).

Trout stream restoration has continued to grow in North America, as can be judged by the string of studies and guide books which have been published and are still being published (studies - Saunders and Smith 1962, Hunt 1971, 1988, Riley and Fausch 1995, guides - White and Brynildson 1967, Finnigan *et al.* 1980, Buchanan *et al.* 1989, Adams and Whyte 1990, Lyons and Courtney 1990, Hunter 1991, Hunt 1993, Newbury and Gaboury 1993). In addition to such publications, the restoration philosophy figures prominently in more populist North American fishing magazines. Many restoration studies have continued to be conducted by government departments and related bodies. For example, in 1977, Wisconsin State passed legislation requiring adult trout anglers to buy an annual 'stamp', all of the proceeds of which were channelled directly into trout stream restoration schemes (Kmiotek 1977). This is an interesting form of fisheries funding which generated on average $425 000 per year between 1978-84. However, restoration schemes are also promoted and aided, often jointly with public bodies or independently, with groups of angling enthusiasts in organisations like Trout Unlimited.

1.4.3 Habitat restoration in Britain

The North American situation, whilst considered far from ideal (Hunter 1991), contrasts quite strongly with most British experience. Examples of published fish habitat restoration have often been conducted privately (e.g. Swales 1982a, Anon 1995, Giles and Summers 1996). Few habitat improvement studies have been performed by government departments (one example being Morrison and Collen 1992). However, a considerable amount of improvement work has been conducted by the EA and the preceding National Rivers Authority (NRA) and Water Authorities. However, these schemes have seldom been appraised, form no part of any overarching strategy and, indeed, often have been opportunistic (Mann and Winfield 1992).

1.4.4 The future of habitat restoration in Britain

However, the philosophy of trout stream restoration is appreciated in Britain. A study commissioned by the NRA in 1992 revealed that NRA staff considered that some 7182km of trout streams are in need of restoration work in England and Wales (Mann and Winfield 1992). The EA has recognized that there is a need for guidance on trout habitat restoration for both internal and external fishery managers, given the widespread interest in the subject and the amount of largely disparate information available. In addition to some other publications (e.g. McCubbing and Locke 1996), this manual has been produced in response to this need, and it is hoped, will promote the development of trout habitat restoration as a discipline and lead to successful implementation of habitat restoration.

1.5 The Philosophy of Stream Restoration

1.5.1 Differences in philosophy

This manual describes the restoration of stream habitat for trout. Whilst there is great interest in this specific issue, it must be recognized that trout are but one element in the stream ecosystem, and that stream restoration/management may be carried out for many other reasons

(Brookes and Shields 1996b). Basically, there are two opposing philosophies of habitat restoration. One is targeted at some particular species (e.g. trout) and may involve the creation of a "hyper-habitat" in which some other species may even be deliberately disadvantaged. The other philosophy seeks to be all-embracing, in trying to restore a high degree of biodiversity without deliberately favouring any particular species. The goal could even be to restore geomorphological forms without any specific ecological aims (Brookes and Shields 1996b). However, in reality, it is unlikely that any restoration, however specific, will purely concentrate on one aspect of the ecosystem, whilst even with the most general restoration, some elements of the ecosystem will always be favoured.

Another issue is the definition of "restoration". In the purest sense it implies a complete return to some pre-disturbance state (Brookes and Shields 1996b). Other definitions under the umbrella of restoration include "rehabilitation" (a partial return to pre-disturbance conditions), "enhancement" (any improvement in environmental quality) and "creation" (the creation of some habitat type which never formerly existed). A final term, "naturalization" implies the creation of some new habitat types to enhance a channel where full restoration or rehabilitation is not possible (Brookes and Shields 1996b).

1.5.2 Potential for conflicts of interest

An important point is that restorations with different objectives applied to the same stream may produce different results, and so, conflicts of interest can arise. Therefore, because of the specificity of habitat restoration for trout, potential for conflict does exist. One potential example, of many, concerns trout and salmon. Although trout and juvenile salmon have many habitat requirements in common, they have a number of important distinctions. One of these is that salmon prefer shallow fast water whilst trout prefer deeper pools (Kennedy and Strange 1982), so any scheme which seeks to increase trout stocks by creating pools at the expense of shallow water may benefit trout at the expense of salmon.

At the same time, habitat restoration for trout (including "enhancement" and "naturalization"), often has many common objectives with those of other interests. As trout are also part of the general ecology of a stream, the existence of good habitat for trout means there will be good habitat for many other species. For example, much of the advice contained in this manual is likely to benefit the threatened native white-clawed crayfish (*Austropotamobius pallipes*), otters (*Lutra lutra*) and water voles (*Arvicola terrestris*).

The potential for conflict between restoration for trout and broader interests depends on the condition of the stream to start with. In a stream which is badly degraded, restoration for trout may go a long way to fulfil the objectives of many other interests. Likewise, many aspects of stream restoration which is aimed at some other objective may also benefit trout (e.g. the creation of riffles, pools and meanders). On a pragmatic note, Brookes and Shields (1996b) noted that highly focused restorations should not be dismissed as they are often the only form of restoration which can realistically be accomplished, and any naturalization of badly degraded river is preferable to none at all.

Conflicts are most likely to arise in cases where a relatively good habitat is being fine-tuned to create a hyper-habitat for trout. It is also the case that there are some fishery management practices (not recommended in this manual) which may not bring wide conservation benefits and may actually degrade the quality of the habitat for trout (e.g. the close mowing of banks to facilitate angling). A distinction needs to be made between such practices and those of genuine habitat improvement for wild trout because some confusion is apparent in the wider conservation literature (Drake and Newbold 1995, Summers 1996).

As there are both clear conservation benefits to be gained from trout habitat restoration and potential conflicts, it is important when considering habitat restoration for trout to balance the objectives with wider conservation objectives at the outset. Detailed information to assess the likely impacts of different practices can be found in Lewis (1997). There is also an EA research project underway appraising fishery management practices in relation to conservation issues and to provide guidelines to help minimize conflicts. In addition to these sources, it is recommended that wide ranging consultation is made to ensure that the benefits of trout habitat restoration are as broad as possible. If this is done, it must be concluded that trout habitat restoration is a commendable and worthwhile practice.

2. THE TROUT STREAM ENVIRONMENT

2.1 Introduction

Trout habitat restoration mainly involves modifying the physical habitat of the trout. It will be shown in Chapter 3 that the physical habitat is fundamentally important to trout. Therefore, before habitat restoration is considered, this chapter describes the physical environment of streams in detail. This includes, most importantly, the fundamental processes by which the wide diversity of streams and rivers are created. The physical form of a stream channel results from the physical forces of flowing water operating on sediments and rock with vegetation acting as a regulator between the two. Therefore, this chapter considers firstly, the purely physical effects of flowing water on sediments, and then the impact which vegetation has on these processes.

To complete the description of the stream environment, the ecology of streams is briefly considered. This is not considered in detail as, apart from a few aspects, alteration of the general stream ecosystem is not considered in this manual.

2.2 Physical Processes in Streams

2.2.1 Introduction

Streams are formed by complex physical processes many of which are essentially conflicting and have complex feedback interrelationships. The form a particular stream takes is basically an equilibrium state between such processes and this may be sensitive to changes caused even by small perturbations. Streams should not, therefore, be seen as comprising of distinct components which may be interchanged. In order to fully appreciate what trout habitat is and to be able to restore it, it is necessary to understand how streams work. A good introduction to this subject is provided by Richards (1982).

2.2.2 Sediment transport

Basically, in nature, a stream channel is a conduit for water flowing under the force of gravity which maintains itself by continually eroding material from the land surface and re-depositing it somewhere else. In different parts of a river catchment the balance between erosive and depositional processes differs. For example, where gradients are steep in upland areas, erosive processes tend to dominate, and so, streams in such areas may be carved into bedrock or coarse bouldery material. In such streams the form of the channel is often dictated by the nature of the surface over which it flows - e.g. by following joints in the rock.

Where depositional processes dominate, the discharge (i.e. the volume of water moving in a given time), gradient and the nature of the sediments transported from upstream will dictate the form of the channel. Such streams are termed “alluvial”. Alluvial processes tend to be associated with lowland areas, but it should be remembered that they are really a product of gradient, and even in upland areas, it is common for streams to be composed of a mixture of alternating eroding and alluvial reaches. In fact, upland streams are usually amalgamations of both erosive and alluvial features - e.g. where gravel bars are deposited amongst protruding rocks.

In erosive streams, the form of the streambed has largely been imposed on the current flow regime by a multitude of processes in the geological past. However, alluvial streams are subject to ongoing processes of scour and deposition which produce regular and predictable features.

2.2.3 Alluvial Streams

Pools and riffles
Sediments, when deposited on alluvial streambeds are arranged into many different types of features. Ripples and dunes which occur in sand bedded streams or on sea beaches are familiar small scale examples. Whilst these are small features, the major large scale feature of alluvial stream morphology is the existence of "pools" and "riffles". Over a wide range of sediment sizes and stream powers, sedimentary processes produce a regular wave-like undulation in the level of the bed of a stream. This phenomenon is widespread in nature and faithfully forms under experimental conditions. It has been found that the distance between successive high points on the bed of the channel tends to be between 3 and 10 times the width of the channel, though most commonly about 6 (Shields 1996). While the spacing tends to be closer on steeper streams, a wide variation can be found in nature because of variations in the sediment composition and other features.

The reasons for the regularity of the pool-riffle phenomenon are not exactly known, but complex properties of the mechanics of flowing water are thought responsible (Yalin 1971, Yang 1971, Richards 1982). These processes give rise to the phenomenon of "secondary circulation". Water flowing down a channel is composed of distinct cells which move in a spiral fashion. Where this secondary circulation converges at the bed in mid-stream the bed is scoured, creating a trench (Fig. 2.1). Where, flow cells diverge in midstream, material scoured from trenches upstream is deposited, but scour occurs along the banks, causing the channel to widen (Fig. 2.1), which further spreads the stream's energy over a greater area permitting the deposition of even more material. As scour troughs get deeper and the crests of deposits rise, velocities in the troughs reduce and those at the crests increase, until an equilibrium is ultimately reached at which time velocities are too high to permit new sediment from being deposited on crests.

Once formed, scour troughs and crests are essentially self reinforcing and maintain themselves. This is because the current accelerates as it flows off down slope from a crest, concentrating, as it does so, in the narrowing channel and consequently maintaining bed scour. On approaching the next crest, the flow spreads out again and slows down and so on (Fig. 2.2).

It is important to note that these features are created when the discharge is high. However, when the discharge decreases, these become relic features which effectively impose conditions on the flow. The water flowing over a crest becomes shallow and fast and that in a trough impounded and slow. Thus, in essence, alluvial streams are effectively composed of regular sequences of broad crested low profile gravel weirs (see Section 8.5.6). The shallow areas so formed, are termed riffles and the deep areas, pools.

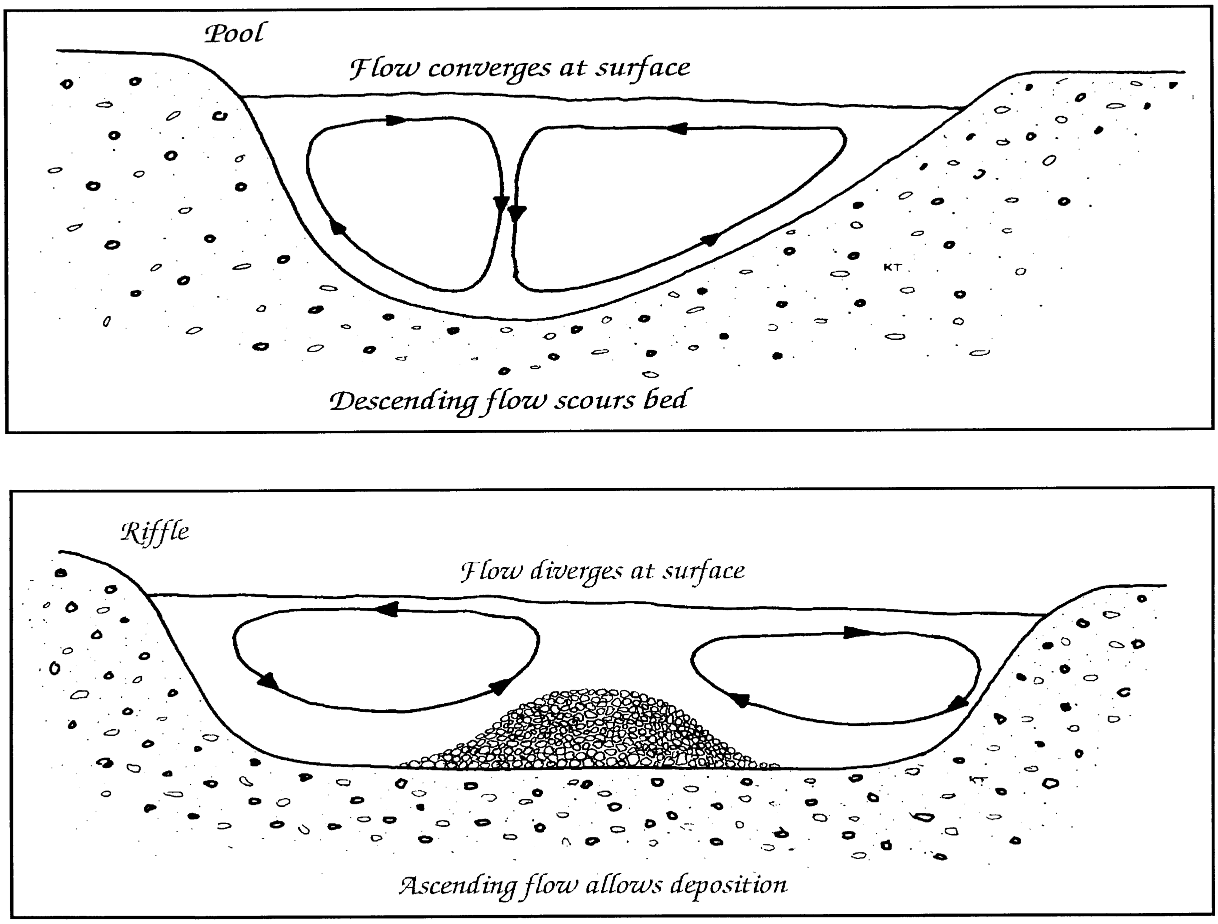


Figure 2.1 Secondary flow circulation in pools and riffles

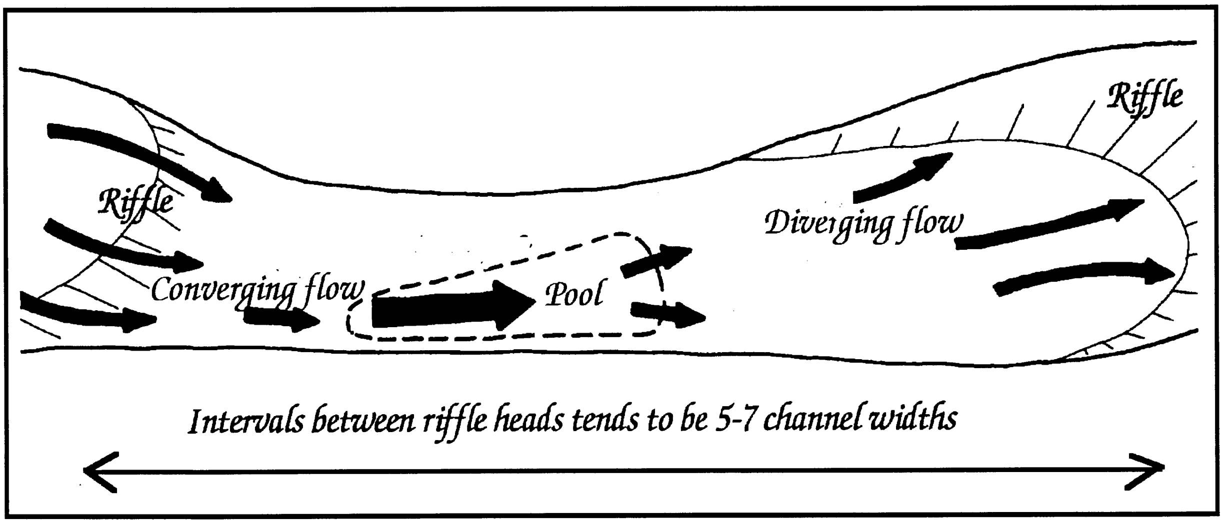


Figure 2.2 A pool-riffle sequence

Meandering

In nature, it is rare that a riffle crest is aligned perpendicularly to the streambanks. Rather, they tend to be aligned diagonally so the effective flow dispersal width is even greater for the given width between banks. It is also commonly the case that successive crests are aligned at different directions such that the current alternates between different sides of the stream.

This latter phenomenon gives rise to another characteristic of alluvial streams - meandering (Fig 2.3). Pools tend to exist on bends, with riffles in the inflections between bends. As the "thalweg" (the main current) is shunted from one bank to the other, erosion of alternate banks results, with corresponding deposition on the inside banks. Given that the riffle crest to riffle crest spacing averages about 6 channel widths, the wavelength of meanders tends to be about twelve channel widths. However, like the pool-riffle sequence, meandering may not necessarily follow a regular pattern in nature.

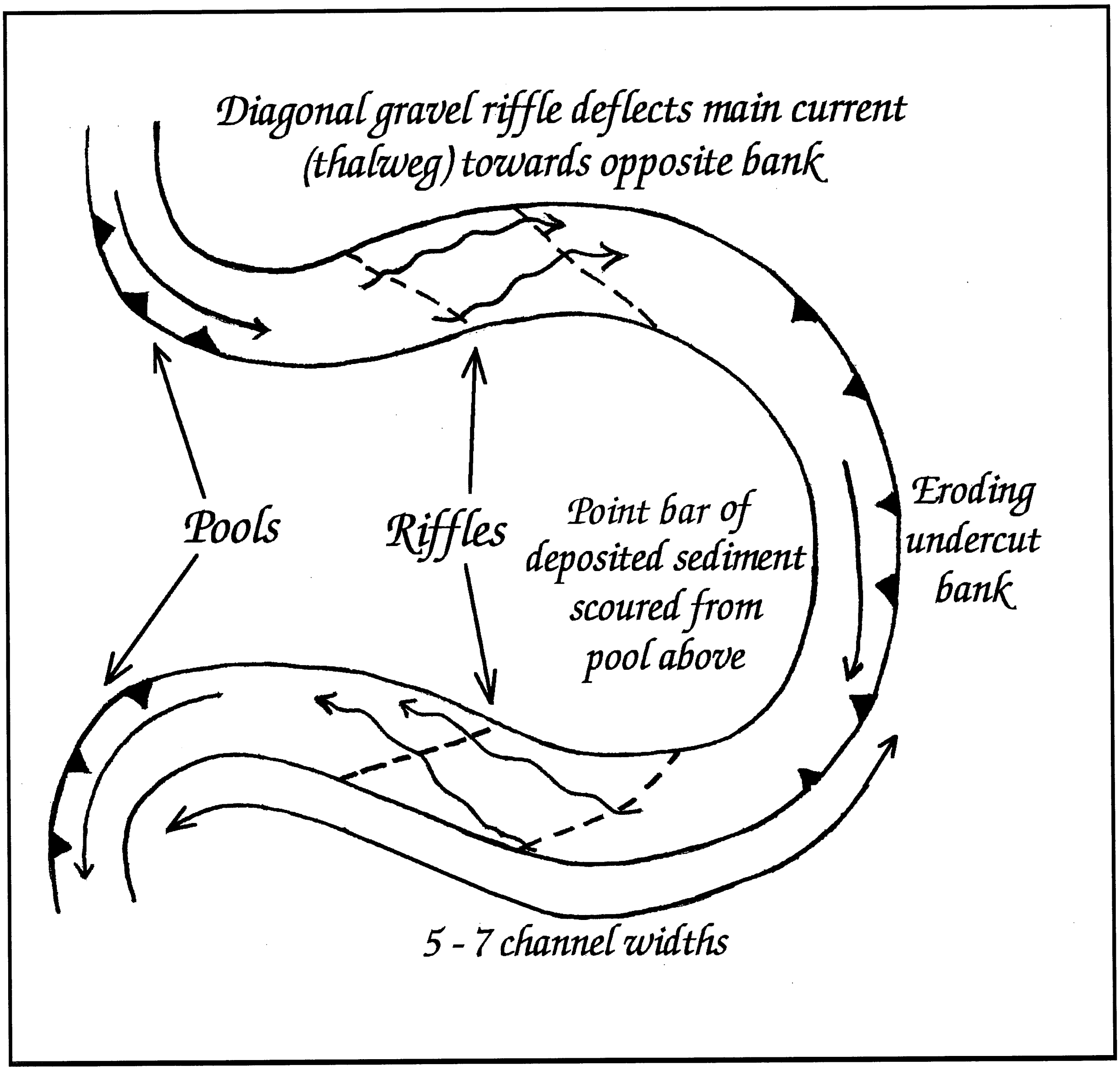


Figure 2.3 Pool - riffle sequence on a natural river meander

Effects of stream power and sediments

The width of a stream, which controls *inter alia*, the pool-riffle spacing and so meander wavelength, depends on the power of the stream, and the nature of the bank and bed materials. For example, a bank consisting of cohesive, erosion resistant sediments (e.g. clay or hard packed gravel) will allow the formation of deep, narrow channels, whilst really soft sediments will result in wide shallow channels (Schumm and Khan 1972). The former type of channel also tend to be highly sinuous (sinuosity is defined as the ratio of channel length to straight line length over a reach) whilst the latter tend to be relatively straight (Schumm and Khan 1972). Thus, variations in the nature of the sediments along a stream bank will result in variations in width and thus variations in the pool-riffle spacing etc. Different sediment types also have different structural properties which greatly influence the form of sedimentary features. For example, angular gravels may readily form riffle bars, but fine sands will not. Therefore, the form that pools and riffles take is greatly dependent on the type of sediments in the stream and the rate of delivery of sediments from upstream.

The stability of pools, riffles and meanders

A very important property about the, admittedly, complex processes outlined, is that once initiated, for whatever reason, they tend to be self-reinforcing. Thus, pools, riffles and meanders tend to be permanent features (Gregory *et al.* 1994). Of course, depending on the power of a stream and erodibility of the sediments, streams can be very dynamic and the entire channel may migrate. However, even if that does occur the basic form tends to remain. A river might be described as being in a “dynamic steady state”.

Intragravel flow

An important feature for pool-riffle streams for salmonid fish is that not all of the flow is contained within the channel itself. A small proportion of the flow can actually pass downstream through the bed at intervals. The most important thing in this respect is not that water may flow through the bed of a stream, but rather that there may be periodic interchange between the bed and the open stream above. In natural alluvial streams, the level of the bed varies and this has a big impact on intragravel flow. A hydraulic head difference will exist between a riffle crest and the downstream face of the riffle or the bed of the pool below. As a consequence water tends to penetrate into the gravel on the upstream face of a riffle and emerges on the downstream face (Stuart 1953a, 1954, Vaux 1968). The importance of this phenomenon for trout is explained in Section 3.3.4.

High-power streams

In powerful streams with a high gradient, the sediments deposited may consist of large particles such as cobbles and boulders, which may be quite angular in shape. Though such sediments do not form features with the same regularity as gravels or sands, they still do form predictable features. An almost universal feature of gravels and boulders when they are being deposited in a stream is that they form an “imbricated” structure. That is, the long-axis of each stone tends to be aligned into the current but dips at an angle to the bed. Thus, the most upstream point of the stone rests on the bed with the downstream end resting on the leading edge of the next stone downstream. All the stones effectively pin one another in place, creating an “armour” against bed erosion (Richards 1982).

2.2.4 Erosive streams

In high power streams where erosive processes dominate (e.g. in hard, rocky, steep channels) the regular sequences of pools, riffles and meanders seen in alluvial streams do not exist. In such streams the existence of physical variation depends on structural variations in the underlying rock or deposits on the valley floor. The erosive power of flowing water and stones rolling along the bed will differentially attack weak and strong points producing features which need not be created in a regular manner. Typical features in such environments are rocky shallows, waterfalls and plunge pools.

2.3 Effects of Vegetation on Stream Structure

2.3.1 Introduction

The physical features described above are formed by the effects of flowing water on sediments. However, vegetation, both beside and within streams, has a major impact on whether sediments can be mobilized by water, and so, is an important influence on stream structure. Also, vegetation is, in itself, an important part of stream structure. As the effects of vegetation are also dependent on its type, the management of vegetation is an important, and often most achievable, element of stream restoration. Therefore, this section describes the impact of different types of vegetation.

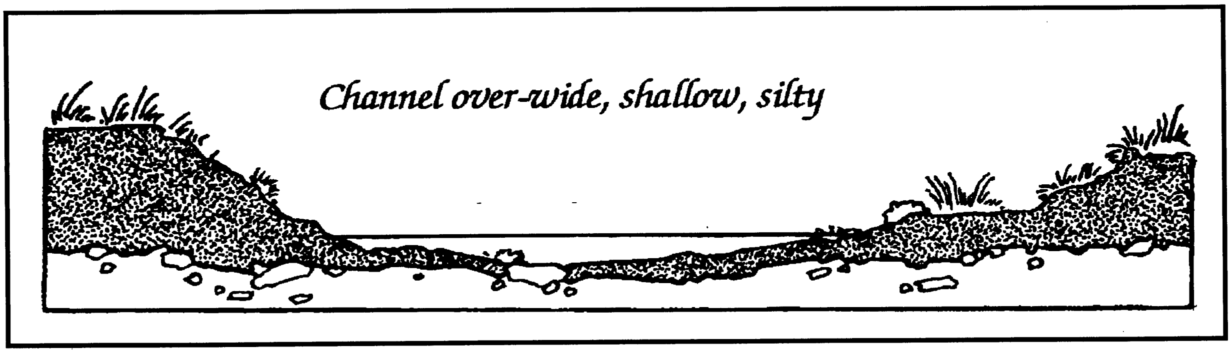
2.3.2 The influence of vegetation on physical processes

Riparian vegetation

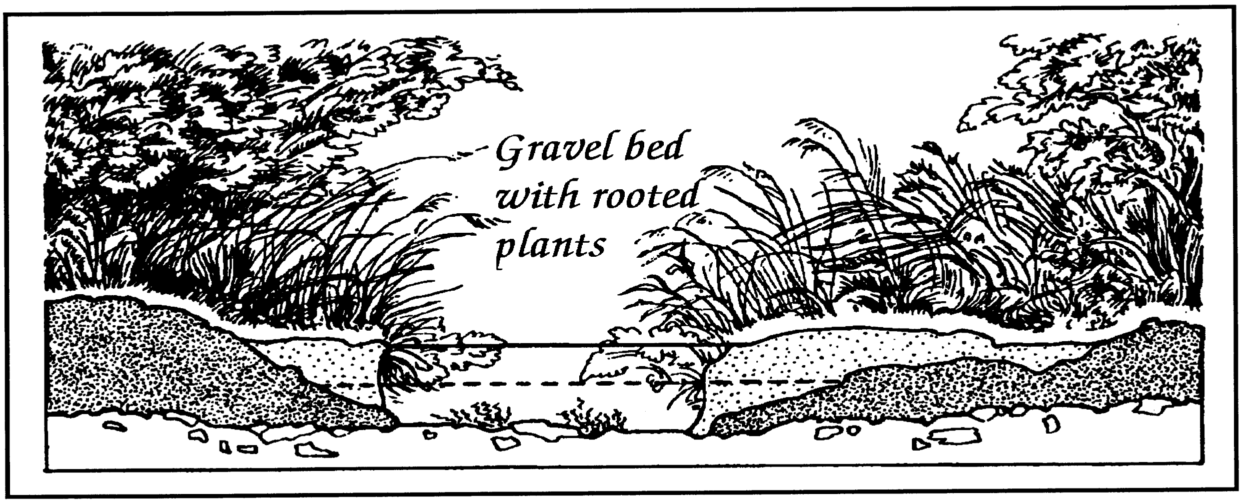
The main impact of riparian vegetation on stream structure is to increase bank stability through the binding effects of roots and direct protection of the sediment surface from stems and leaves. Tree roots are the most effective in stabilizing a bank face. However, the shade created by trees actually suppresses herbaceous vegetation and low bushes which are more effective at protecting the soil surface. Thus, apart from directly at the tree's own roots, the upper surface of a bank may be more prone to erosion (White and Brynildson 1967). The impact of trees on channel form depends on how mobile a stream is. For example, a stable stream where trees roots are unnecessary to maintain the banks will become wider and shallower (Fig. 2.4), but deeper and narrower pools may result in a mobile channel.

In-stream vegetation

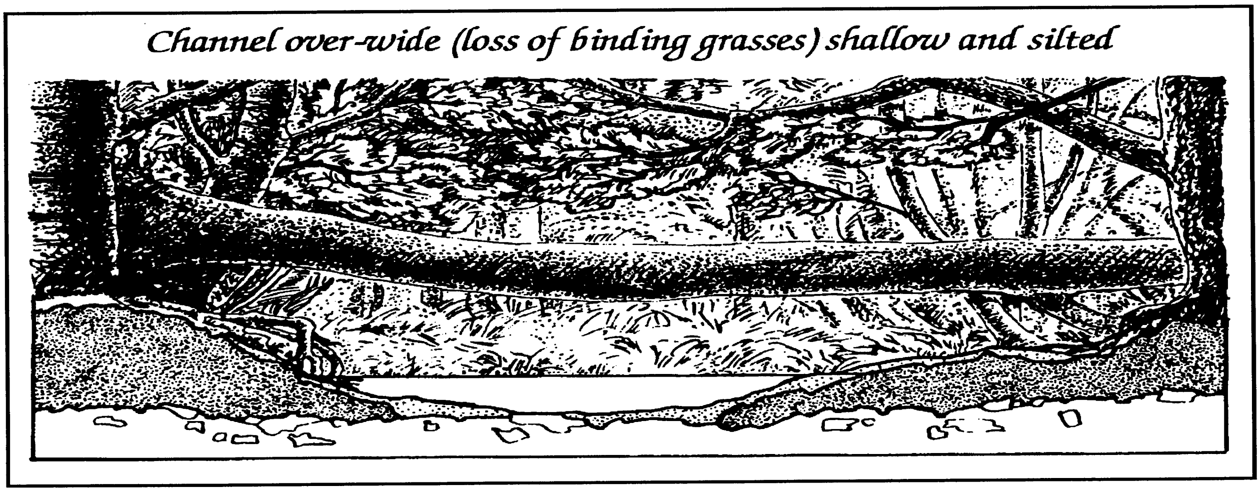
Both submerged and emergent plants growing in a stream have the effect of reducing the average current speed (Dawson 1989), though, if the plants grow in clumps, plumes of faster-flowing water can result. The slack water zones created in the lee of plants encourage the deposition of fine sediment which can become consolidated by further plant and root growth. Thus, riverbed plants may cause a shallowing of streams by raising the bed and promote lateral spreading of the current which may, in turn, lead to erosion and channel widening. By binding the sediment and encouraging deposition of fine material, vegetation may also prevent the formation of pool-riffle sequences. Vegetation has, therefore, a major impact on the physical structure of streams and adds another complicating, sometimes even overriding, factor on top of the physical processes described in Section 2.2.



Riparian vegetation suppressed by grazing



Well lit stream with grasses and bushes



Mature woodland with low light levels

Figure 2.4 The progressive effects of riparian vegetation on channel shape (Adapted from White and Brynildson 1967)

2.3.3 The influence of physical processes on vegetation

Whilst vegetation affects the physical structure of streams, it is also the case that geomorphological processes have, in turn, a profound impact on vegetation. As will be described in Chapter 3, vegetation is, in itself, an important element in trout habitat so it is important to consider those factors which affect vegetation.

Riparian vegetation
The main impact of riverine processes on riparian vegetation relate to whether a stream bank is actively eroding or aggrading. For example, typically at a bend pool, a stream will cut into a bank which has terrestrial vegetation, be it trees, or grasses, on top. The root systems of these plants bind the top of the bank but the lower layers may be more prone to erosion. Thus, an undercut may form, with an edge of terrestrial vegetation fringing over the eroding bank beneath, and this is usually excellent habitat for trout. From time to time, pieces of bank slump into the stream and some aquatic emergent vegetation may obtain a toehold on the ephemeral ledges so formed. On the inside of a bend, where fine sediments are deposited, emergent plants grow. These, in turn, trap more sediment causing the deposit to consolidate. As it does so, and becomes drier, the species composition changes. Thus, a succession of different types of vegetation exist alongside a river bend, with the actual rate of development of such a succession depending on the rate at which the stream migrates to and fro across the floodplain (Gurnell 1995).

In-stream vegetation
Substrates and current speeds will also influence aquatic vegetation. Coarse substrates are only suitable for certain species of algae and moss but finer sediments may make a more suitable rooting medium for larger plants. Particular current speeds also encourage particular plants. For example, water crowfoot (*Ranunculus* spp.) thrives in fairly fast water, whilst starwort (*Callitriche* spp.) pefers slower water, whilst Canadian pondweed (*Elodea canadensis*) is often found in almost still water (Ward *et al.* 1994). The complexity of the relationships between geomorphological and biological variables is evident when it is considered that these plants will, in turn, influence the physical structure, velocities etc., affecting the plants again in turn. As an example of this, in many chalk streams, *Ranunculus* grows profusely in spring when discharge is high, but when the discharge falls in summer, the stems and leaves impede the current causing the *Ranunculus* growth to decline, and by late summer, biomass is also in decline (Dawson 1989). This is a good example of the dynamic nature of stream systems and the feedback relationships referred to earlier.

2.3.4 Interactions between riparian and in-stream vegetation

Whilst many factors influence the growth of plants within a stream (e.g. photoperiod, temperature, water depth and clarity and nutrient status), there is an interaction between riparian vegetation and that in-stream. Shading by trees, or even taller herbs in small streams, suppresses in-stream plant growth (Dawson and Kern-Hansen 1979). This results in differences between wooded and open streams. For example, wooded streams, which may already be wider and shallow because of bankside erosion, lack the plants which reduce current speeds and dam back the flow, and so are even shallower. Consequently, the beds of such streams, lacking the binding effects of plants, are also more directly influenced by physical processes than open streams and, so, riffles and pools can be more highly developed.

2.3.5 The effect of woody debris in streams

Woodland streams are frequently wide and shallow in Britain where it is commonly the case that woodland is managed. However, the situation can be different in mature natural forest where trees and woody debris regularly fall into the channel. Log-jams tend to create impoundments in which there are accumulations of inorganic sediment and organic material (twigs, leaf litter etc.). The current is constricted by these obstructions and so scouring occurs immediately downstream creating pools with deposits of gravel at their tails (Angermeier and Karr 1984, Cummins 1986, Wilzbach *et al.* 1986, Bilby and Ward 1989, Shirvell 1990). In prehistoric Britain, fallen trees would have been a major influence on stream morphology, especially in small streams. Of course, as has been shown, alluvial streams may have a tremendous physical variation in the absence of woody debris, but this is not necessarily so in high gradient erosive rocky streams. In such streams, fallen woody debris has been found to be very important in creating a diversity of current speeds and depths. The debris creates pools and traps deposits of gravel and other features which could not otherwise exist (Platts 1991).

2.4 The Effects of Human Intervention

2.4.1 Man as a geomorphological agent

In addition to the natural processes described, man is also a potent geomorphological agent on rivers and streams. In fact, over large parts of the British Isles, man’s intervention has been a major influence on channel form. This holds true from the smallest of ditches to rivers tens of metres wide. The human impact on channel form includes both direct and indirect effects. Direct effects include the deepening, widening and straightening of streams to improve land drainage or navigation, the cutting of new channels to supply water for power and irrigation, the construction of dams and weirs and bank stabilization. Indirect effects include the consequences of land use change (increased sediment availability, increased nutrient levels, bank damage by livestock) and water abstraction. Much of stream restoration involves restoring damage caused by some or other of these impacts. More detail of these impacts are given in Chapter 4.

The role of natural processes
The direct effects, as the name implies, are deliberate actions taken to modify the form of a channel. With the indirect effects, some of the controls on channel form are altered (often unintentionally) and the altered “natural” processes result in a change in the channel form. For example, increased sediment yields caused by erosion from ploughed land could result in the accretion of fine sediments within the channel downstream, resulting in the shallowing of pools and increasing the frequency of overbank flooding.

The important point to remember is that, irrespective of the human impact, natural processes will continue to operate, though the controlling factors will have changed. As a result, streams will recover from direct modification, but the time taken varies. Some types of stream recover quickly from particular forms of modification and these may be repeated regularly (e.g. dredging in a low power stream carrying a high sediment load). However, at the other extreme, some impacts will not be erased in a very long time (e.g. where entire drainage systems have been deeply channelized).

2.4.2 Implications for habitat restoration

The widespread human impact on modern streams means that many of the features described earlier in this chapter (e.g. pools, riffles and meanders) are no longer present. As will be described in Chapter 3, such features form a very important part of trout habitat. Therefore, a major part of trout habitat restoration has been the restoration of physical diversity to such streams (Mann and Winfield 1992).

2.5 The Stream Ecosystem

2.5.1 Introduction

This section provides a brief introduction to the ecology of trout streams. Whilst trout stream ecology is an enormous and important subject in itself, many aspects of the ecology are difficult to alter relative to the physical habitat. Therefore, the general ecology is not considered in depth. Rather, the important issues and those aspects of the ecology which respond to management are highlighted.

2.5.2 Primary production

Sources of production
The ecology of streams is based on two forms of primary plant production. These are "autochthonous" (in-stream plants and algae) and "allochthonous" (vegetable matter falling into the stream from the riparian zone) production (Moss 1980). Many factors influence the amounts of these two forms of production, and not surprisingly, the relative importance of the two types can differ markedly between streams.

Controls on in-stream production
The amount of in-stream production which can occur in a particular stream depends on many factors. Stream fertility, temperature, light incidence and degree of shading are very important in determining production and also species composition. Basically, nutrient rich, well lit lowland streams are capable of high productivity, whilst cold acidic upland streams may be very unproductive (Ward *et al.* 1994). The importance of nutrients was demonstrated by Shamsudin and Sleigh (1994) who found that the annual production of algae in the River Itchen, a chalk stream in Hampshire, was of the order of 600g dry weight/m^2/year, whilst that in a small acidic stream in the nearby New Forest only amounted to only 75g dry weight/m^2/year. The importance of light is shown in that even shading by bankside vegetation can reduce instream macrophyte production to practically zero (Dawson and Kern-Hansen 1979).

Other factors such as water velocity and substrate type also have important effects on primary production, especially in determining species composition. For example, slow water with sand/silt beds may favour species like the yellow water lily (*Nuphar lutea*) and Canadian pondweed (*Elodea canadensis*). Swifter flowing streams, like chalk streams, are associated with species like water crowfoot (*Ranunculus* spp.), whilst, apart from algaes, turbulent rocky streams may be dominated by mosses (Ward *et al.* 1994).

The important point, therefore, is that instream primary production is extremely variable, both between and within streams.

Value of riparian production

The value of organic inputs to a stream from the riparian zone also depends on many factors, so this also varies between streams. Obviously, the quantity of inputs is important, but so also is quality, for leaves and stems from different species break down at different rates. For example, deciduous leaves break down relatively quickly but waxy conifer needles take a longer time (Egglishaw 1985). The quantity and quality of inputs will, then, depend on the species composition and abundance of riparian vegetation and its proximity to the stream (Conners and Naiman 1984).

The degree to which litter can be retained within a stream is also fundamentally important (Dawson 1980). Obviously, if all litter is washed away it will have no value. Litter retention is related to stream discharge, the type of the litter and the size and the gradient and roughness of the channel (Cummins 1986). For example, a clean, featureless channel will retain little material, but a forested stream with fallen trees and branches may retain considerable amounts of litter, though this ability is progressively reduced as streams increase in size (Bilby and Ward 1989) as do litter inputs per unit area of stream anyway (Conners and Naiman 1984). This necessity for roughness is compounded as leaf fall from trees generally coincides with increased discharge in autumn.

The instream production / riparian production paradox

As shading from bankside vegetation is a major controlling factor on instream production (Dawson and Kern-Hansen 1979, Bilby and Bisson 1987) conditions which are suitable for high riparian inputs lead to low instream production. For example, for riparian inputs to be high, the banks must be tree-lined, but the shade so created may have the effect of suppressing instream production. This means that streams tend to be dependent on one or other form of production rather than on a mixture.

2.5.3 Invertebrate production

Types of invertebrates

Vegetable matter in streams forms the basis of the food chain for invertebrates. The many species of stream invertebrates perform different functions. Some species, known as "grazers" consume algae which grows on the substrate (e.g. some mayfly species and snails) or on the surface of higher plants (some mayfly species especially). Others, referred to as "shredders" consume litter which is being decomposed by fungi and bacteria (e.g. many caddis species, water lice and shrimps). There are also filter feeders which intercept fragments of litter or algae drifting in the water column (e.g. midge and gnat larvae and some caddis species). Thus, a whole variety of invertebrates allows the utilisation of all types of organic material and at different stages of decomposition (Moss 1980). Finally, some species of invertebrates are carnivorous (e.g. alder fly, damsel fly, dragonfly, some caddis and stonefly larvae plus flatworms and some leeches), eating other invertebrates.

Physical habitat requirements

The various invertebrate species have different habitat requirements. The nature of the substrate is considered an important factor. In general, highest invertebrate productivity and diversity is found in riffles with cobbles and gravel (Gore 1985). In a recent study of lowland rivers in Britain, with regard to substrate type, the greatest variety of invertebrate species was again found amongst cobbles and gravel, with silt being the next best and sand being the poorest of all (Wright *et al.* 1994). However, all vegetation types possessed a greater species diversity than even cobbles and gravel. The submerged stems of emergent vegetation (especially species like reed sweet-grass (*Glyceria maxima*) and reed canary-grass (*Phalaris arundinacea*)) was best of all, followed by submerged plants, then algae. However, it should be pointed out, that in terms of food for higher organisms, it may be that low variety environments can still be good since actual numbers may be high though species diversity poor (Ward *et al.* 1994).

Although many invertebrate species prefer riffles, a stream composed purely of riffle habitat may not be ideal because, in times of low flow, pools may temporarily store fine sediment instead of it spreading over riffle areas (Gore 1985). Sand and silt can reduce invertebrate numbers by clogging the crevices in which they live and where litter fragments accumulate (Egglishaw 1985). However, some invertebrates do prefer fine substrates. For example, the larvae of the mayfly (*Ephemera danica*), which for anglers is perhaps the most important fly in many English trout streams, burrows in fine sediment trapped around the roots of plants (Wright *et al.* 1981). Therefore a mixture of riffles and pools will provide habitats for a wide variety of invertebrates.

Links between primary and invertebrate productivity

Invertebrate production and species composition is influenced by the amounts of instream primary production and riparian inputs to a stream. As these are very variable, invertebrate production also varies greatly depending on the particular circumstances of individual streams. For example, the annual production of herbivorous invertebrates in the Bere Stream, a chalk stream in Dorset, (Westlake *et al.* 1972) is ten times that of the Takami River in Japan (Tusda *et al.* 1975).

2.5.4 Fish production

The diet of trout

Trout are carnivorous fish, as to a great extent are all the other species of fish which typically occur in the same type of streams (e.g. bullheads (*Cottus gobio*), chub (*Leuciscus cephalus*), dace (*Leuciscus leuciscus*), eels (*Anguilla anguilla*), grayling (*Thymallus thymallus*), gudgeon (*Gobio gobio*), minnows (*Phoxinus phoxinus*), pike (*Esox lucius*), salmon, stone loach (*Noemacheilus barbatulus*) and three-spined sticklebacks (*Gasterosteus aculeatus*)). Trout have a fairly catholic diet which typically reflects what is available to eat. When young, they depend entirely on invertebrates and when older they may eat an increasing proportion of small fish (Frost and Brown 1967, Maitland and Campbell 1992). Trout are opportunists and have adapted to the different food resources available in different environments (Maitland and Campbell 1992).

Trout eat a very wide range of invertebrate species: mayflies, midges, stoneflies, caddis, freshwater shrimps, beetles, snails, worms, crayfish etc. However, some invertebrate species are more available to trout than others because of their habitat requirements and behaviour. For example, species of mayfly with free swimming larvae (e.g. Baetids) are more readily taken than cased caddis larvae (Frost and Brown 1967). Older trout, especially, may eat bullheads, grayling, gudgeon, loaches, young salmon, sticklebacks and even amphibians. However, all these fish species depend on invertebrates so, irrespective of what they eat, trout are ultimately dependent on numbers and species of invertebrates, which in turn are dependent on primary production and inputs to the steam. Therefore, as the primary and secondary productivity of streams varies, so also does the productivity of trout (Waters 1988).

2.5.5 Managing the stream ecosystem to maximize trout production

Trout production varies in different streams according to environmental differences, many of which are not subject to basic control, except perhaps at great expense. However, the dominant form of primary production in many streams may be controlled through management of riparian vegetation to increase or reduce shade. This will affect the production of invertebrates and their species composition. An important issue is what is the effect of this on trout?

In the literature, there is a difference in opinion on this issue and a sometimes heated debate has arisen (Platts and Nelson 1989). A main reason for this is that because the two forms of primary production are to a degree mutually exclusive, one or other form of production will appear most important in a given stream. However, in a comparative study, a forested stream contained much more organic matter than a clear-cut stream, but fish production in early summer was consistently greatest in the latter (Bilby and Bisson 1987). The type of invertebrates found most commonly drifting in the water column and in the stomachs of juvenile coho salmon (*Oncorhynchus kisutch*) were mainly those which relied most heavily on algae or algae based detritus (e.g. Baetids and Chironomids) rather than those which prefer leaf litter. Also, it was found that algae and algae-based detritus has generally more protein and is more digestible to invertebrates than terrestrial plant material. In another comparative study, cutthroat trout (*Oncorhynchus clarki*) were more abundant and grew faster in clear-cut as opposed to forested streams and this was in part, at least, attributed to increased amounts of invertebrates like ephemerids and chironomids and more efficient foraging by trout in the brighter conditions (Hawkins *et al.* 1983, Wilzbach *et al.* 1986).

In conclusion, it appears that for trout, instream primary productivity should be promoted at the expense of riparian inputs. However, this will undoubtedly depend on factors like stream fertility and litter retention in wooded streams. For example, one study found invertebrate abundance to be lower in streams with a regenerating tree cover than ones which had been clear-cut and experienced increased in-stream production. However, invertebrate abundance increased again in old forested streams where litter was trapped by fallen trees (Wilzbach *et* *al.* 1986). This is an issue which requires further research, but one of which fishery managers must be aware.

A final consideration is that shade from trees will reduce summer water temperatures. In warm environments this may be critical for the survival of salmonids. There is practically no information on the necessity of shading in England and Wales, but O' Grady (1993) considered that summer temperatures in Ireland were not high enough for there to be a need for shading.

2.6 Overview: Stream Processes and Stream Diversity

2.6.1 The complexity of stream processes

As described in this chapter, the stream environment, both in terms of physical and biological structural elements, is formed as a result of the interaction of many complex processes. These processes are ultimately governed by large scale controls on the wider catchment, including climate, geology and physiography. Figure 2.5 is a schematic representation of the system and summarizes the complex interlinkages which ultimately govern channel morphology and thus habitat, ecology and trout production.

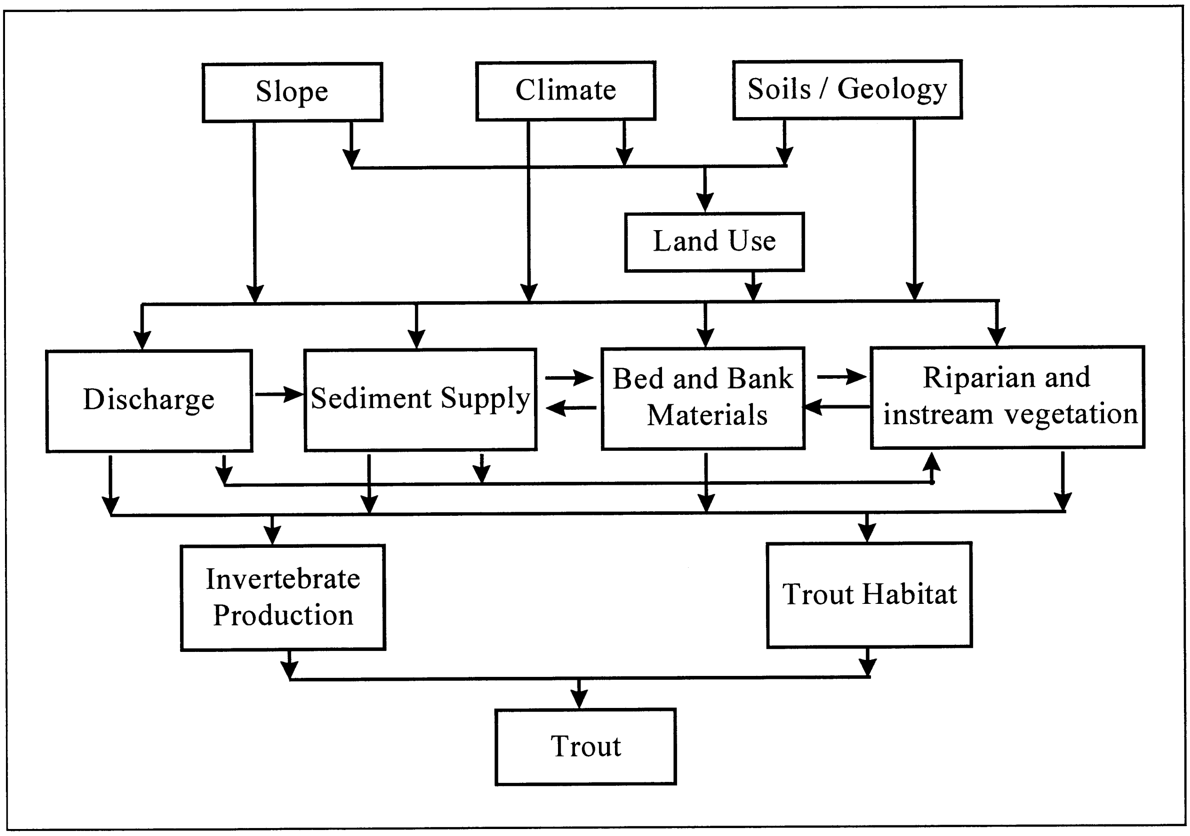


Figure 2.5 The interrelationship of the controls on stream habitats (Adapted from Knighton 1984)

2.6.2 The diversity of streams

Owing to the varied nature of the controls on stream morphology and their complex interlinkages, there is a practically limitless variation possible in the form of stream channels and, therefore, stream habitats. This is true both within and between catchments.

However, in practice, some of the important controls may give rise to characteristic river forms which may become associated with these controls, geology being a good example. This commonly leads to the classification of streams according to various aspects of their form. Such classification may be done at a popular level (e.g. fishermen's classifications of "chalk streams", "spate rivers" etc.) or by following a more systematic approach (e.g. Holmes' (1989) classification by plant type and Huet's (1949) classification by fish habitat). As examples of broadly different types of stream, four different streams are shown on Figs. 2.6 to 2.9. These are, a chalk stream, a pool-riffle alluvial stream, an upland stream and a large upland river. However, while it is common to think of streams as being of different types, the distinction between different types are never clear (Kondolf and Downs 1996). Rather than assuming streams fit into discrete types, the important skill which must be acquired is to be able to recognize why streams are different and what the controls on these differences are.

For example, Fig. 2.6 is a stereotype "chalk stream". It is a relatively wide and shallow alluvial stream with a gravel bed, crystal clear water and abundant instream plants, especially *Ranunculus* spp., but lacks a well defined pool riffle sequence. There are probably several factors which contribute to this form. Firstly, the products of chalk weathering tend to result in streams with coarse flint gravel beds but soft silty banks and these erode outwards in preference to bed scour where there are no tree roots to bind the bank. The plants also help bind the gravel bed, further contributing to lateral displacement. This stream, like many chalk streams, has also been straightened in the past, and so channel features which may have existed naturally have been removed, and the stream power may be insufficient to restore them. Chalk streams tend to have relatively low stream powers because of their relatively low gradients and the dampening of spates caused by the buffering effect of the aquifer.

Fig. 2.7 is also an alluvial stream, but differs from Fig. 2.6 in that the width to depth ratio is lower and there is a well defined sequence of gravel riffles and deep narrow pools with undercutting banks. These differences have arisen because this stream has a higher gradient and is more prone to spates, has more cohesive banks (especially where there are tree roots) and fewer plants than the chalk stream. This means that,. in addition to bank erosion, the river bed gravels are also subject to scour, producing the pools and riffles.

Fig. 2.8, an upland erosive stream, is characterized by a bed and banks of bedrock and large boulders. Alluvial features are not dominant because the high flood velocities prevent deposition of all but the largest material. The dominant features, steps and plunge pools, result from the nature of the underlying rock.

Fig. 2.9 is an example of large river in an upland area. Again this is a stable erosive channel which has worn down to bedrock and the major features of the river are to a great extent conditioned by the geology of the valley.

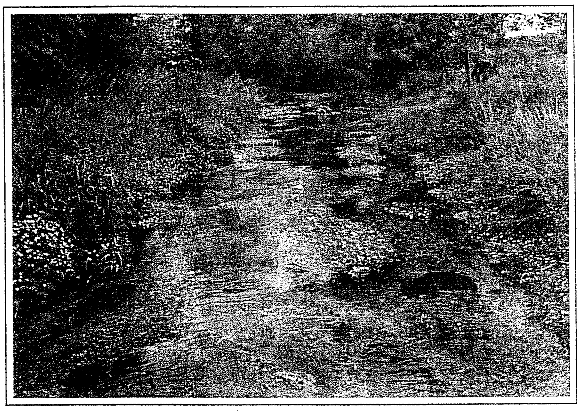


Figure 2.6 A chalk stream
(Photo: N. Holmes)

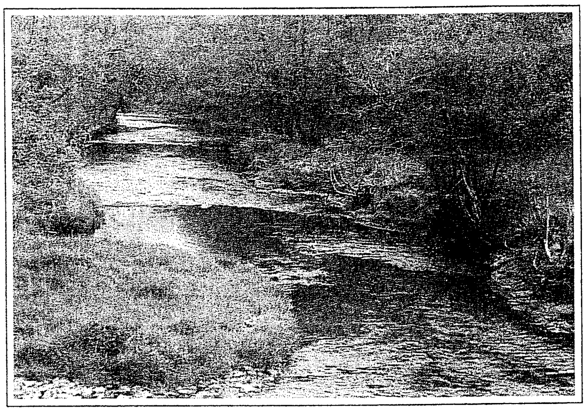


Figure 2.7 A pool-riffle alluvial stream
(Photo: D. Summers)

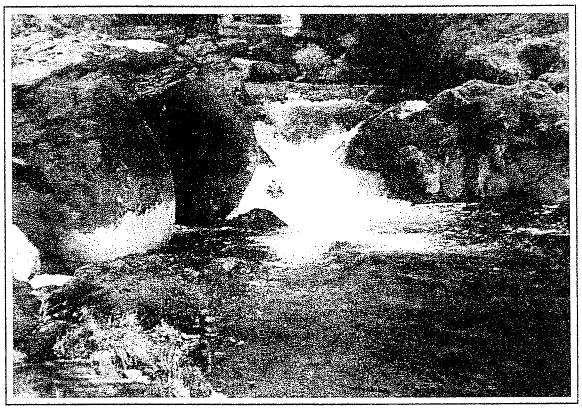


Figure 2.8 An upland stream
(Photo: N. Holmes)

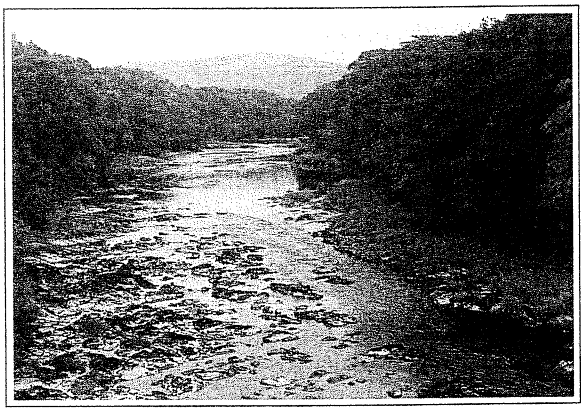


Figure 2.9 A large upland river
(Photo: N. Holmes)

2.7 Implications for Stream Restoration

2.7.1 Introduction

This chapter has stressed that streams are created by dynamic processes which are controlled by dynamic factors at both the catchment and local scale. Man has widely interfered with these factors and much of stream restoration seeks to rectify this. A number of important skills are required to do this.

2.7.2 Recognizing habitats to be restored

The first step before a stream can actually be restored is to recognize how the stream has been degraded. That is, what are the symptoms of the degradation, and what were the causes (for example, a symptom would be if a stream was straight, uniform and incised, and the cause would have been channelization). Fundamental to this, is that the natural form of the stream must be known. However, this can be difficult. If historical information in the form of maps or photographs are available these can be used. Frequently there is no such information and so the natural form of the stream must be predicted on the basis of catchment topography and geology, climate, knowledge of geomorphological evolution, land-use change etc. Thus, a thorough understanding of the functioning of different types of riverine systems is necessary.

Essentially, the important thing is to understand why a particular stream is the way it is. Those factors which are natural and the impacts of man must be recognized. When in doubt, seek expert advice.

2.7.3 The need to work with processes

Once a likely natural stream form has been identified, the next question is whether it is possible to restore former conditions, or whether it is only possible to perform a naturalization. Whichever of these options is selected, a restoration scheme should then aim to restore self-reinforcing or stable channels and to stabilize or restore controls at the catchment level if this is also necessary. At the same time, it is important to consider how the restoration scheme will impact on the rest of the riverine system.

These requirements mean that a thorough understanding is needed of hydraulic processes and how different techniques of re-creating channel features actually work. The important thing is that channel forming processes must be steered to accentuate what the stream is inherently trying to create itself. Rivers do not consist of discrete components which can be assembled in any desired manner.

Again, the important point is that complex issues are frequently involved, so professional guidance should be sought wherever possible.

3. TROUT HABITAT REQUIREMENTS

3.1 The Life Cycle

3.1.1 Introduction

Trout require different habitats at different stages in the course of their lives. Therefore, before describing what these actual requirements are, this section briefly describes the life cycle of the trout. The main stages in the life cycle of the brown/sea trout are shown in Fig. 3.1 and are summarized below.

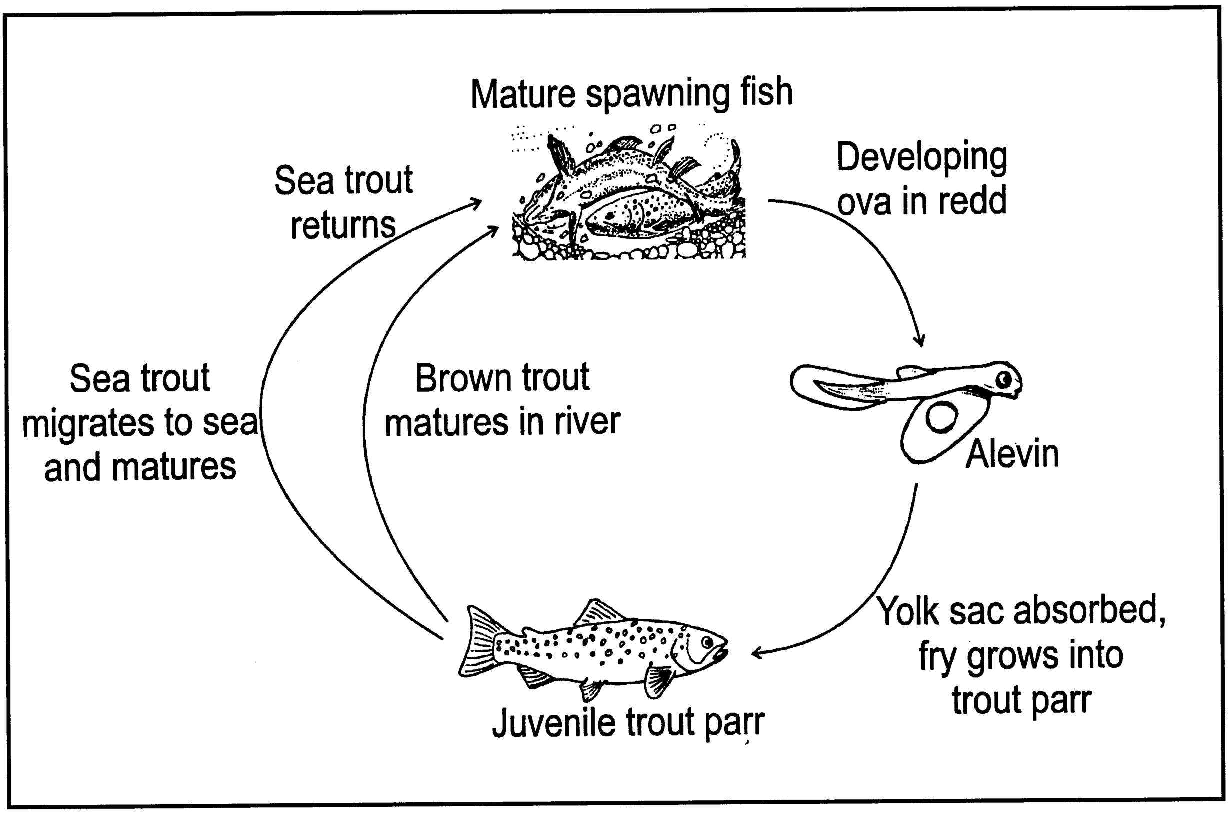


Figure 3.1 The life cycle of the trout

3.1.2 Spawning and incubation

Trout spawn during the late autumn or winter. This differs according to location, with spawning commencing earliest in the more northern and upland areas of Britain and latest in the warmer streams of southern England (Frost and Brown 1967). The process of spawning is described in detail in the next section, but basically, the eggs are buried amongst gravel where they develop at a rate dictated by ambient temperatures. The number of eggs laid by a female trout is variable according to the size of the fish, and many range from as little as one hundred to several thousand (Elliott 1994).

3.1.3 Hatching and emergence

In the early spring the trout hatch from the eggs. At this stage they still have a "yolk sac" attached and are known as "alevins" (Allan and Ritter 1977) and these continue to live under the gravel until their yolk is used up. During this stage high mortalities may occur if conditions are not suitable for successful incubation, but if they are, mortalities may be negligible. After the yolk sac is used up during the spring, the alevins are then known as "fry" (Allan and Ritter 1977). At this stage they emerge from the gravel and commence feeding. Again, as for the egg stage, survival rates to emergence can be high.

3.1.4 "Fry" and "parr"

At some point in their lives the growing trout fry become known as juveniles or "parr". Unfortunately, in the literature, there is some variation in interpreting what fry and parr are. For example, trout have sometimes been referred to as fry for the whole of their first year (Allan and Ritter 1977). To avoid this confusion, Allan and Ritter (1977) suggested that trout should become known as parr as soon as they disperse from the spawning site, and that the fry stage may only last for days. However, this misuse of terminology still persists and fry is still often used as a convenient name for very small (though how small is undefined) trout. In this manual fry are considered to be immediately post-emergence, but there is some latitude as many of the studies cited have used the term to differentiate 0+ aged trout more generally from older juveniles.

Typically, very high mortality occurs during the first few weeks of post emergence life. This is often when the highest mortality rates occur. However, the rates of mortality do vary according to factors like habitat quality and densities of fry. For example, even within a single Cumbrian stream, it has been found that survival rates over the first few weeks may vary from only a few percent to nearly 40%, though they are most typically of the order of 10% (Elliott 1994). Survival rates general increase as parr get older.

The juvenile or parr stage lasts until a trout either matures in freshwater or migrates to sea as a "smolt".

3.1.5 Variations in the life history of trout

Up until the juvenile stage, the life history of trout is essentially quite similar. However, after that a great amount of variation is possible, both between populations and even between siblings. At the first instance, trout can be split into those which remain in freshwater as "brown" trout, and those which become "sea" trout. However, even within these two categories immense variation is possible.

Brown trout

Freshwater resident "brown" trout vary greatly in the life history strategies they adopt. For example, some may move very little, spending their entire lives within the confines of a small stream. On the other hand, some may migrate away from spawning areas, both downstream and upstream, to other parts of the river system or into lakes (Elliott 1994). Consequently, trout experience different growth rates, survival rates, ages at maturity, longetivity etc. Females may mature as early as two years old (Avon & Dorset River Authority 1973) and may continue to spawn on an annual basis thereafter, making annual migrations between spawning and feeding areas. Individuals in some populations can live in excess of 10 years (Frost and Brown 1967).

Sea trout

Those trout which become sea trout undergo a physiological transformation into saltwater tolerant "smolts" in the spring of the year and migrate to sea. The age at which smolting occurs varies according to growth rates as juveniles, and can take place from age 1+ upwards depending on the environment (Elliott *et al.* 1992), but in Britain this is most commonly at age 2+ or 3+ (Fahy 1978).

On entering the sea, the strategies adopted by sea trout are again variable. Some sea trout return to freshwater during the first winter (these are known in different localities as, "herling", "whitling", "peal", "finnock" etc.), of which some may be mature and others still immature (Elliott *et al.* 1992). These fish then return to sea in the spring and return again as adults to spawn the following winter. However, some sea trout remain at sea over their first sea winter, only returning to freshwater on their spawning migration.

Most sea trout in Britain return to spawn in freshwater by their second winter after leaving freshwater. However, some sea trout do spend two winters at sea, but these appear to be practically unique to the rivers Coquet and Tweed (Nall 1930).

The incidence of repeat spawning, with periods of sea feeding in between, varies in different parts of Britain. In some rivers, sea trout populations may comprise of significant numbers of fish which have spawned several times (e.g. the rivers of the west coast of Scotland), whilst in others, repeat spawners are present in much smaller numbers (e.g. on the east coast of Scotland) (Nall 1930). From one long-lived Scottish population, Nall (1930) found one sea trout to be 18+ years old.

Sea trout generally return to freshwater in the spring or summer, some months before they actually spawn. They tend to migrate to the vicinity of spawning tributaries and may remain in wait for several months before making a final migration during the days immediately prior to spawning (Elliott *et al.* 1992, Evans 1994)

Reasons for variations in life history

The wide variety of strategies adopted by trout appear to be determined by both genetic and environmental factors. For example, Walker (1990) showed that the tendency for anadromy persisted when the offspring of sea trout were transplanted into a stream which normally only produced "brown" trout. However, it has also been shown that the proportion of trout which remain as "brown" trout, from the same families, can also be influenced by feeding opportunities as juveniles (Anon 1992). However, it is likely that the different strategies adopted are in a large part adaptations to different environments (Elliott 1994), and as stated earlier, this can result in major differences between populations. For example, in harsh environments where the growth of trout is slow, trout tend to invest a smaller proportion their energy in gonad production but spawn over several seasons than in more productive environments where trout tend to be proportionately more fecund and may only spawn once (Elliott 1994). It is also the case that considerable variation can exist within a population, and, commonly, populations are comprised of both brown and sea trout. In fact, it has been widely found that males tend to remain in freshwater as brown trout with females migrating to sea (Elliott *et al.* 1992).

3.1.6 Spawning migrations

Although both brown and sea trout may migrate considerable distances away from where they were themselves were spawned, they do home back to their natal streams at spawning time (Stuart 1953b, Elliott *et al.* 1992). This is the last major element in the life cycle before returning to the spawning stage.

3.2 Habitat Limitations on Trout Populations

3.2.1 Introduction

The ultimate purpose of this manual is to provide information on the restoration of habitats which will primarily result in an increase in the size of brown trout populations. In order to understand how restoring habitat can affect populations it is first of all necessary to appreciate why habitat can regulate trout numbers. This is now described in this section.

3.2.2 Stream productivity

Assuming the habitat is optimum, the ultimate biomass of trout which a stream can produce will depend on the amount of food available and temperatures experienced. It is considered that the maximum production of trout in any stream is likely to be of the order of 20 g/m^2/year (Mann and Penczak 1986). However, there is relatively little other information to relate trout production figures to measurable parameters of different streams.

However, while biological productivity may effectively put a ceiling on trout biomass, it need not necessarily put a ceiling on numbers *per se*. This is because a maximum trout biomass may be expressed as many small fish or fewer big ones (Le Cren 1969). However, biological production will generally affect the growth rates of trout of a given age and the ultimate maximum size, as demonstrated between trout in chalk streams and softwater streams (Mann *et al.* 1989). A further complication is that biological production in itself may not completely determine maximum size of trout, as the type of food items also need to be taken into consideration. High production of small food items may result in rapid growth of small fish, but not for large trout which require large food items for energetically efficient foraging (Allen 1969). This was borne out by Crisp and Beaumont (1995) who found that, from four streams, those with the most rapid juvenile growth had the lowest asymptotic length. Therefore, biological productivity needs to be quantified in a more meaningful form than, say, just gross energy production.

That the relationship between biological and trout production has not been clearly quantified, is not a major problem for trout habitat restoration. This is because relatively little can be done to influence the biological productivity of a stream compared to the physical habitat, and the latter also has a major impact on the numbers and size of trout in a stream. Consequently, this manual concentrates on habitat restoration. However, biological productivity will set limits on what is achievable through habitat restoration, and biological productivity should always be considered when contemplating habitat restoration to see if habitat restoration could meet the desired objectives. For example, it would be pointless to consider improving habitat in an infertile upland stream for large trout if such areas of good habitat as do exist only hold small slow growing trout.

3.2.3 Territoriality and "carrying capacity"

The actual physical habitat is very important in determining trout numbers because, from emergence, trout are territorial animals, defending a definite feeding position in a stream (Kalleberg 1958, Le Cren 1973, Elliott 1990). Therefore, a given habitat can only accommodate a certain number of trout - the "carrying capacity".

When a habitat is at its carrying capacity, some "dominant" fish succeed in defending a territory whilst others do not. The dominant fish, therefore, gain a competitive advantage and so may grow faster than subordinates. This, in turn, may further improve the competitive advantage of dominant fish. Thus, a hierarchical structure develops with dominant fish occupying territories and subordinates being marginalized (Kalleberg 1958, Elliott 1990, Titus 1991). Subordinate fish are either forced to move or die as a result of competition. This is known as "density-dependent mortality" - i.e. the proportion of the population dying varies with initial population size.

A number of factors influence the size of territory defended. The most important reason is fish size; territory size increasing as body length increases (Elliott 1990, Grant and Kramer 1990). However, Kalleberg (1958) also found that, as water velocities increased, trout remained lower in the water column and consequently territory size decreased because of increased visual isolation from neighbours and the increase in energy required to fend off neighbours in a strong current. He also found that "cover" from objects like rocks and plants increased visual isolation and reduced interaction. Among salmonids in general, territorial behaviour also increases as food availability decreases (Mason and Chapman 1965, Slaney and Northcote 1974, Dill *et al.* 1981) but decreases as temperatures fall and feeding ceases with the onset of winter (Mason and Chapman 1965, Bjornn 1969, Cunjak and Power 1986, Gibson 1988, Fraser *et al.* 1993, Griffith and Smith 1993). It is also the case that at very low current velocities a tendency towards schooling rather than territoriality may develop (Kalleberg 1958). Aggressive behaviour amongst small fish can also be reduced if a large fish is nearby (Gibson 1988). Thus, in summary, territoriality is not a constant condition, but in the main, seems to be linked with securing a good active feeding position in a current (Gibson 1978). Hence, different habitats, or even the same habitats under different conditions can have different carrying capacities.

As trout get older they lose some of the attachment to a specific site in the stream which is so characteristic of fry (Kalleberg 1958). The typical behaviour of adult trout is to be resident (except perhaps for migrations at spawning time) in a localized area and live within a dominance hierarchy with other trout (Jenkins 1969, Solomon and Templeton 1976, Gowan *et al.* 1994). Position in the pecking order is determined largely by size, which within a particular environment, is largely a function of age (Bachman 1984). The "dominant" fish in each hierarchy (which might include all the fish living in one particular pool) spends its life within a prescribed "home range", within which there may be a number of "foraging sites" which it may use at will at different times. The other trout in the hierarchy have to settle for sites which superior trout are not using at any given time. The overall dominant trout will pick any site it chooses, displacing by aggression any subordinate trout which may be using the site. Dominant trout do not tolerate other trout in front of them, so the hierarchy tends to be distributed in a linear manner downstream from the dominant fish. Therefore, as the dominant trout moves around, a jostling for positions between the various ranks of subordinates occurs as the different fish rearrange themselves according to the fluctuating circumstances (Bachman 1984, Jenkins 1969). This form of behaviour may still be expected to put a ceiling on numbers as Jenkins (1969) found that fish which he described as "transients", which belonged to no social structure, constantly moved around and normally came off worst in clashes with "resident" fish. Occasionally though, a persistent transient would manage to enter an established hierarchy.

3.2.4 The habitat "bottleneck"

At different stages in life, trout have different habitat requirements and so, particular habitats will be able to accommodate higher numbers of trout of a given life stage. Depending on the availability of different habitats, the potential for density-dependent mortality to operate will differ at different stages in life. For example, if there is abundant adult and spawning habitat in a stream, but little fry habitat, very high mortality could result at the fry stage with adult habitat ultimately being under used. If, on the other hand, there was abundant fry and juvenile habitat and little adult habitat, the former habitats may be under populated and density-dependent mortality may not even occur until the adult stage.

As an example of the first of these scenarios, Elliott (1994) described trout population changes in Black Brows Beck, a small stream in Cumbria. Typically, numbers of surviving trout in August/September of their first year of life increased as the initial egg deposition increased. However, an egg deposition of *ca.* 30 to 50 eggs/m^2 produced a survivor density of *ca* 2/m^2, but as initial egg densities increased thereafter the number of survivors fell, such that at egg depositions of *ca.* 120/m^2 numbers of survivors are just over 1/m^2. Thereafter losses are proportionate and density-dependent mortality no longer operates.

Illustrating another scenario, Crisp (1993b) found that, in some Pennine streams, while numbers of "swim-up" fry varied between 0 and 10/m^2, the number of survivors in August was always around 10% of the initial number. However, losses thereafter increased in proportion to the number of fish in August.

The concept of a habitat "bottleneck" is a critically important one to grasp. Thus, in any stream, the overall population size may be limited by the lack of habitat for one or more life stages while the habitat for other life stages may not be fully utilized. The concept illustrated in Fig. 3.2, and is a central concept in trout stream restoration.

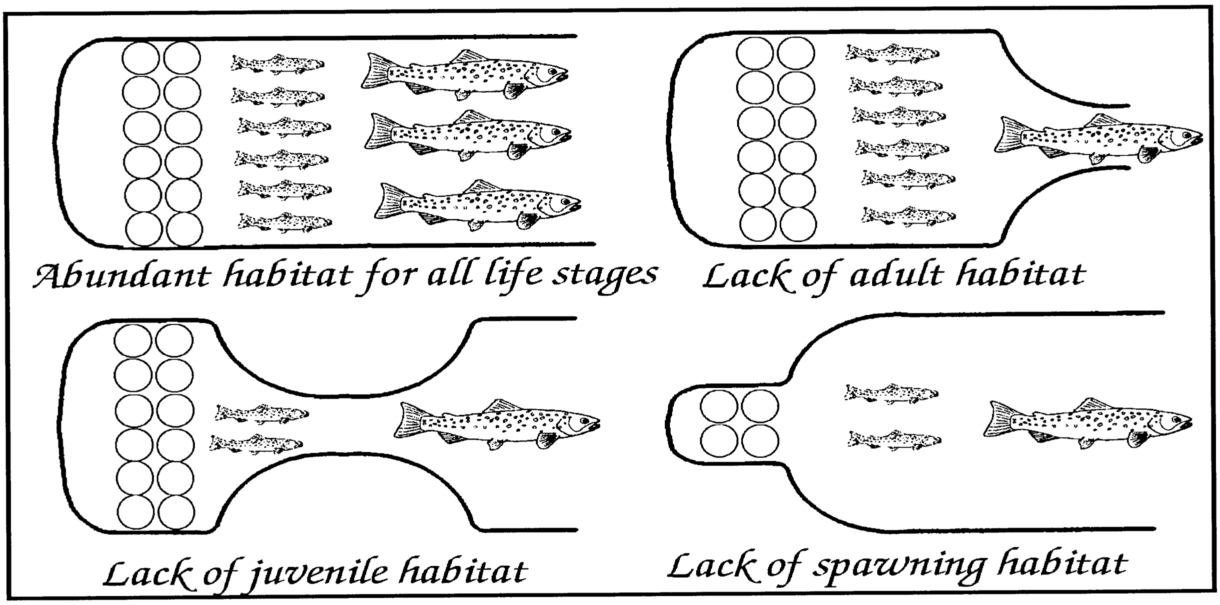


Figure 3.2 The concept of trout populations being constrained by habitat bottlenecks (Adapted from García de Jalón (1995))

3.3 Spawning Habitat Requirements

3.3.1 Introduction

The suitability of spawning habitat for brown trout is likely to depend on several major factors. The site must be accessible to adult trout, it must be suitable for trout to be physically able to spawn and it must also provide suitable conditions for the incubation of eggs. While the first of these is important, this manual is really only concerned with the latter two. This section describes the types of habitat which can be considered appropriate for spawning by satisfying these two requirements. However, in order to understand why certain habitats are required, it is firstly necessary to describe the various processes involved in spawning and the subsequent incubation. A summary of spawning habitat requirements is provided in Box 6.1.

3.3.2 The processes of spawning and incubation

The actions of spawning
Salmonid fish - that is trout, salmon and charr (*Salvelinus alpinus*) - spawn in late autumn/winter by excavating "redds", holes in gravel into which eggs are laid and fertilized. The excavation work is considered to be performed by the female, although there have been a few instances when males have been observed cutting redds (Crisp and Carling 1989). The female fish swims on her side, and by vigorous flexing of her body and tail, dislodges gravel into the water column which is then washed downstream by the current. A depression results in the streambed and the dislodged gravel accumulates below it. When the depression is deep enough, the female sheds her eggs and these are simultaneously fertilized by the male who releases a cloud of milt into the depression. The initially sticky fertilized eggs accumulate in crevices between large stones in the

base of the depression. The female then proceeds to cut into the gravel immediately upstream of the eggs, using silt-free material from a new excavation to infill the previously cut depression and cover the eggs. An individual redd may consist of a number of distinct pockets containing eggs as the female releases batches of eggs into each new depression created (Greeley 1932, Stuart 1953a, Jones and Ball 1954, Hardy 1963, Milner *et al.* 1981, Ottaway *et al.* 1981, Crisp and Carling 1989).

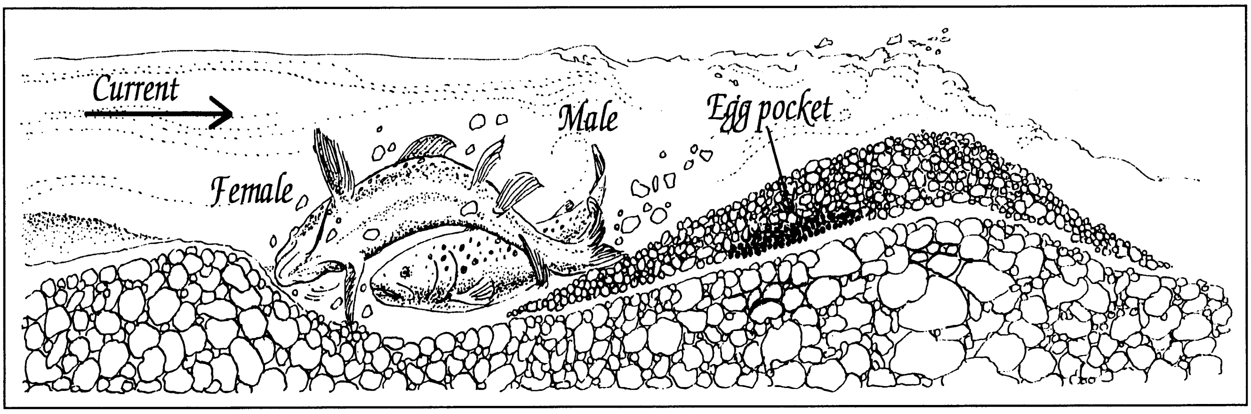


Figure 3.3 Trout spawning

Incubation of eggs and alevins

Once buried, the trout eggs require a continuous throughflow of water which contains dissolved oxygen (DO) and removes waste products such as ammonia. The rate at which development proceeds depends on temperatures experienced and levels of DO. Where DO levels are at saturation, hatching occurs after about 450 degree days. After hatching the little fish are known as alevins and, as yet, do not feed. A sac containing yolk is attached under their bodies and this is gradually absorbed. Full absorption occurs after about another 400 degree days. For more details see Crisp (1981) and Elliott (1994). The alevins continue to live under the gravel and are affected by similar environmental conditions as the eggs.

Much research has been performed on DO requirements of eggs and alevins of Pacific salmonids, though relatively little has been done for brown trout. Critical levels of DO are hard to ascertain since low DO levels, though not necessarily lethal, may have many subtle effects on the incubation process which can have ramifications later in life. Also, DO requirements vary with species, stage of embryonic development, initial size of the egg and water temperature (Alderdice *et al.* 1958, Silver *et al.* 1963, Shumway *et al.* 1964, Brannon 1965, Chapman 1988). From a critical review of the literature, Chapman (1988) recommended that, to be safe, any reduction in DO levels from saturation may reduce survival to emergence or even post emergence survival.

As the yolk sac is used up, the alevins wriggle upwards through the gravel to emerge at the surface. In order for this to be possible, the gravel must contain clear interstices. If, for example, there is a large amount of fine sediment amongst the gravel the fry may not be able to wriggle out (see Chapman 1988 for a review). Bams (1969) found that sockeye (*Oncorhynchus nerka*) alevins "butted" blockages of sand in order to create a free passage and Crisp (1993a) found that brown trout alevins could push through an 8 cm thick sand barrier.

3.3.3 Suitable sites for redd construction

The most important determinant whether a trout can spawn at a given site is whether the gravel is small enough and loose enough for a trout to dislodge it and the current fast enough to then displace it downstream. Thus, many studies have tried to quantify water velocities, depths and substrate sizes at spawning sites. These are summarized in Box 3.1.

Water velocity and depth
It can be seen that the reported range is wide for all these parameters (Box 3.1). Mean water column velocities are quoted between 15 cm/s and 95 cm/s, with most between *ca.* 20 cm/s to 40 cm/s. The depth of water is also variable with even the averages quoted by the various studies varying from about 15 cm to 50 cm.

Box 3.1. Characteristics of brown trout spawning habitat

	water velocities	**water depth**	**substrate size**
1	15-20cm/s up to twice female body length in cm/s	variable but not less than body depth	coarse sands to cobbles but median grain size 10 to 20 mm
2	mean - 39.4 cm/s	mean - 31 cm	mean 14 mm
3	generally > 30 cm/s	mean - 25.5 cm	mean 6.9 mm
4	20 to 60 cm/s	20 to 50 cm	-
5	35 to 95 cm/s	18 to 46 cm	-
6	24 to 37 cm/s	12 to 18 cm	26 to 75 mm
7	30 to 40 cm/s		mean ranging from 10 to over 100 mm, commonly about 80 mm
8	20 to 70 cm/s	over 20 cm	0.75 to 7.5 cm

1 - Crisp and Carling (1989) (also includes Atlantic salmon), 2 - Shirvell and Dungey (1983), 3 - Witzel and MacCrimmon (1983), 4 - Johnson *et al.* (1995), 5 - Nelson (1986), 6 - Grost *et al.* (1990), 7 - Ottaway *et al.* (1981), 8 - Raleigh *et al.* (1986).

Substrate
Reported substrate sizes range from coarse sands to cobbles greater than 100 mm diameter (Box 3.1). This wide range of was recognized by Ottaway *et al.* (1981) who considered that, in practice, trout would spawn wherever they could physically move the gravel. Assuming velocities are of the correct order to move dislodged gravel, gravels will only be unsuitable if they are too big or compacted because of the degree of angularlity, sorting of sizes, sedimentation, lime concretion, binding by roots etc.

Unfortunately, there is little guidance in the literature to objectively assess how loose gravel needs to be. Indeed, if it is too loose and unstable trout may equally avoid it. From the authors' experience, trout may spawn in a wide range of gravel types, even when considerable pressure is required to dislodge the surface gravel with a boot. However, it is not known if such conditions are preferred or not.

3.3.4 Suitable sites for incubation

Whilst trout may be able to spawn in a wide range of substrate types/velocities, site selection may be narrowed in a particular stream because the site must also be suitable for the incubation of eggs. Several factors may be important in this respect. Unfortunately none of these can readily be quantified but their potential effects need to be recognized.

Substrate composition
The composition of the substrate may be important for the successful incubation of eggs. This is because the substrate type influences the rate of intragravel flow, which in turn influences the residence time of intragravel water and so the level of DO. Many studies have shown that substrates which permit a poor throughflow of water (usually attributed to a high content of fine sediment, compaction, shape of particles) result in low embryonic survival (McNeil and Ahnell 1964, Hausle and Coble 1976, Turnpenny and Williams 1980, Witzel and MacCrimmon 1983, Olson and Persson 1986, Maret *et al.* 1993). Increasing the proportion of fine sediments within a gravel framework containing eggs has been shown to have a deleterious effect on permeability and embryo survival (e.g. Hall and Lantz 1969, Phillips *et al.* 1975, Hausle and Coble 1976,). For example, Hall and Lantz (1969) found that the survival of coho salmon (*Oncorhynchus kisutch*) embryos decreased from about 75% when the proportion of fines less than 0.83mm by volume was about 15% to almost zero when fines reached 30%. However, it has proven difficult to arrive at more than general conclusions about the quantities of fine sediment which are damaging (Everest *et al.* 1982). This is because a measure of percentage of fines does not take into account the amount of void space between the larger gravels which will in turn vary according to the size and shape of gravel particles.

A major problem in extrapolating from the experimental studies cited above occurs because the actual process of redd construction alters the substrate in a manner so as to increase the porosity. It has been found that both small and large salmonids winnow fine sediment from the gravel during excavation and, in areas where salmonids regularly spawn in high numbers, the substrate may be maintained in a "cleaner" condition than nearby unused areas (McNeil and Ahnel 1964, Everest *et al.* 1987, Chapman 1988, Ringler and Hall 1988, Young *et al.* 1989). If the gravel is not cleaned, it will at least be loosened which will increase its porosity (Crisp and Carling 1989). A number of studies have stressed the potential importance of the hydraulic properties of the "egg pocket" in that permeabilities and cleanness can be much higher than even those close by within the redd tail (Chapman 1988, Young *et al.* 1989, Rubin 1995). Therefore, it appears that even if the surrounding gravel is clogged with silt, conditions for incubation may be considerably better within the actual redd. As a consequence of this, no good information exists on how clean riverbed gravels need to be for successful spawning and incubation.

Infiltration of sediment into redds

Although redd construction may improve conditions for incubation, fine sediment can re-infiltrate into redds post-spawning (Beschta and Jackson 1979, Carling 1984, Frostick *et al.* 1984, Lisle 1989, Havis *et al.* 1993, Sear 1993). It has been found that, the finer the sediment, the easier it will penetrate "clean" gravel (Beschta and Jackson 1979). Very fine sediment tends to fill a clean gravel matrix from the bottom upwards (Beschta and Jackson 1979, Carling 1984, Alonso *et al.* 1988), but coarse sand may penetrate a short way into a gravel matrix and lodge, forming a partial seal which prevents the intrusion of further sand or finer particles (Koski 1975, Beschta and Jackson 1979). Beschta and Jackson (1979) considered that the settling of fines within the gravel was primarily under gravitational influence, but the rate of intrusion increased with water velocity above. Sear (1993) found that the depth of penetration by fines was related to discharge, so a shallow redd (e.g. a brown trout redd) is more likely to silt up under lower current velocities than a deep redd (e.g. a salmon redd). However, silt and fine sand may, therefore, be drawn down into a redd even though high surface velocities prevent surface deposition and it appears that the stream bed surface is sediment free (Cooper 1965). Carling (1984) found that the rate of deposition of fines in gravel is related to the concentration of such sediment in the river but that well sorted gravel was so efficient at trapping fine sediment, that even at low concentrations, such gravels are liable to "silt up" rapidly.

Unfortunately, there is little information to explain to what extent gravels in different rivers, or even in different parts of a river, are likely to silt up. It is only possible to give very general advice in that silt-free rivers are likely to provide good conditions for incubation but ones containing substantial loads of fine sands (less than at least 0.83 mm diameter), silts or clays, but lacking in coarse sands, may have problems with redd siltation. Thus, rivers flowing off hard crystalline rocks like granite, schist or gneiss may be unlikely to have problems, but clays, chalk, shale, or any other rock which readily weathers to clay, may potentially be bad. Consequently, sedimentation would be unlikely to a problem in the northern highlands of Scotland but may be widespread on the sedimentary rocks of lowland England. Indeed, this has been found to be a real problem on southern chalk rivers (Scott 1994, Summers and Giles 1995).

Riverbed hydraulics

One potential indicator of the likelihood of redd siltation relates to the actual hydraulic conditions within the redd. As will be described presently, in some parts of streams, water may penetrate into the gravel and at other places intragravel or groundwater may be upwelling to the surface. Depending on whether water is downwelling or upwelling through a redd, sedimentation may be promoted or prevented. It has been considered from anecdotal evidence that brown trout in English chalk streams may select areas of rising springs for this reason (e.g. Sawyer 1952). In North America, it has been demonstrated that brook trout (*Salvelinus fontinalis*) do actually seek out sites where there is upwelling of groundwater (Greeley 1932, Benson 1953, Hale and Hilden 1969, Webster and Eiriksdottir 1976, Witzel and MacCrimmon 1983) as may also several species of Pacific salmon (Leman 1989). However, chinook salmon (*Oncorhynchus tschawytscha*) spawn where river water penetrates into the gravel (Leman 1989).

Stuart (1953a) also found that brown trout tended to spawn where stream water was downwelling into the gravel. In addition, a number of studies in North America have found that brown trout appear to have no affinity for areas of rising groundwater (Hansen 1975, Witzel and MacCrimmon 1983, Beard and Carline 1991). For example, Hansen (1975) found that brown trout spawned in areas where there was either no groundwater or where there was a groundwater/river water mix, but avoided pure groundwater. Therefore, the spawning of brown trout over upwelling groundwater has still to be confirmed in Britain.

Conclusions

Whilst it is undoubtedly the case that egg incubation success is dependent on physical habitat characteristics, recommendations regarding the identification of suitable sites can only be very general. It may be expected that gravel sites in rivers which are silt-free may be suitable for incubation, but in rivers carrying a significant fines load, gravel of the correct size for spawning with suitable water velocities may still be prone to silting up and this cannot be readily predicted. Major research is still required to produce guidelines to predict the likelihood of spawning and incubation success in a given river.

3.3.5 The location of spawning habitats within the riverine system

The previous sections described the micro-features of spawning habitats. However, these particular microhabitats can often be found in specific areas within streams.

Alluvial Streams

Classically, in alluvial streams, salmonids are claimed to spawn where the stream bed rises at the tails of pools as the water spills over into riffles (Stuart 1953a, 1954, Crisp and Carling 1989). At such a point the difference in hydraulic head between the pool above and the riffle below causes water to be drawn down into the bed to upwell again in the lower riffle (Stuart 1953a, 1954, Vaux 1968), hence the existence of pool-riffle sequences is considered important for salmonid spawning. Even the form of a redd - a convex pile of gravel - is claimed to induce drawdown into it (Vaux 1968).

Erosive streams

In rocky upland streams where there are often no pool-riffle sequences, redds cannot be located in the places described above (Ottaway *et al.* 1981). Those authors considered trout would spawn on any areas of gravel where they could physically move the gravel. Also it is considered that in an upland stream, the first spate would flatten out a redd, so its shape would be of little importance in inducing drawdown (Ottaway *et al.* 1981*)*.

Stream size

In Britain, it appears that trout generally spawn in small streams. Although large trout live in large rivers, they may not actually spawn there. For example, Bembo (1992) and Bembo *et al.* (1993) found that in the River Usk, Wales, brown trout spawning largely took place in streams less than 2.75 m wide with 0+ trout being practically absent from the main river. In a survey of 150 streams ranging from *ca.* two to 20 m wide in the River Tweed catchment, Gardiner (1989) found that 0+ trout densities were highest in the smallest streams with practically none in streams wider than 10 m. In the catchment of the River Ugie, Aberdeenshire, Summers (1991, 1992) found that 0+ aged trout were practically restricted to streams less than about five or six metres wide. Such a concentration of spawning within the tributaries has also been found on the River Don, Aberdeenshire, (Shields 1996), the River Scorff, Brittany (Maisse and Baglinière 1990) and in the River Tees (Crisp *et al.* 1974). As a further indication of how small a stream trout may spawn in, Black Brows Beck, a widely studied sea trout nursery stream in Cumbria only averages 0.8 m wide (Elliott 1994) and the highest density of 0+ trout found in the River Ugie catchment in 1992 was in a stream only 0.46 m wide (Summers 1992).

However, the above examples generally come from areas with a moderate to high gradient. The authors have observed brown trout spawning successfully in chalk streams between five and ten metres wide (e.g. the River Piddle, Dorset and the River Till, Wiltshire) and similarly sized limestone streams in the Cotswold area (e.g. the rivers Avon, Coln and Windrush). Wheeler (1993) also reported wild trout spawning on a stretch of the River Itchen, Hampshire, which is over ten metres wide. Therefore, the significance of stream size may depend on the nature of the stream. In upland streams it may, in part, reflect a lack of suitable spawning areas in large rivers - currents may be too fast and substrates too coarse. Though this may be the case in some rivers, there may be other explanations, for example, velocities may often be too high for trout fry in large rivers, as will be described presently.

3.4 Limitations on knowledge of habitat requirements of free swimming trout

3.4.1 Introduction

Providing general quantitative definitions of what constitutes good habitat for trout has not proved easy (Heggenes 1988b). There are a number of factors which make detailed description of trout habitat difficult and this applies to trout at all stages in life. Before describing what can confidently be concluded for trout of different life stages, the sources of difficulty are described as follows.

3.4.2 Differences in stream type

As has been mentioned previously, trout can live successfully in widely differing riverine environments ranging from placid chalk streams to turbulent mountain rivers. The features of habitat which trout use therefore vary from stream to stream. Numerous studies have tried to describe trout habitat with quantifiable parameters and, not surprisingly, the results have shown considerable variation (Heggenes 1988b). While suitable habitats may be definable in particular stream types, there has, as yet, been little attempt to characterize habitat types in this way.

3.4.3 Interactions between habitat parameters

While it has been usual for studies to try to separate the effects of different quantifiable habitat parameters (e.g. current speed, depth, type of substrate etc.), in fact, their effects on trout may not be independent of each other. For example, in a given stream, current speed, depth and substrate type are all related, and so, selection by trout of only one of these factors could mean that trout appear to select them all. To further complicate matters, these complex interrelationships will also vary between stream types.

3.4.4 Influence of competition and predation

Whilst trout may intrinsically prefer certain types of habitat, they may often be forced to utilize less favourable types, and so it is not always clear that observed habitat use reflects the optimum choice. For example, fry may be forced into the shallowest water by older trout or even other very dominant fry (White and Hunt 1969, Bohlin 1977, 1978, Gosse and Helm 1982), pike (Greenberg 1993) or avian predators (Bugert and Bjornn 1991). Movements at night of young trout into shallower water or out of crevices in the substrate are considered to be a probable response to a daytime predation threat (Campbell and Neuner 1985, Griffith and Smith 1993).

3.4.5 Differences in habitat use with age

As trout grow, their habitat requirements gradually change. Comparability in the reported results from different studies depends on definitions of different life-stages being similar. This is perhaps most important in the first summer as the fish are growing stronger. For example, Harris *et al.* (1992) found that 0+ brown trout were able to cope better with the more general depths and current speeds in a stream in July even than in June.

3.4.6 Conclusions

Given that empirical data on trout habitat use contains so much variation as to make the prediction of suitable habitat difficult in all stream types, an alternative approach is used in the remainder of this chapter. This involves considering what trout actually require from their environment and then using this information to predict which habitat types will be able to provide for these needs in any type of stream. It is accepted that knowledge of what trout require is also imperfect, but a number of conclusions can be made.

3.5 The habitat requirements of trout fry

3.5.1 The requirements of trout fry from their environment

Behaviour after emergence
Trout fry emerge from the gravel under the cover of darkness, usually in the early part of the night. The immediate reaction on leaving the gravel is either to actively swim downstream or be drifted downstream (Moore and Scott 1988). On settling in a relatively sheltered position, they commence feeding, which they do in a "sit-and-wait" lifestyle. They maintain a position in the stream by swimming into the current a centimetre or two above the bed (Le Cren 1973) and pick off invertebrates which drift downstream.

The need for low current speeds
Newly emergent trout fry are not powerful swimmers. They cease to be able to hold station in current speeds near the bed over about 10 cm/s, this value increasing somewhat at higher

temperatures (Heggenes and Traaen 1988, Crisp and Hurley 1991). As they get older they become more powerful swimmers, and by 8 weeks, have been shown in experimental conditions to be at least physically capable of holding station in currents of 50 cm/s (Heggenes and Traaen 1988), although reported observations in the wild are considerably less (e.g. Bird *et al.* 1995). Trout fry actively try to avoid high current speeds by positioning closer to the bed or seeking low velocity niches at higher mean water column velocities (Kalleberg 1958, Heggenes and Traaen 1988, Bird *et al.* 1995).

The need for low current speeds immediately places constraints on the habitats which can be used by trout fry. These are areas where either mean water column speeds are low or where bed roughness and vegetation creates pockets of slack water. Heggenes (1988b) considered that shelter from stones etc. may be essential for fry to get out of the current.

Feeding opportunities

The quantity of drifting invertebrates, and therefore food availability for trout fry, which pass a given spot is related to the current speed (Elliott 1967). However, energy expenditure by trout is higher at increasing current speeds. Therefore, within the speed range with which fry can cope, the best feeding sites may be the least energetically efficient. The optimum feeding sites for salmonids are those where energy expenditure is lowest relative to energy gain (Fausch 1984). These are sites where there is a large velocity differential over a distance of about two body lengths (Fausch and White 1981, Fausch 1984) - i.e. pockets of slow water in close proximity to a strong flow. This is true for all life stages of stream salmonids (Bachman 1984, Fausch 1984), but trout fry being the weakest swimmers, will seek the slowest (i.e. most sheltered) sites of all.

Bearing in mind that the data do not take account of stream type, examples of mean water column current velocities reported in different studies are given in Box 3.2 and a further summary is provided in Box 6.2. A wide range of mean velocities is reported, from 0 to 40 cm/s, although most report under 30 cm/s.

Depth of water

It is commonly found in studies that trout fry are associated with relatively shallow water compared to older trout (Heggenes 1988b). However, it is not known whether particular depths confer advantages to fry (e.g. more efficient feeding) or other factors like reduced interaction and predation by larger fish, or whether deep water is associated with some other habitat factor which is not preferred.

Again, bearing in mind the applicability of the data, examples of depths used by fry reported in different studies are given in Box 3.2 with a further summary in Box 6.2. These studies suggest that fry can be found in anything from less than 10 cm deep to up to 60 cm deep, although most seem to suggest depths less than 30 cm.

Protection from danger

All trout, including fry, require shelter from danger. This is generally termed “cover”. For example, Lambert and Hanson (1989) found that 0+ brown trout rarely were observed more than 90 cm from some sort of cover. Grant and Noakes (1987) found that brook trout fry were also more easily frightened with increasing distance from cover. As well as affording a hiding place from predators, cover will also provide protection from the current and visual isolation from other fry.

Box 3.2. Habitat requirements of brown trout fry

		Water Depth	Mean Water Column Velocity
Balgliniere and Champigneulle (1982)		10 to 40 cm	-
Belaud *et al.* (1989)		15 to 30 cm	0 to 30 cm/s
Bird *et al.* (1995)		mean 38 cm	mean 41 cm/s
Bovee (1978)		<60 cm	0 to 40 cm/s
Harris *et al.* (1992)	June, by day	6 to 18 cm	0 cm/s, rarely > 6 cm/s
	June, by night	3 to 10 cm	0 cm/s, rarely > 6 cm/s
	July, by day	6 to 18 cm	0 to 12 cm/s
	July, by night	3 to 10 cm	0 cm/s, rarely much higher
Heggenes (1988b)		10 to 20 cm	-
Kennedy and Strange (1982)		<20 cm	-
Loar (1985)		<40 cm	0 to 20 cm/s
Larsen (1972)		>10 cm	-
Lambert and Hanson (1989)		<60 cm	<30 cm/s
Raleigh *et al.* (1986)		30 to 60 cm	6 to 30 cm/s

A number of different types of cover have been reported. For example, Heggenes (1988a) found that fry would shelter in the interstices amongst coarse gravel (50 mm diameter or greater) where there is little fine sediment in the voids. These gravels were preferred to the finer gravels normally used for spawning. Griffith and Smith (1993) also found that during the winter in a big river, 0+ brown trout hid amongst boulder substrates within a metre of the bank where the water was relatively shallow (less than 50 cm) and the current slowest, but not if the boulders were embedded in silt. Some of these emerged at night to feed, by holding station in the slow current. Heggenes and Saltveit (1990) reported brown trout hiding in the substrate in winter in a Norwegian stream, as have workers in other areas (Heggenes 1988b).

Kelly-Quinn and Bracken (1988) found that densities of trout fry were highest where there was a complex substrate. Moore and Gregory (1988) found that densities of cutthroat trout

(*Oncorhynchus clarki)* fry in shallow river margin areas were related to the amount of cover provided by stones and debris, while Mortensen (1977b) reported that in a Danish stream the dredging of plants reduced numbers of 0+ trout. The cover value of aquatic plants was also noted by Bird *et al.* (1995). The use of submerged marginal (grasses and branches of trees) and emergent vegetation has also been widely observed by the present authors.

In summary, trout fry have been reported sheltering in any form of crevice into which they can get. Cover can be provided by many things, but some types of cover will probably afford better protection than others. Plants, for example, may only provide seasonal cover. However, there is a lack of detailed information to be more specific.

Conclusions
Trout fry need areas of low current velocities near the stream bed with nearby cover from either stones, debris or plants. As bed velocities are influenced by features which also provide cover, increasing amounts of cover over what is necessary for protection will provide even more habitat at higher mean current velocities. However, the items providing cover should not be so large as to provide cover for juvenile or adult trout as these may displace fry.

3.5.2 Relating habitat needs to stream type

Introduction
Having described the basic needs of trout fry this section describes what is known about where these habitats are known to occur in different stream types. While it is accepted that there has been a lack of such work, some important distinctions can be made.

Stream size
Most descriptions of trout fry habitat have been based on streams not more than a few metres wide (e.g. Bohlin 1977, Egglishaw and Shackley 1982, Kennedy and Strange 1982, Elliott 1994). Characteristically, fry are normally observed in riffles or shallower areas of such streams. However, Bohlin (1977) found that they preferred to use “pools” in a stream tank in the absence of older trout. Therefore, in small streams where 1+ year old trout are also present, fry may actually be forced to live in areas with higher than preferred mean velocities.

Relatively, little information is available from larger rivers, but Lindroth (1955) reported fry occupying shallow marginal areas. Moore and Gregory (1988) also found that the fry of cutthroat trout could live in such slack water areas in large rivers. They also showed that increasing substrate complexity in such areas increased fry numbers. Therefore, in contrast to small streams, trout fry will be restricted to the slowest areas in big rivers. Indeed, it has been widely found that trout recruitment largely takes place in small tributaries, at least in moderate to high gradient streams, although more widespread recruitment has been observed in lower powered chalk streams (Section 3.3). Of course, it cannot necessarily be concluded that it is fry habitat which is limiting in all these instances.

Locations relative to spawning habitat
Of course, whether potential fry habitat is used or not does depend on the existence of spawning habitat within the distance which fry can disperse from redds. A dispersal of up to several hundred metres has been reported for both trout and salmon within the first few weeks but then

slows down (Le Cren 1973, Mortensen 1977a, Egglishaw and Shackley 1980). However, even then, the distribution of fry can still be quite clumped, and conditions within the crowded areas may lead to high mortalities (Elliott 1986), whilst those fry which disperse into underpopulated areas can experience better survival and growth rates (Egglishaw and Shackley 1980, Kennedy 1988). Therefore, some studies suggest that immediate post-emergence dispersal appears insufficient to achieve the highest possible survival rates. However, other studies find some dispersal of viable 0+ trout occurring throughout the summer (Solomon and Templeton 1976, Milner *et al.* 1979, Kelly-Quinn and Bracken 1988, Mann *et al.* 1989, Crisp 1993b). Nevertheless, it is probably safest to assume that dispersed spawning habitat is to be preferred for most effectively populating a stream.

Conclusions
Practical conclusions on potential trout fry habitat are that fry seem to be largely restricted to smaller streams or to shallow river margins and live where physical protection from the current and predators allows. However, even then, some of this habitat may be unused because of a lack of nearby spawning habitat or the suppression of fry numbers by older trout.

3.6 Habitat Requirements of Juvenile Trout

3.6.1 The requirements of juvenile trout from their environment

Introduction
The distinctions made here between fry and juveniles, and indeed adults, are somewhat arbitrary. The requirements of trout change gradually as they grow, so the following details are generalizations.

Feeding opportunities
As with fry, juvenile trout continue to seek areas of low current speed near a faster main current. Juvenile trout are capable of utilizing a much greater range of current speeds than fry, but reported snout velocities are still low, though variable. For example, Heggenes and Saltveit (1990) reported 5 to 10 cm/s, while Bird *et al.* (1995) reported a mean snout velocity of 21 cm/s. Juvenile trout have been observed to remain near the bottom of the water column, though further off the bed than fry (Blades and Vincent 1969, Bird *et al.* 1995).

Mean current speeds reported in various studies are shown in Box 3.3. The range is greater than that reported for fry, being from 0 to 60 cm/s, although speeds in the lower part of the range are most commonly reported.

Objects in the stream which provide protection from the current and also cause the current to be concentrated in specific zones, thereby improving feeding niches, are still sought (Blades and Vincent 1969, Heggenes 1988b, Rincón and Lobón-Cerriá 1993). These consist of stones, woody debris and plants. However, it may be possible to have too much obstruction to flow. For example, prolific plant growth can choke a channel, leaving no open water (Seymour 1970). In such circumstances low velocities result, and fine sediments deposit on the stream bed. Such conditions are not ideal for a drift feeder like the brown trout. Selective weed-cutting becomes an important habitat management technique under such circumstances.

Depth of water

Generally, it is stated that trout progressively move into deeper water as they get bigger (Solomon and Templeton 1976, Elliott 1984, 1986, Cunjak and Power 1986). However, as with mean current speeds, there is considerable variation in the depths reported for juvenile trout. Those around 30 cm are commonly reported as most preferred, but they may exceed 60 cm (Box 3.3).

Protection from danger

As for fry, shelter is important for older trout to dart into if danger threatens (Boussu 1954, Lewis 1969, Hermansen and Krog 1984, Wesche *et al.* 1987, Heggenes 1988b). This is true for both juveniles and adults. However, as they get larger, trout may venture farther from cover. For example, Lambert and Hanson (1989) found that although fry scarcely strayed more than 90 cm from cover, juvenile and adult ventured as far as 3 m. However, distinctions are seldom made between juvenile and adult trout in studies. Therefore, the remainder of this section on cover refers to both juvenile and adult trout.

Cover essentially takes two forms; bankside and instream.

Box 3.3. Habitats used by juvenile trout

	water depth	**mean water column velocity**
Belaud *et al.* (1989)	about 30 cm	<40 cm/s but 0 cm/s most preferred
Bird *et al.* (1995)	mean 42 cm	mean 38 cm/s
Bovee (1978)	<90 cm	<50 cm/s, but about 0 to 10 cm/s most preferred.
Heggenes and Saltveit (1990)	30 to 60 cm	5 to 30 cm/s, snout velocity, 5 to 10 cm/s.
Johnson *et al.* (1995)	25 to 55 cm	15 to 60 cm/s
Loar (1985)	about 30 cm	<30 cm/s but 0cm/s most preferred
Moyle et al. (1983)	about 30 cm	0 to 50 cm/s
Shuler *et al.* (1994)	27 to 57 cm	9 to 45 cm/s by day but 3 to 45 cm/s at night.

Bankside cover

Some studies have found that the most important types of cover for trout take the form of undercut banks, tree roots or low dense riparian vegetation (e.g. low growing shrubs, bushes, tall grasses or invasive emergents) which drapes some way onto or below the water surface. The value of this has been shown by Boussu (1954) and Wesche *et al.* (1987). Bankside cover was also found by Lewis (1969) to be an important determinant in whether trout occupied a particular pool or not. Its importance was also emphasised for brook trout by Binns (1994), who found that they packed into pools during droughts, but only those ones which had good cover.

In a narrow deep channel, shade alone may constitute cover (Hermansen and Krog 1984) and if proper cover is denied, adult trout will still seek shade (Baldes and Vincent 1969). Even when cover is available, trout will utilize the most shaded area (Butler and Hawthorne 1968). As well as shelter, some degree of shade may make feeding stations more attractive. Fausch and White (1981) found that brook trout tended to feed in shaded or indirectly lit positions, perhaps because it was easier to see drifting food and Gosse and Helm (1982) found that brown trout like to lie in highly shaded areas adjacent to areas of high light intensity. However, an important point is that shading by tall trees is often not beneficial to the overall trout population because instream plants and lower growing vegetation which provide direct physical shelter are suppressed. For example, O' Grady (1993) found that numbers of trout in tree lined sections of Irish streams averaged 28.5% of those in adjacent open sections.

Bankside cover is essentially required as a refuge both from predation and, in some situations, excess current speeds. Bachman (1984) found that trout did not display aggressive behaviour when hiding. Therefore, although cover is very important, it may only be necessary up to a certain degree, with greater amounts bringing no additional benefit. This was demonstrated by the example of Hartzler (1983) who installed extra cover in a stream which already had a lot of cover but found that trout numbers did not increase.

Instream cover

Although the use of bankside cover is widely reported, juvenile and adult trout have also been reported to seek the protection afforded by stream bed objects. These include rocks, boulders, woody debris and submerged macrophytes (Boussu 1954, Belaud *et al.* 1989, Shuler *et al.* 1994).

3.6.2 Relating habitat needs to stream type

Stream size

The requirements of relatively shallow depth and low current speeds, coupled with abundant cover, mean that in different types of stream, different habitats are used. It is frequently stated that trout parr live in relatively slow, pool and glide habitats with abundant cover (Jones 1975, Bohlin 1977, Kennedy and Strange 1982, Heggenes and Saltveit 1990). This is true in small streams where pool depths may be less than *ca.* 60 cm, but is not applicable in large rivers where pools are deeper and swift. In large Swedish rivers, Lindroth (1955) and Karlstrom (1977) found that trout parr were restricted to shallower margins. Therefore, in streams of a certain but undefined size, juvenile habitat may be the dominant habitat, whilst in large powerful rivers the abundance of juvenile habitat may be limited and only adult trout can cope with conditions.

The need for bankside cover has also been found to depend on stream size. It is most critical in small streams, as water depth in itself provides cover in larger streams. For example, Wesche *et al.* (1987) found that cover was a necessity in streams with an average discharge less than 2.75

m^3/s, but was not so important in larger streams. Fortunately, however, smaller streams do tend to have a higher relative degree of bankside cover than larger streams. This is because, the smaller the stream, the greater the ratio of depth to width tends to be (Kozel and Hubert 1989). Therefore, small streams do potentially make good trout habitat (Hunt 1971). It follows from this that instream cover in the form of boulders and plants is likely to be more important in wide streams, as the ratio of open stream habitat to undercut bank increases in these waters.

Stream gradient

Important distinctions can also be made between small streams of different types. Upland streams are often subject to spates and droughts and are not highly biologically productive (Crisp *et al.* 1984). The most productive trout streams appear to be those with a lesser gradient. For example, in the Rocky Mountains, Lanka *et al.* (1987) found that the highest trout biomass occurred in smaller streams at the transition zone between boulder beds and lower gradient gravel beds. Kozel *et al.* (1989) also found that channels with a gradient of between 0.1 and 1.4% were narrower, deeper, had steeper banks and more overhanging vegetation than streams with a gradient between 1.5 and 4%. The latter type of stream could only hold small trout, but the former could also hold large trout because of the presence of deeper pools. Similar findings were also made by Larscheid and Hubert (1992), who concluded that streams flowing across "meadow" land were best for brown trout.

In forested streams, debris in the form of tree trunks and branches has the effect of producing a step-like stream profile with impoundments and plunge pools. In high gradient streams these slower areas created by woody debris are often the only places where juvenile trout are likely to occur (Platts 1991).

Relationships with other habitat types

In order for a habitat to be populated with juvenile trout, there must also be spawning and fry habitat in the locality. So, while some habitat for juvenile trout may be found throughout a catchment, small streams, where spawning often takes place, seem to have a disproportionate importance. However, in different river systems, the nature and distribution of such streams can vary. As a result, the availability of nursery streams of adequate quality could be a major limiting factor on trout numbers in large rivers. A river with many small tributaries may be more productive of juveniles than one which has few small tributaries.

Although much juvenile production may take place in small streams, they do not always contain habitat to allow trout to grow on. Several studies have found that brown trout make directed migrations, often in the spring, out of such streams when they are about 15 cm long (Needham and Cramer 1943, Solomon and Templeton 1976, Milner *et al.* 1979, Bembo *et al.* 1993, Shields 1996). Whilst many trout may emigrate from nursery streams into larger receiving watercourses in the spring, those trout which are to become sea trout will undergo the smolting process at this time and migrate to sea. Up until the time they leave the nursery streams the habitat requirements of those trout which will go to sea appear to be identical to those for juvenile "brown" trout.

3.7 Habitat Requirements of Adult Trout

3.7.1 The requirements of adult trout from their environment

Feeding opportunities

Like fry and juveniles, adult brown trout typically hold a station in an area of low current speed and feed on invertebrates which drift downstream in a nearby zone of faster water (Bachman 1984). The need to lie in a low velocity zone was stressed by Shirvell and Dungey (1983) and Bachman (1984), but there is considerable reported variation in these velocities. Bachman (1984) reported an average of around 8 cm/s, Baldes and Vincent (1969) 12 to 21 cm/s with Shirvell and Dungey (1983) reporting a mean of 26.7 cm/s. Some of this variation may be due to the larger size of trout observed by Shirvell and Dungey (1983). Baldes and Vincent (1969) also found that trout avoided turbulent water near the bed.

Mean water column velocities reported from different studies range from less than 10 cm/s to over 80 cm/s (Box 3.4), but, again, most are at the lower end. Objects, such as rocks and plants, which create current speed differentials have also been found to be important (Heggenes 1988b).

Box 3.4. Habitats used by adult trout

	Water depth	**Water velocity**
Bachman (1984)		snout vel. *ca.* 8 cm/s, surface vel. 60 to 70 cm/s
Baldes and Vincent (1969)		bed vel. 12 to 21 cm/s
Belaud *et al.* (1989)	30 to 60 cm	mean <40 cm/s, but <10 cm/s most preferred
Bovee (1978)	> about 60 cm	mean <40 cm/s
Gosse et al. (1977)	60 to 120 cm	mean 6 to 50 cm/s
Johnson *et al.* (1995)	40 to 60 cm	mean 10 to 30 cm/s
Loar (1985)	20 to 40 cm	mean < about 25 cm/s
Shirvell and Dungey (1983)	mean 65 cm	mean snout vel. 26.7 cm/s
Shuler *et al.* (1994)	33 to 69 cm	mean vels. 21 to 63 cm/s by day and 21 to 83 cm/s by night

While drift feeding is cited as typical trout behaviour, some environments produce large trout (over about 40 cm) which lead relatively solitary, roving lives. Such fish are thought to be principally piscivorous (Clapp *et al.* 1990, Jenkins 1969). They may have home ranges of several kilometres, and although using regular daytime hiding sites, emerge at night and range about in various habitat types from shallow riffles to deep pools and side channels. One such fish was found to venture as much as 1.5 km from its lair returning by morning (Clapp *et al.* 1990).

Depth of water
Adult trout are typically associated with deeper water than fry or parr (Heggenes 1988b). Depths reported are presented in Box 3.4, and a summary is presented in Box 6.4. These fall within a considerable range, being from 30 cm to over 100 cm.

Protection from danger
For all trout, cover is an important habitat requirement. While older trout may feed at a greater distance from cover than younger trout (Lambert and Hanson 1989), and it has also been found that the older the trout the more of the daytime it spends under cover (Bachman 1984, Clapp *et al.* 1990).

Those factors which can provide cover are described in detail in Section 3.6.1 and are not repeated here. However, a distinction will be that a larger niche is required by larger trout. Thus it has been found that, although substrate type is important for fry, it seems to matter relatively little for large trout (Gosse and Helm 1982, Rincón and Lobón-Cerriá 1993). For example, Clapp *et al.* (1990) found that large brown trout (over 40 cm long) "preferred" to lie over silty sediment. In this instance the trout lay in well sheltered refuge areas which were probably selected for their cover value whilst substrate type probably happened to be coincidental. However, it may be that the cited studies only took place on streams which lack really coarse substrate material (e.g. boulders) which could be important in some instances.

Conclusions
Adult trout have been found to live in a wide range of habitats, so long as current speeds near the stream bed are less than about 30 cm/s, with the depth being over 30 cm and the presence of nearby cover.

3.7.2 Relating habitat needs to stream type

Stream size
Adult trout can be found practically throughout a river system. While, it has frequently been reported that trout recruitment is restricted to smaller streams, with adult habitat further downriver (Section 3.6.2), some adult trout can survive in even the smallest of streams (e.g. Wilfin Beck in Cumbria (Elliott 1994)).

However, differences in habitat use are apparent between small and large streams. Deeper pools with abundant bankside cover appear essential in small streams (Heggenes 1988b). As the deepest pools in small streams frequently have the lowest current speeds, Heggenes (1988b) considered that observations from such streams may be responsible for the widely stated (but not universally applicable) view that adult trout prefer the deepest and slowest parts of streams. The value of such pools was demonstrated by Kraft (1972) who found that habitat conditions varied much less in the deep shady pools than in shallower glides as flows were drastically reduced. Large brook trout left the glides, but not the pools, under low-flow conditions. A pool formed between two riffle bars is, in a large measure, a pond at low flows, so even in severe droughts, such habitat can contain sufficient water to allow trout to survive and is the last to dry up (Bohlin 1977, 1978). Well developed pool-riffle sequences are, therefore, vital in streams subject to low-flows.

However, Heggenes (1988b) also pointed out that in powerful rivers, adult trout have been found to use areas with a relatively high water column current speed. There, the slowest areas tend to be in the shallow margins where juvenile trout may be found, and adult trout tend to be found in the deeper water, which just happens to be relatively fast flowing, with some degree of shelter being obtained from the bed.

The common factor between habitat use in small streams and big rivers is that adult trout use those areas available to them in which they feel most secure. In a small stream this will mean abundant cover in the deepest areas. In larger rivers depth of water alone can make up for cover to an extent, and so adult trout may be less constrained by the existence of overhead cover. Therefore, a wide range of habitats may be suitable in a big river, but only very specific ones in a small stream. This is the opposite of the case for fry (Section 3.5.2).

Locations relative to other habitats
Adult trout may migrate considerable distances away from spawning areas and use very different types of habitat, from the lower reaches of rivers to lakes and even the sea. Therefore, habitats many kilometres from nursery habitat may be populated to some extent by adult trout. However, long distance movements are not a necessity. For example, Solomon and Templeton (1976) considered that the close proximity of spawning, nursery and adult holding areas in a stream would reduce the necessity of long distance movements. Therefore, on larger rivers, it is likely that the widespread distribution of good nursery streams throughout a catchment will be better than a restricted distribution.

3.8 The Catchment Habitat Continuum

3.8.1 Rivers as integrated systems

Earlier, it was shown that river systems can be viewed as integrated systems, both in terms of physical and biological processes. In fact, stressing the importance of this phenomenon is a major theme of this manual. It should, therefore, be no surprise that the same is also true of trout habitats.

3.8.2 Trout within the overall catchment

Trout, at some stage in life, can utilize a wide range of habitats available within a river system. Spawning/nursery habitat may include some of the smallest tributaries, though it is unlikely that they may live to adulthood in these, unless particular factors (e.g. an impassable waterfall) force them too. In a larger sized stream, spawning, nursery and adult habitat may exist in close juxtaposition, but as streams continue to get larger their nursery potential decreases and they merely have value as adult habitat. At the furthest extreme, the sea also provides habitat for fish growing to adulthood. The entire river system, estuary and the sea can, therefore, be viewed as a habitat continuum as shown in Figure 3.4.

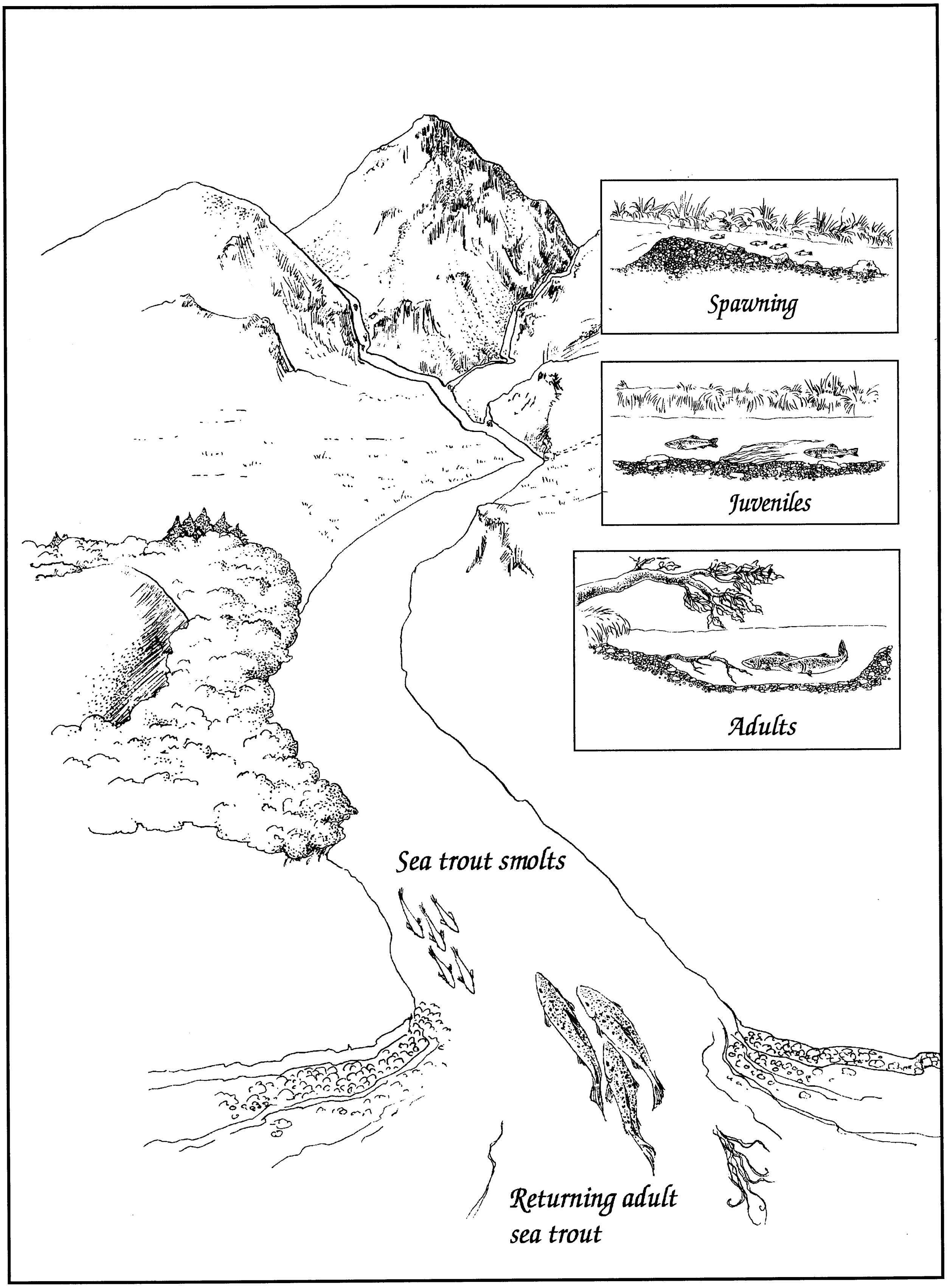


Figure 3.4 The catchment habitat continuum

3.8.3 Requirements to facilitate migration

Whilst trout may use habitats throughout a catchment in the course of their lives, they can only actually do so if they can move freely within it. Thus, the ability to move throughout a river system is a major habitat requirement for trout. This is true for the downstream displacement and deliberate migration of juveniles and smolts and for adults to migrate upstream.

A number of problem factors can prevent the movement of trout within a river. These include natural and man made obstruction (e.g. waterfalls, log jams, dams, weirs, tidal barrages), poor water quality, offtakes etc. However, a very important factor is the level of flow and it can have a complex relationship with the types of obstruction listed. For example, some obstructions may only be passable under certain flows, and water quality barriers may also be exacerbated under certain flows.

Whilst obstructions are often point issues, requiring specific consideration with respect to flow, flow may also influence the ability of trout to migrate within a stream channel. However, the actual quantification of flow requirements has proved a problem. Most work of this nature has been on salmon (Elliott *et al.* 1992), whose migrations are stimulated by increases in flow (Banks 1969). Likewise, it has been widely found that the spawning migration of brown trout into tributary streams from lakes or larger rivers is also stimulated by an increase in flow (Stuart 1957, Frost and Brown 1967, Avon & Dorset Water Authority 1973, Solomon and Templeton 1976). Specifically considering salmon, Webb and Hawkins (1989) suggested that it was a relative change in flow rather than any absolute amount which is important. However, whilst the migrations of sea trout may also be facilitated by increases in flow, they have widely been found to actively migrate under conditions of low flow at night, both in the course of their upstream migration and immediately prior to spawning (Elliott *et al.* 1992, Evans 1994).

Therefore, the firmest conclusions which can be made are that flows must at least be sufficient for trout to be physically able to migrate.

The importance of the catchment perspective
Another important consideration is that since trout can use habitats throughout a catchment, factors which affect habitats in specific areas can have effects on trout elsewhere in the system. Thus, it is very important that rivers need to be regarded as a whole. When considering habitat management, it is essential that it is considered first on the catchment scale before considering the local scale. For example, it may be pointless to improve adult habitat in the lower reaches of a river if nursery streams are being degraded. It is essential that the location of problems is ascertained in the first instance and these may not always be immediately obvious.

4. TROUT HABITAT DEGRADATION AND THE NEED FOR RESTORATION

4.1 Habitat degradation

4.1.1 Introduction

The previous chapters have described how trout stream habitat results from complex interactions between physical and biological processes and that man can, and does, alter these processes in a great many ways - very often in a manner which is ultimately detrimental to the stream ecosystem. Many, if not all, of our streams and rivers have been affected to a greater or lesser extent by human activities and it is because of this that some form of "stream restoration" is justified. The factors which impact on streams differ in different areas, and different types of stream vary in their susceptibility to a particular impact. This means that habitat degradation is also extremely varied. However, particular stream types are associated with particular problems. While an exhaustive description would be lengthy, this chapter describes in greater detail some of the common practices which affect rivers and their impacts on particular stream types.

4.1.2 Catchment land-use

Practically all the land adjacent to streams and rivers in Britain is used for some purpose or other. Different types of land use have different impacts on streams and the impact of any land use also varies according to the type of the stream. The effects of different types of land use are now considered.

Arable farming
Modern arable farming has a number of significant impacts on receiving water courses (National Rivers Authority 1992a). A major problem of sediment run-off, and this is thought to have become worse in recent years as a consequence of more widespread adoption of autumn as opposed to spring sowing of crops like barley, wheat and oilseed rape. This means that the soil is effectively bare for a much longer period, and that during the wettest part of the year. Nutrient inputs have also increased in recent decades and this has had the effect of increasing primary production within streams (often changing trophic status). Increased plant growth in the channel further traps more of the fine sediment released by the increased erosion. As a consequence, periodic dredging (the effects of which are considered below) is often considered necessary to maintain the stream's drainage capability.

Where land is used for arable production, then the land drainage may be improved which will mean that the stream hydrology will have changed. Streams may often be channelized (see below) to further improve this.

Livestock farming: lowlands
In many lowland valleys, floodplain land is unsuitable for arable production and is commonly grazed. Often, streambanks are not fenced and stock (both cattle and sheep) have free access

to streams. Where stock densities are low, the effects of this may be minimal. However, if high densities are involved, the damage done can be severe. Firstly, the riparian vegetation may be removed, and if the water is shallow enough, in-stream vegetation as well. The banks may be "poached" by the animals' hooves, pushing material into streams (Fig. 8.6). The end result is that channels become wider with shallow soft banks. Pools with undercut banks disappear, and, indeed, the pool-riffle sequence itself may be obliterated. If overall gradients are low, such streams tend to be wide, shallow, have uniform bed gradients and accumulate deposits of fine sediment. Streams in such a state, which are common in southern England, for example, have a very different ecology from that which would otherwise prevail. Little cover is available for fish, spawning habitat is destroyed, invertebrate diversity is reduced, stream temperatures are more variable and there is also very little cover for bankside fauna.

Livestock grazing: uplands

In upland areas of Britain, grazing pressure from sheep frequently has a significant impact on streams (Anon 1995). As in lowland streams, bankside cover is again removed. This is not only directly to the detriment of fish habitat, but also reduces the amount of both litter and terrestrial invertebrates falling into the stream, and this can be a relatively significant source of fish food in some upland streams. Sheep again can cause channel widening and shallowing by breaking down the banks, and the thin fragile soils so damaged, may take a very long time to replace.

Forestry

Forestry is another land use which impacts on streams and their ecosystems, and one which has increased in upland areas, especially. The direct influence of trees on the riparian system has already been described (Section 2.3). For example, trees can "tunnel" streams, overshading them and substantially reducing their primary (e.g. algal), secondary (e.g. mayfly) and tertiary (e.g. salmonid) productivity (O' Grady 1993). Clearly, any planting immediately adjacent to a stream will have impacts on the structure of a stream and may fundamentally change the ecosystem.

Another problem which forestry causes in some parts of Britain is to increase the level of acidity in streams. Coniferous trees filter airborne pollutants (e.g. sulphur compounds) which have the effect of increasing the acidity of run-off. This acid run-off can directly enter watercourses where the buffering properties of the soils are poor. Unfortunately, coniferous trees are often planted in areas where soils are relatively poor in basic metal ions like calcium which are the most vulnerable areas of all. Consequently, there are a number of areas of Britain where pH levels have fallen to such an extent to have severe ecological impacts. Examples include the Cambrian Mountains in Wales or in Galloway in Scotland. A comprehensive review of the effects of coniferous afforestation on fisheries was performed by Egglishaw (1985).

4.1.3 Dredging/channelization

Extent of dredging

In the British Isles many miles of rivers and streams have been subjected to some form of dredging at one time or another. In England and Wales, this has been estimated at some 24% of main river (Mann and Winfield 1992) and up to 96% of channels in some lowland areas

(Brookes and Shields 1996b). This may have occurred to aid navigation, alleviate flooding or most commonly to improve land drainage for the benefit of agriculture. In England and Wales it was commonplace for the former Water Authorities to dredge larger river channels but now this practice tends only to be done where it is really necessary, and even then in a more sympathetic manner. Small streams and ditches are commonly excavated by land-users themselves. Dredging can occur across a wide spectrum of land types, ranging from draining fertile lowland valleys to cleaning upland channels in preparation for forestry.

Effects of dredging

Dredged rivers and streams, whatever the reason for the dredging, usually have very different characteristics from the original channel and these were summed up by Keller (1975). At best, only plants and soft sediments may be removed. However, most commonly, riffle bars are removed, obliterating pool-riffle sequences. This results in a more uniform channel lacking in diversity of depths and current speeds. The overall channel shape and capacity may be altered, often producing a steep sided “incised” channels with high banks which produce higher flood velocities and lower summer water levels. Sometimes dredging operations merely “clean” the meandering channel of a river, but commonly rivers have been “channelized”, that is a new straight channel is created and the old meandering channel infilled. Straight channels have a higher gradient than the channels they replace and so flood velocities are higher, and this may then result in increased erosion. Only where there is excessive channel widening and deepening do channelized streams have lower velocities.

Where stony material is present in the floodplain, the new stream bed may be composed of coarser unsorted sediments than the original bed, and these may be too coarse for the stream to move and, consequently, pool-riffle sequences cannot re-form. Thus, except where gradients are very low, dredged streams usually amount to a continuous riffle or glide with relatively little variation in current speed. There are no pools, and such streams lack cover from riparian and instream vegetation, at least for a time.

Major quantities of sediment may be mobilized after dredging works are carried out because of increased velocities and that the bank sediments have little protection. This sediment then contributes to the degradation of the stream downstream. The lack of features in the stream further mean that vegetable matter and debris are not readily retained in the stream, reducing the amount of food available for invertebrates and cover for fish. Also, by shortening streams during channelization, the amount of habitat available to stream flora and fauna is immediately reduced.

In some ways, the effects of dredging can be viewed as the antithesis of damage by livestock. By dredging, material is taken from the bed and placed on the banks and a steeper hard bedded channel results, whilst with livestock, material from the banks is pushed into the bed, the gradient lessens and the bed becomes softer.

Examples of dredging damage

Clearly, dredging can be extremely damaging to fish habitat, and indeed, has been shown to be so. One “before and after” study of routine land drainage works on a lowland river has shown 15% to 100% reductions in “large” fish species abundance. Chub and dace were the principal species affected, and the small numbers of brown trout present before the works disappeared afterwards (Swales 1982b). Swales also provides a useful literature review indicating the generally damaging effect to fisheries of dredging schemes.

As an example of how long dredged river sections can take to recover, it took the River Severn at Llandinam, mid-Wales, 125 years to almost recover its original shape by re-meandering after being realigned during railway construction in the early 1850s (Brookes 1992). However, deeply incised streams will never recover naturally in an historical time-scale, and so, restoration will ultimately be necessary if natural channel forms are to be restored (Brookes and Shields 1996b), or indeed natural fisheries resources, in such streams.

4.1.4 Flow regime alteration

Man frequently alters the flow regimes of streams and rivers, sometimes deliberately (e.g. flood defence schemes) or, very often, unintentionally. Drainage schemes are frequently implicated as causing streams to have a more variable flow regime, i.e. with having violent spates of short duration and lower base flows (Skaggs *et al.* 1994). River regulation by reservoirs, hydro-electric dams, irrigation systems etc. obviously change river regimes. Water abstraction, both direct and from groundwater, also has an effect, most especially pronounced at the lowest flows (Hunt 1996). Urbanisation results in drastic changes to flow regimes (Hollis 1975). Instead of the ground having a soaking capacity, it is covered with waterproof tar and asphalt which instantly sheds any rain into drains and thence straight into watercourses.

Alteration of flow regimes can have a profound effect on both the physical and biological processes in streams. For example, where drainage has been improved, channels will enlarge through erosion to accommodate increased flood peaks (Park 1977). The reduced base flows are then spread over a greater area of stream bed, so during low flows, the stream becomes even shallower and slower as a consequence. Reduced depths and velocities in summer, whether the result in changes in channel shape or absolute discharge, may result in changes in the plant and invertebrate communities, sediment deposition rates, water temperatures and the loss of habitat for trout. Finally, flow regime alteration may have an impact on movements of trout within a river system.

4.1.5 Impoundment and obstruction

In many parts of Britain, streams have a long history of being impounded by weirs and dams. These were frequently associated with mills of various types and irrigation systems, but more recently with water supply and hydro-electricity. Such features can have significant physical and biological consequences.

Effects of impoundments

Impounded water upstream of a weir is slowed and this results in sediment deposition and increased temperatures in summer. This can effect the immediate stream ecology by promoting species of plants, invertebrates and fish which prefer slow flowing, muddy weedy habitats as opposed to those which prefer more swiftly flowing water. An impoundment also causes a change in the base-level of the river which can translate itself into physical impacts some way upriver. Sediment deposition can occur for some way above the actual impoundment resulting in reduced channel capacities and ultimately changes in the flooding frequency etc. (Leopold and Bull 1979). The dams themselves can also act as barriers to movements of fish and other fauna.

4.2 The Need for Restoration

As described in the previous section, a great range of practices impact, or have impacted, on British rivers and streams in a manner which has damaged, not only trout habitat, but their wider conservation potential. Irrespective of the environment, relatively few streams could be said to be in some form of "pristine" condition.

Since habitat degradation has been widespread and natural recovery may be an extremely slow process, intervention in some form to restore habitats may be considered to be justified over much of Britain. The scale of the problem is well illustrated by the fact that over 7000 km of rivers and streams in England and Wales are considered to be in need of restoration (Mann and Winfield 1992). Of course, not all of this is potential trout habitat. There is also much interest in river restoration in the wider field of conservation, as shown by projects like the River Restoration Project (River Restoration Project 1993) or guides like *The New Rivers and Wildlife Handbook* (Ward *et al.* 1994) and Brookes and Shields (1996a).

5. HABITAT RESTORATION PROJECT MANAGEMENT

5.1 The need for project management

The successful restoration of a trout stream involves many steps. Many issues need to be considered. For example, the deficiencies in the habitat need to be correctly identified, a scheme must then be designed according to best principles and then the results must be appraised. Within each of these steps there are further issues to consider. For example, in designing a scheme, issues like practicability of the work, costs, effects on third parties and legal consents have all to be considered. Therefore, each restoration scheme needs to be viewed as a project in its own right and must follow a planned management structure if it is to be performed efficiently and effectively. The lack of good project management and planning has been widely implicated as contributing to the poor standard of many restoration schemes (Mann and Winfield 1992, Orth and White 1993).

This chapter describes a project management model, which if followed, will ensure good practice. The model essentially comprises a series of relatively simple, but often overlooked steps. These steps have been identified through consideration of a variety of published restoration schemes (e.g. White and Brynildson 1967, Hunter 1991, Orth and White 1993).

5.2 The project management model

5.2.1 Introduction

The project management model is depicted on Figure 5.1. It consists of a series of thirteen simple but logical steps, some of which involve making decisions or definitions (depicted in diamond boxes), whilst the information gathering and implementation steps are presented in rectangular boxes. The model is essentially a representation of the core steps which are applicable to all scales of restoration schemes, the level of detail or information required for each step varying with the scale of the project.

5.2.2 Step 1: Problem identification

Problem perception
All restoration schemes start off with some initial perception that there is some problem which may require tackling. It is fundamentally important that initial thoughts are documented because, as a project develops, new information may come to light and it is easy to forget how much progress may have been made in understanding the problem.

The initial perception may arise for many reasons. For example, someone may have been familiar with a stream for some time and observed (or perceived) a decline in trout catches which they wish to arrest. Another example could be that routine surveys by fisheries authorities show up a decline in numbers.

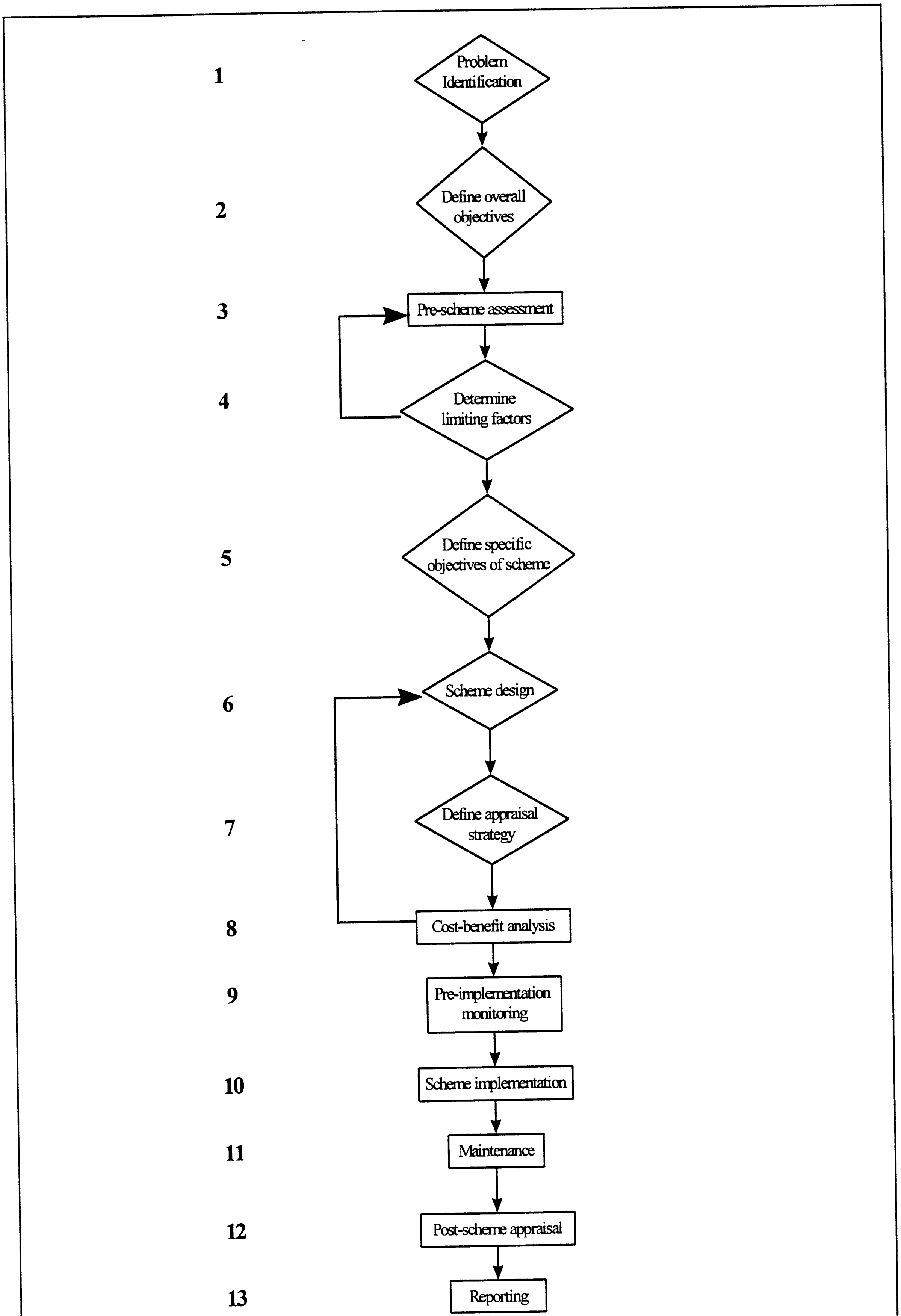


Figure 5.1 The Project Management Model

Problem identification
A perceived problem affecting a trout stream could stem from many sources. In addition to a deterioration in habitat quality, this could include water quality, water abstraction, over-fishing, a deleterious impact of stocking alien fish, blocking of the passage of migrants, and so on. Before a habitat restoration scheme should proceed it is obviously necessary to ascertain that it is likely to be habitat which is causing the problem.

Potentially, investigation of potential problems could be extremely involved. In practical terms, hypotheses should be made about other factors which may be important and any available relevant data (e.g. water quality and biological data from the EA) should be consulted to see if any such factors are likely to be causing problems. For example, in an upland area where soils are poorly buffered, levels of acidity should be determined as they could be affecting trout eggs. On the basis of such considerations, an informed decision should be made as to whether habitat restoration is likely to succeed.

5.2.3 Step 2: Defining overall objectives

Having identified reasons why stream restoration is considered to be necessary, the stream restorer must then make it clear in broad terms what the overall aims of the restoration are. The broad objectives will differ between schemes depending on the scale of schemes and who is conducting them. For example, an overarching catchment scale restoration strategy performed by the EA could have very different considerations and objectives to an individual fishery owner. The objective of the catchment strategy may be to increase trout production in terms of the river as a whole, whilst the riparian owner may really be ultimately concerned with increase the number of catchable sized trout in his water, or indeed, more abstract concepts like fishing potential. Other considerations include whether it is intended that the stream should be restored to its “natural” state or to some other state which may represent a hyper-habitat for trout.

When formulating objectives, it is necessary to obtain input from other interests who may be affected in some way by the restoration scheme. This will involve consideration of the effects a restoration scheme is likely to have on other fisheries interests, the wider ecology of the river, riparian land uses or any other river users and whether these effects are acceptable to other interests. Thus, objectives should be modified to take into account a wide interest. EA fisheries, and catchment management plans are an appropriate vehicle for this task.

The overall objectives of a scheme will dictate the manner in which the restoration is carried out and also set criteria by which the success of the scheme may be judged. For the efficient and effective implementation of the project it is important that the initial objectives are appropriate. A good concept is that of the SMART (Specific, Measurable, Achievable, Realistic and Time-based) objective. Such objective setting requires some degree of prior knowledge, so caution is required in poorly understood situations. For example, it may be a reasonable objective to double numbers of adult trout in five years in a stream containing good adult habitat but no spawning habitat if nearby good quality streams hold high populations of adults, but not if the reference streams were in a fundamentally different type of environment.

5.2.4 Step 3: Pre-scheme assessments

Once the objectives of the scheme have been decided it is then necessary to conduct detailed survey work to identify the distribution of different habitat types and the location of problems. There are two aspects to such surveys - the catchment scale and the local scale.

Analysis of the entire river/catchment system

A fundamentally important aspect of the approach to tackling habitat problems in the first instance is to determine the causes of degraded habitat, not merely to identify the symptoms (Hunter 1991). For example, it would not be enough to know that fine sediment was collecting in pools and depriving trout of habitat; it would be equally important to find out where the sediment was coming from. Given that many problems facing streams are not generated locally, it is, therefore, important first of all to investigate the processes at work in the wider catchment system, so that problems observed at the local level (the symptoms of catchment scale processes) can be put into their wider context.

Analysis of local habitat quality

Having considered the catchment scale, it is necessary to conduct an “on the ground” survey to quantify the existing habitat for all the various life stages of trout. Methods for performing this are described in detail in Chapter 6. Fish population data obtained from EA surveys are very useful in checking the accuracy of habitat determination. If such data are unavailable, surveys may have to be undertaken specifically. The techniques employed are also described in Chapter 6. It is also important to consider the wider biological capabilities of the stream. Information on water quality, invertebrates and plants can generally be obtained from the EA. If such information is not available, surveys may be conducted specially.

Since some habitats are only critical for trout at certain times of the year (e.g. spawning habitat in winter and fry habitat in spring/summer) the habitat surveys have to be repeated at several different times in the year. Such surveys should take into account water conditions and be performed under the ideal type of conditions for that life-stage. For example, spawning tends to take place at elevated water levels, but adult habitat may be most constrained at the height of summer drought. A full year, may therefore be required for the initial habitat survey.

5.2.5 Step 4: Identification of limiting factors

After conducting the pre-scheme assessment to determine which habitats are present or absent the stream restorer must then identify, as far as possible, which habitats are most limiting numbers of trout in the stream or causing the fishery to under perform. This can be difficult, the but steps involved are explained in Chapter 6. It is important that constraining factors should be ascertained in as rigorous a manner as possible. The intensity of such an investigation will depend on the scale of the project and the resources available.

5.2.6 Step 5: Defining specific objectives of the scheme

Although a restoration scheme will have an overall objective, a number of specific procedures may be involved in achieving this end. Each step to achieving the overall aim will have its own specific aim. For example, it may be decided that a population is limited overall by a lack of spawning habitat. Therefore, to effect an overall increase in the population, the specific objective would be to create spawning habitat. It is only by meeting specific objectives that increases in fish numbers will materialize.

Again, as with overall objectives, specific objectives should fit the SMART description.

5.2.7 Step 6: Designing the scheme

Nature and locality of scheme

Having diagnosed the limiting factors affecting trout numbers at both the catchment and local scales, decisions have to be made as to what must be restored and where. For example, if there is abundant headwater nursery habitat but little suitable adult habitat downstream, then improving the latter may be a priority. However, if it were the other way around, then restoration of headwater areas, or maybe even improved catchment management, will be required. This also points to the required scale of restoration. In the first example, localized restoration schemes in the main stem of the river (such as typically conducted by individual fishery owners) would be beneficial, but in the latter case, restoration has to be considered at the catchment scale. A good example of this is the River Tweed in Scotland (Anon 1995). Frequently, however, there may be a combination of both types of problem, so both local improvements for adult trout and catchment management can have beneficial effects.

Selection of treatments

The next stage in the process is to design the necessary treatments to the habitat. Particular habitats may be re-created in a number of different ways and many factors have to be taken into account in weighing up the pros and cons of each possibility. At this point it is often necessary to integrate different disciplines like fisheries and freshwater ecology, engineering and geomorphology. Habitat creation should be viewed very much as an inter-disciplinary specialism.

The two main types of treatment are either to treat the causes of problems at source or else employ mitigation works to offset problems without actually tackling the cause. An example of the former would be the prevention of silt inputs in a river where siltation of spawning habitat is a problem, whilst the cleaning of spawning gravels would constitute the latter. Ideally, habitat improvements should treat the causes as far as possible, and this often involves work at the catchment scale. However, even if it is not possible to treat the causes, then schemes should still be designed as part of some overall strategic plan for the catchment. For example, schemes should not impact adversely on fisheries in other parts of the catchment but should rather give rise to benefits elsewhere too. It would be possible, for example, for a scheme to increase adult holding capacity in one area at the expense of juvenile habitat which may impact on fisheries further downstream (Mann and Winfield 1992).

Therefore, there may be a number of options regarding the choice of a technique which is technically capable of overcoming some habitat problem. The process by which alternative techniques are selected in order of preference is shown in Fig. 5.2.

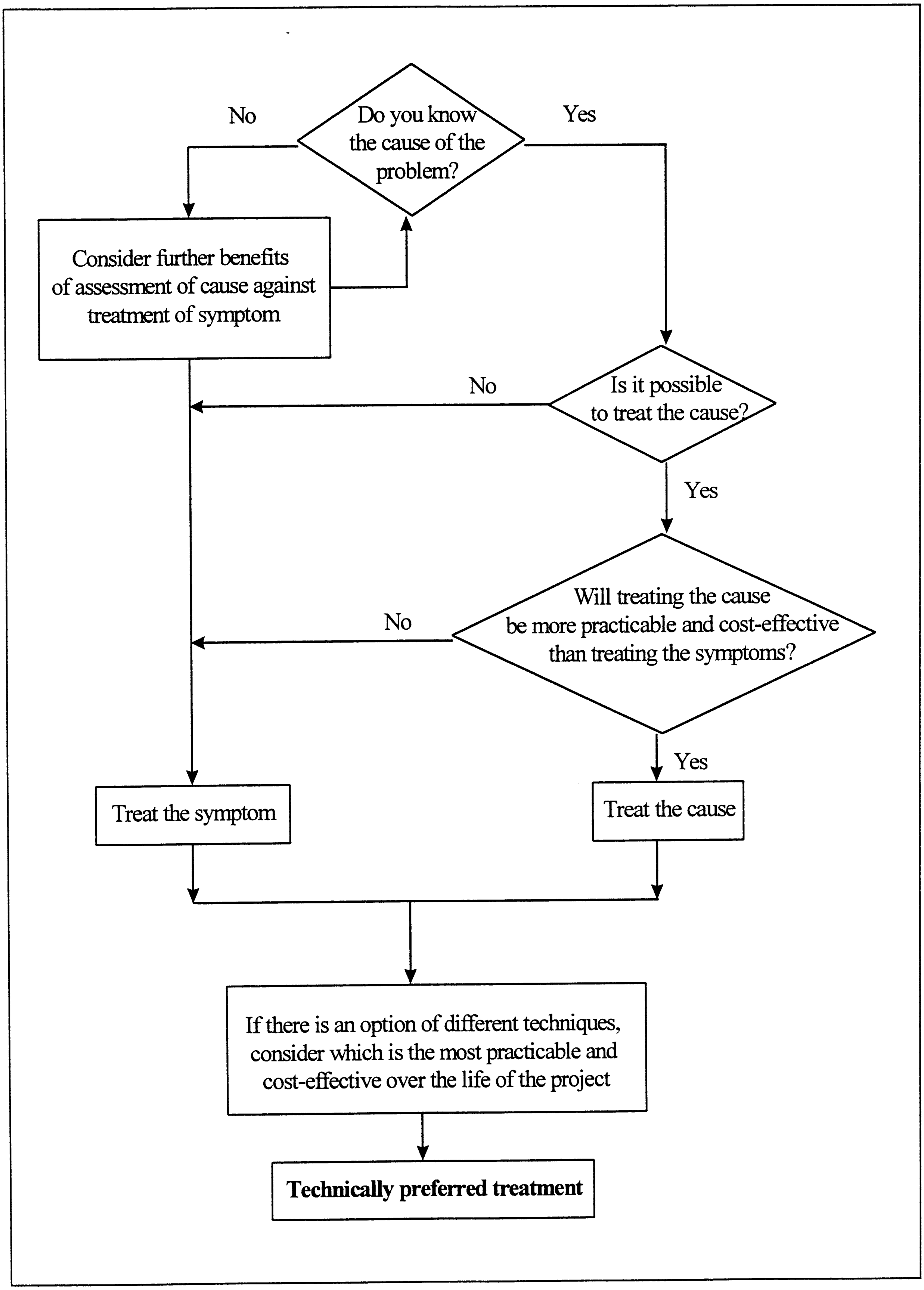


Figure 5.2 Decision making process to identify a suitable restoration technique

Legal consents

Once feasible techniques have been identified, the final consideration is whether they will have adverse effects on the wider environment or property. For this purpose, private promoters of habitat restoration are legally obliged to obtain consent for habitat improvement works from the EA, and sometimes from other organisations (see below). Projects undertaken by the EA are consented via routine internal planning liaison procedures but may also require consent from English Nature, the Countryside Council for Wales or the local authority in some instances.

However, parties external to the EA who seek to perform restoration work are strongly advised to firstly consider the potential effects of different techniques on the general stream ecology, land drainage etc., and to discount unacceptable techniques. After this, they should consult with other parties who may be better informed as to the potential effects of proposed techniques. These will include other fisheries interests, local landowners/land-users, EA flood defence engineers and conservation organisations. Only after techniques have been considered acceptable by these different interests should an official application be made. Consenting is an important element which must not be overlooked. Some important guidelines are provided below.

Guidelines to legal consents required

The diversity of techniques, scheme design and relevant legislation prohibits the provision of specific guidance within this manual. However, some important general advice can be provided with respect to promotion of projects by external parties;

1. Work in the assumption that **all** river habitat restoration projects will require consent from one or more agencies.

2. Consult at an early stage with your EA Area Fisheries & Conservation Officer and EA Area Planning Liaison Officer **prior to making an application.**

3. **Consult at an early stage** with your local planning authority.

4. **Leave sufficient time** for consultation, application and determination of consent. The EA has a responsibility to determine the applications within two months of receipt.

5. **If the location of any proposed work is within a designated Site of Special Scientific Interest (SSSI) consent will be required from English Nature (EN) or The Countryside Council for Wales (CCW).** This will be known by the site owner and can be checked with the Area Fisheries & Conservation Manager.

The relevant legislation is described in the Appendix.

Final plans

After a feasible scheme has been decided on and legal consents obtained, a sequence of implementation can finally be drawn up. Thereafter, with the plan finalized, the required materials have to be assessed along with the logistics of the operation. The scheme is then almost ready to be implemented.

5.2.8 Step 7: Define appraisal strategy

The desired end product of all restoration schemes is that the objectives are achieved and trout numbers are increased accordingly. It is most important, therefore, that schemes be properly appraised. Appraisal involves pre- and post-scheme assessments to assess both habitat change and the response of the fish population or fishery and potentially also invertebrate populations, riparian and in-stream plant communities.

In Chapter 7 the design of experiments to appraise population changes are detailed. A major problem is that to be thorough, an appraisal may require monitoring of the fish population for several years before a restoration to establish a true baseline. Certainly, in a really large scale expensive long-term restoration, long term appraisal should be built into the plan. Therefore, large scale restorations should not be entered into hastily. Furthermore, given that any restoration scheme will take some time to mature - the structures have to bed in, plant communities become established - and the generation time of trout, it may take a number of years before the true impact of the scheme may be observed. For example, in one of the most thorough appraisals of a habitat improvement, Hunt (1976) reported that the full response by brook trout to an improvement in a Wisconsin stream took six years. Thus a commitment ought to be made to appraising a scheme for a number of years.

Rigorous appraisal can add considerable expense and commitment to a restoration project. Where such rigorous appraisal cannot be justified, less detailed appraisals may still provide useful information and should be performed in preference to performing no appraisal at all.

5.2.9 Step 8: Cost-benefit analysis

A final consideration before a scheme can be implemented is whether or not it is cost-effective. The cost to be considered is that of the entire scheme including the cost of appraisal. Cost-effectiveness is a difficult concept to define and is likely to mean different things according to the promoter's aims. The subject is covered more fully in Section 7.5.

5.2.10 Step 9: Pre-implementation monitoring

After a scheme has been finally designed and decided on, it is necessary to implement the first stage of the appraisal process - that is a survey of the habitat and fish population. This provides a baseline to compare effects against.

5.2.11 Step 10: Scheme implementation

Once a scheme is fully planned and surveys completed, work can be implemented. The procedures involved in carrying out the various different types of improvements are described in Chapter 8. A very important point is that if the work is to be undertaken by contractors, rather than by the scheme designers themselves, it is important that the scheme designers oversee the works continually in case the specification is misinterpreted.

5.2.12 Step 11: Maintenance

However, once habitat improvement works are actually performed, it is frequently only the start of the project. Habitats may not always develop exactly as hoped, and so some modification may be required at some later date. Also, some of the materials used may fail or get damaged and will need to be repaired at some point in time. Fences will have to be maintained, bankside vegetation will need to be managed to prevent overshading, accumulations of debris that may prove to be a flood hazard removed etc. All these issues need to be considered at the start otherwise they will jeopardise the long term success of the scheme.

5.2.13 Step 12: Post scheme appraisal

After the scheme is implemented, surveys of the habitat and trout population need to continue in accordance with the plan decided in Step 7. These will provide the data to assess the success of the scheme.

5.2.14 Step 13: Reporting

It is most important that all the steps in the project are fully documented. Once all are completed and the success or otherwise of the project assessed the results must be reported. The lack of appraisal and reporting has been a major constraint on the development of fish habitat restoration (Mann and Winfield 1992). This aspect is, therefore, an imperative. If possible, results may be published in scientific journals subject to peer review. However, there is currently a lack of opportunity for the dissemination of work which is not of this standard. The rectification of this situation is a recommendation of this study (see Chapter 11).

6. PRE-SCHEME ASSESSMENT AND LIMITING FACTOR IDENTIFICATION

6.1 Introduction

In Chapter 3, it was shown that, although trout exist in a broad range of environments, they do require some fairly specific types of habitat which, even in widely different environments, have elements in common. It was also shown that the available habitat in a stream which is suitable for a particular life stage can limit the potential size of the population if that habitat is scarce relative to habitats for other life stages.

The philosophy behind trout stream restoration is to increase the available habitat, for particular, if not all, life stages. However, the big question facing the would-be stream restorer is which elements of the habitat are most lacking in a particular stream, or the lack of which habitats is currently limiting the overall population? Unfortunately, this is not always an easy question to answer but this chapter describes how to identify limiting factors, as far as is possible.

Whilst trout numbers are ultimately limited by the presence or absence of habitat at the local scale, the local habitats themselves are frequently products of catchment scale processes. It is not sufficient to only ascertain that there are habitat deficiencies at the local scale but, most importantly, to ascertain why. Therefore, pre-scheme assessment consists of looking at habitats at several levels - the macro or catchment scale and the meso or local scale. At each level, different types of information are obtained. Initially, surveys must be performed on the physical habitat. Then further surveys are performed to obtain fish population data to aid the identification of limiting habitats.

6.2 Habitat Assessment

6.2.1 Introduction

At the time of writing, there exist a number of alternate methodologies regarding the assessment of riverine habitats. This important area is currently the focus of a research project which will determine which methodologies are most appropriate for fisheries assessments and how these may be improved. Against this background, this section presents some ideas on practical habitat assessment, but these should be seen as examples and not overly prescriptive.

6.2.2 Macro-scale habitat assessment

The first stage in any catchment assessment is to become familiar with relevant macro-scale features of the catchment. A good review of such an assessment is provided by Kondolf and Downs (1996). The important features to consider include:

Stream network

A base map must be made of all the streams within the catchment of interest. The Ordnance Survey 1:50 000 scale map will make a convenient template. If possible, this map should be digitized and stored on computer to facilitate subsequent data management.

Catchment topography

On the above map, stream gradients are recorded. Gradient is ascertained from the Ordnance Survey map by dividing the vertical distance between two contour lines (15 m on a 1:50 000 map) by the length of stream between contour lines.

Geology and land use

Rock types within the catchment can be found from geological maps. Land use may be determined from land use capability maps, aerial photographic surveys or from direct field observations. A field survey is useful in noting where streams have been dredged, where there has been ploughing for forestry planting, moorland drainage etc.

Hydrology

Hydrological data should be obtained from the EA for gauging stations throughout the catchment. Ideally average daily flow data should be obtained, but at a minimum, average monthly flows should be obtained for a number of years. The locality and magnitude of water abstractions should also be assessed.

Water quality

Water quality and chemistry data can be obtained from the relevant department of the EA. Information can be provided on water quality throughout catchments, based on a standard classification. In addition, information can be provided on biological indices of water quality which are especially valuable.

Historical changes

Historical changes in land and river use should be ascertained throughout the catchment. This information may be gleaned from a variety of sources such as previous studies performed on the catchment. Alternatively, interviews with persons who are familiar with the catchment could be conducted.

Interpreting the catchment data

Having obtained these data, characteristic problems which are likely to exist can be ascribed to specific areas of the catchment. For example, stretches of stream with low gradients alongside arable land are likely to be prone to dredging, areas of arable land on sedimentary rocks with steep slopes may be prone to surface erosion, and high gradient streams on crystalline rocks with sheep grazing may be expected to have relatively little silt inputs but may suffer from bank damage.

Once the initial broad survey of the catchment has been completed, a habitat suitability survey must then be performed to investigate habitats at the meso or, local, level. However, as trout may be dependent on habitats in different parts of the catchment, it is necessary to perform such a habitat survey throughout the whole of those areas of the catchment where trout are likely to occur.

6.2.2 Meso-scale: the "Walk-over Survey"

Introduction

The meso-scale survey is invaluable in establishing a database of habitat quality throughout a catchment. It is the main method of identifying those areas where trout production may be occurring or where habitat restoration may be necessary.

There are a number of ways in which habitat can be characterized at this level. These all entail taking measurements of certain physical characteristics of the channel (e.g. width, depth, substrate type) and relating these to known trout habitat requirements. The various methods essentially differ in the precision with which the stream characteristics are quantified and in the manner by which these data are turned into a measure of trout habitat suitability. They all have their place in particular circumstances. Increasing sophistication requires more time and cost, important considerations when long stretches of stream need to be inventoried. For a catchment wide survey of habitat the simplest method recommended is the "walk-over survey".

The walk-over survey: subjective assessment

At its simplest, a walk-over survey may consist of an experienced operator making subjective assessments of the habitat value of different stretches of the stream and noting the presence of likely obstructions to migration, with the information being recorded on a large scale base map. In this manner, many kilometres of stream can be covered in one day. Whilst experienced individuals can subjectively identify good and bad habitats, the accuracy of this method will be variable and there is no standardization of the method. However, such a survey is perfectly adequate in identifying chronic problems (e.g. to identify recently channelized reaches or badly overgrazed reaches).

The walk-over survey: semi-quantitative assessment

By incorporating some simple measurements, the walk-over survey can be made more rigorous and habitat quality appraisal set on a quantitative basis. Such a methodology has been in use by the British Columbia, Ministry of Environment (de Leeuw 1982). This methodology is straightforward and is as follows.

The stream is considered to be composed of successive units in which the width, depth, current speed, substrate and degree of overhead cover are relatively uniform. For example, a unit may be a riffle bar, a pool or a glide etc. A degree of subjectivity is involved in delineating a particular unit. Terms like pool, glide and riffle may be used to aid the mapper, but these should be defined, as different operators may interpret such terms differently.

Within each unit, the average width, depth, current velocity, substrate type, width of overhanging vegetation and depth of water under overhanging vegetation should be determined. In a rapid semi-quantitative assessment, the mapper may identify an "average" part of each unit subjectively by eye and measurements taken from that spot alone may be taken to represent the entire unit.

Current velocity is the only difficult variable to measure. Ideally, it should be measured with a current meter. Velocities tend to be higher near the surface so it is accepted that a measurement of current velocity at 0.6 of the depth, measured from the surface, should represent the mean water column velocity (Richards 1982). If a current meter is not available, a floating object of neutral buoyancy timed over a given length of stream can be used. If a float is used, it should occupy as much of the water column as possible to accurately represent the mean velocity. To save time, current speed need not be measured in each unit. Instead, a section with a very uniform profile, current speed and degree of turbulence should be selected and the current speed estimated there. Then, on the basis of the continuity equation (see below), the mean velocity at any cross-section can be ascertained from measures of width and depth over such a length of stream as discharge may be considered to be constant.

Discharge (m^3/s) = Mean current speed (m/s) × Mean width (m) × Mean depth (m).

The location of objects such as woody debris and boulders should be noted on a sketch map. The proportion of the bed in each unit occupied by plants should be recorded along with the species, if possible. An approximate estimate of the percentage of different substrate types is then made visually. There are a number of standard classifications of sediment types based on their size (e.g. the Wentworth classification (Pettijohn 1976)). The classification provided by de Leeuw (1982) is as follows: fines (i.e. silt), sand, small gravel (2 mm to 4 cm diameter), large gravel (4 cm to 10 cm), cobble (10 cm to 30 cm), boulder (>30 cm) and bedrock.

Overhead cover consists of the degree to which either the bank, grasses, trees or aquatic and emergent vegetation stretch onto or into water which is at least 10cm deep. This should be measured by determining the distance between the true bank and the edge of the fringe of cover. The degree of cover can easily be calculated by dividing the width of cover (i.e. measurements from both sides of the stream combined) by the stream width. The depth of water under the cover should also be recorded.

The value of bankside cover to trout depends on its width relative to the depth of water below. There is little information on what suitable width-cover ratios should be, except that the greater the width the better (Butler and Hawthorne 1968).

Finally, it is important to note the presence of obstructions, or potential obstructions, to fish migration. The location of flow management structures should also be noted.

The transect method

A more detailed way of obtaining quantitative information on available habitat is by the "transect" method (Orth 1983). This involves measuring the depth and current speed at regular intervals across successive cross-sections or transects. Dominant substrate types at each point are noted and the width of overhanging vegetation measured. The spacing between successive transects, depends on how variable the channel shape is. From the many points sampled, the mean depth, width etc. of an entire reach can be calculated.

The need for rapid habitat assessment

For most trout stream restorations, the walk-over type of survey is most appropriate because the stream can be covered quickly. Speed in completing the habitat survey work is vital because several habitat inventories have to be made over the course of the year. For example, it would not be possible to adequately describe spawning habitat by conducting an inventory of spawning habitat during the summer under low flow conditions since spawning normally takes place under higher flows. Likewise, an appraisal of critical adult habitat ought not to be conducted under high flows. It is important therefore that the survey technique be as rapid as possible to ensure that conditions are essentially constant throughout the duration of one survey.

Example of habitat map

A simple example of a habitat map at the 1:10 000 scale is shown on Fig. 6.1. The habitat measurements in this instance were made using the transect method with similar cross-sections being grouped into habitat types (Maddock 1995). A map of this scale, when completed for an entire catchment, is extremely informative in describing habitat availability.

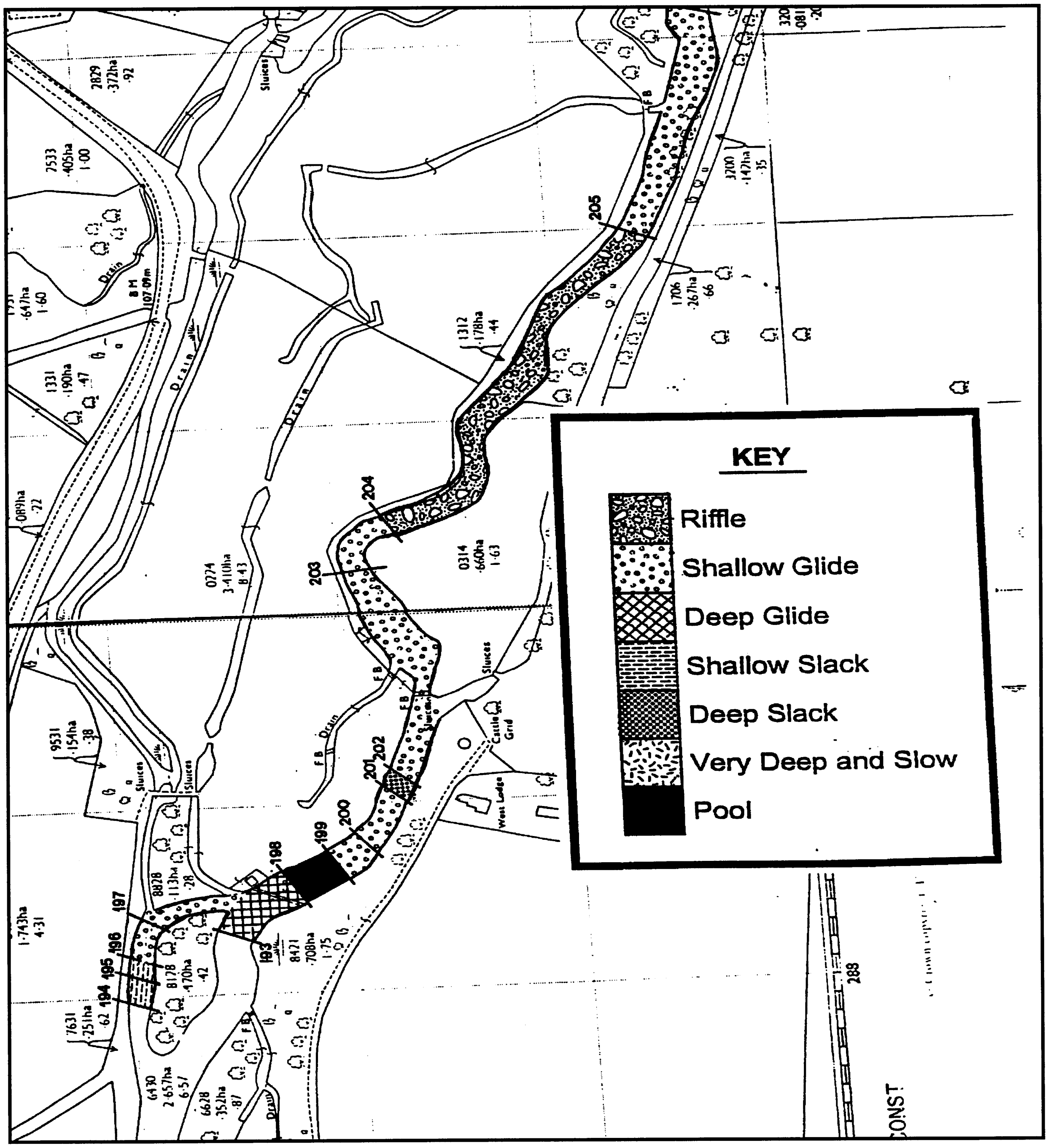


Figure 6.1 An example of a walk-over survey habitat map. From (Maddock 1995)

6.2.3 Interpretation of habitat quality from a walk-over survey

Having obtained descriptive data from the walk-over survey, using either subjective, semi-quantitative or the transect method, the next problem is to convert these data into a meaningful measure of trout habitat suitability. This involves comparing the physical attributes of a stream with what are considered to be "preferred" habitats of trout of a particular life stage. However, it is not easy to define the preferred habitats of trout in a manner which is easy to translate into all stream types. In fact, there is no way of providing a universally robust description of quality trout habitat. This is because trout habitat quality is an amalgamation of many factors and these different factors are to some extent interdependent. For example, the depth of water trout will occupy depends on the degree of cover present. Bearing in mind the difficulties in describing trout habitat, a very simple classification of good trout habitat has been devised and is provided in Boxes 6.1 to 6.4.

Each habitat unit in the stream is considered in turn and is assessed in terms of which of the habitat attributes described in Boxes 6.1 to 6.4 it possesses. Thus, its likely suitability for each life-stage is assessed. For example, a stretch of stream may measure 5 m wide by an average of 60 cm deep with a mean velocity of 20 cm/s and a bed of gravel and silt. There are few plants and little cover. From the depth, lack of cover and type of substrate, it is clearly not spawning, fry or juvenile habitat. It has the potential to hold adult trout but it lacks cover. In this manner, units can be described as Suitable, Potentially Suitable or Not Suitable for each particular life-stage. A complete picture of the availability and distribution of different habitats within a stream can then be built up.

Box 6.1 Brown trout spawning habitat

(Appraisal conducted during the spawning season on the target river - late autumn / winter - under average or slightly elevated flows)

Water depth from 10 to 50 cm, mean current velocity between about 20 and 60 cm/s over gravel substrate (5 to 50 mm), especially on the upstream side of riffles where these exist. Areas which have the requisite depths and substrates may be further checked for suitability by taking more precise velocity measurements over actual gravel areas with a current meter. Some cover from an undercut bank, debris, boulders, weedbeds should be present within a short distance.

However, problems can still occur even if suitable velocities and substrates do exist. The gravel may be badly silted, or silt accumulation in a completed redd may render the habitat useless. It is has already been shown that what may look to the eye like perfectly good spawning grounds may not be. More detailed techniques to ascertain the quality of spawning habitat are described in Section 6.3.

Box 6.2 Fry habitat

(Appraisal conducted April to June)

Depth	10 to 40 cm
Mean velocity	0 to 30 cm/s
Substrate	Rough bed of gravel/cobble/debris or fine gravel if rooted plants are present. Little silt.
Bankside cover	Must be present if there is no cover on the bed.

If there is no bankside or bed cover, or the stream is deep, slow and silty or is shallow and fast, then it will be a poor habitat for trout fry.

Box 6.3 Juvenile habitat

(Appraisal conducted in late summer when water level is lowest)

Depth	10 to 60 cm
Mean velocity	5 to 50 cm/s
Substrate	Rough bed of gravel/cobble/boulders/debris or gravel if rooted plants are present. Little silt.
Bankside cover	Must be present where plants and debris are sparse.

As for fry, if there is no bankside or bed cover, or the stream is deep, slow and silty or is shallow and fast, then it will be a bad habitat for juveniles.

Box 6.4 Adult habitat
(Appraisal conducted in late summer when water level is lowest)

Depth	>30 cm
Mean velocity	10 to 60 cm/s
Substrate	Rough bed of gravel/cobble/boulders or gravel if rooted plants are present. Little silt.
Bankside cover	For a small stream cover must be present. In streams more than about 10 m wide cover is less important.

Further refinements

The end product of the above exercise is a theoretical measure of the habitat quality for a particular life-stage. A sophisticated refinement of this basic approach is the Habitat Suitability Index (HSI), a technique widely applied in North America (see Raleigh *et al.* 1986). This involves observing large numbers of trout and noting the habitat occupied by each in terms of current speed, depth, substrate etc. The frequencies of habitat use, when compensated for habitat availability, are then expressed as mathematical functions which can be shown graphically as "preference" curves. Systematic measurements of relevant habitat variables are then made in the target stream and these are related to the HSI preference curves to arrive at a measure of suitable habitat. As trout may occupy different habitats in different types of stream (Section 3.4), preferences curves should ideally generated for each specific stream. Clearly, such a level of work is prohibitive. However, HSI curves have been generated for some English rivers (e.g. Bird *et al.* 1995, Johnson *et al.* 1995) and these could be used in place of the information in Boxes 6.1 - 6.4 on similar types of stream.

6.2.4 Mesoscale habitat appraisal: empirical habitat comparisons

Introduction

The walk-over method or the HSI methods, as described above, basically produce a theoretical assessment of the quality of the habitat for trout of a given life-stage. However, it does not necessarily follow that these habitats will actually be utilized by such fish because numbers may be limited at some other stage in life. An alternative approach to habitat evaluation has been to relate habitat measurements to observed numbers of trout in other streams so actual expected numbers of trout can be predicted.

Between-stream comparisons

At the simplest level, streams can be identified within the catchment of interest which still have healthy trout populations (assuming these exist) and comparisons can be made between the habitat in such streams and in degraded streams to identify what may be lacking in the degraded streams. This is a very instructive practice for inexperienced operators, but it does involve a less rigorous discipline and may result in important factors being overlooked.

Empirical models
Empirical habitat comparisons have been taken much further with the calibration of computer models. One such model, HABSCORE, is widely used by the EA (Barnard and Wyatt 1995, Wyatt *et al.* 1995). The model is based on empirically derived relationships between numbers of trout in streams and measured variables such as stream width, depth, substrate type, degree of cover and channel gradient. Then, by inputting such data from any stream, the model predicts actual densities of trout in it. To collect the necessary input data, a 100 m section is selected and is then subdivided into 10 m sections and, within each subsection, the amounts of different habitat types (e.g. deep pools, glides, undercut banks) is determined subjectively according to a common format. Every 10 m, the width of the stream is measured and depths are measured at intervals across the stream in a transect. Land use and riparian vegetation are recorded and stream gradients are calculated from Ordnance Survey maps. Water chemistry measurements are also made.

The output of the HABSCORE model is a prediction of how many trout of a particular life-stage there ought to be per 100 m^2, under the assumption that the habitat is in pristine condition and recruitment is not limited. Based, on further empirical data, the model converts this into a Habitat Quality Score (HQS) to denote how good the density of trout is relative to the streams on which the model was calibrated. One constraint on the usefulness of the model depends on the degree to which the stream of interest and the calibration streams are similar. For example, in different environments, growth rates may be different and, hence, required territory sizes may differ in different streams for fish of the same age and so predicted densities may not equate to real densities. However, the latest version of the model is applicable to a wide range of streams in England and Wales, and it is constantly evolving to take in more stream types. Nevertheless, it is important to make sure that the target stream does fall within the range of included stream types.

Empirical models have great potential in terms of habitat appraisal. However, HABSCORE is relatively time consuming. It takes two staff between 30 and 45 minutes to assess a 100 m site and so it would not be practical to survey an entire catchment. That must be performed by the walk-over survey. However, it is possible to use HABSCORE in a stratified manner on representative sites on a given stream which have been identified by the walk-over survey. This will provide further corroboration of the habitat assessment based on the walk-over survey. This is especially important if an operator is inexperienced at identifying trout habitat.

6.3 Trout Population Assessments

6.3.1 Introduction

The various habitat surveys described in the previous sections provide an assessment of the habitat potential of the stream. However, the different survey methods predict habitat quality on the basis of certain assumptions which do not always hold. For example, they cannot predict likely rates of redd siltation or account for the effects of predation etc. To corroborate the habitat surveys it is necessary to perform surveys on various fish population parameters. By comparing real fish population data with what may be expected from the habitat survey will indicate which habitats are limiting (Section 6.4).

6.3.2 Spawning habitat use

Redd counts

Where water depths and clarity allow, it is possible to count the redds made by trout. They are normally recognisable immediately after they have been cut by the presence of a depression in the gravel with an accumulation of gravel downstream. Depending on the size of the trout, the nature of the substrate and the strength of the current, the gravel pile can vary from anything from 10 cm to 20 cm to about one metre (Ottaway *et al.* 1981, Crisp and Carling 1989). Attention is drawn to newly cut redds because the gravel is bright and clean as opposed to being coated in algae. Over time, usually a period of several weeks, algae may recolonize the newly exposed gravel obscuring the redd. In high energy environments especially, a spate prior to spawning may have the effect of washing the gravel so that newly cut redds do not stand out. In such environments redds can be difficult to identify.

Due to these potential problems, redd counting should be repeated at intervals, not longer than once a week, throughout the spawning season. Redds can then be identified as they are created, and frequently the actual fish observed. This latter case is especially important in environments where redds are hard to identify. For the inexperienced operator, it is good training to perform redd counting while fish are actually spawning rather than on a post spawning survey as he/she will readily learn to recognize redds.

New redds, when identified, should be marked, along with their date on a detailed plan of the stream in question. Markers may be used as references to identify their locations in future. This will ensure that even with the passage of time the locations of redds can be identified though the appearance of the stream may change.

6.3.3 Appraising spawning success

There are several methods which may be employed to ascertain how successful any observed spawning is.

Fry emergence trapping

This is the most direct method of appraising the success of natural salmonid spawning. Basically, a funnel shaped net of very fine mesh, is fixed in the stream, into which fry passively drift after emerging from the gravel and are held in a receptacle at the end of the funnel. The actual design of these traps can differ. The netting may actually be spread over the redd and the edges buried in the gravel (e.g. Philips and Koski 1969, Porter 1973). It is important that the netting be supported by a frame since it will be pinned onto the bed by the current, a problem which may be made worse by the growth of algae. On emergence, the fry may have no option but to enter the funnel since there may be no escape. However, in one study (Garcia de Leaniz e*t al.* 1993), salmon fry were found to burrow out underneath such a device. This occurred in an upland stream in Scotland where the gravel may be relatively free from fine sediments and so this phenomenon may not be universal. In a simpler system, Shearer (1961) merely set funnel nets with an open mouth presented to the current which intercepted fry moving downstream. In that instance, the trap would not be specific to one redd and could not be expected to trap all the fry emerging from one redd. However, such a system has the advantage in that it may not cause fine sediment to accumulate on the redd as can occur in a totally enclosed redd (Hausle and Coble 1976).

The methodological problems in using this technique have recently been reviewed by Rubin (1995). A major problem is that the number of eggs in the redd is not known to start with, although this can be estimated (assuming the female lays all her eggs in one redd) if the length of the female can be estimated whilst she is on the redd, and then related to a length-fecundity relationship derived for the population in question. Rubin (1995) concluded that fry trapping was not a guaranteed reliable method of assessing survival rates from spawning to emergence. Whilst, perhaps, not highly precise, fry trapping is likely to be suitable in differentiating between extremely poor survival and high survival rates and so may be appropriate in streams where it is perceived that siltation problems may be bad.

A fundamental consideration if using emergence traps is to be able to predict when fry will emerge from the gravel. In order to do this the date of spawning must be known and water temperatures continually monitored. Emergence will take place after about 840 degree days. However, intra-gravel temperatures may be slightly different and if dissolved oxygen levels are reduced emergence may be delayed. Thus the traps must be placed in good time and left a due length of time.

Redd excavation and freeze-coring

An alternative approach to determining survival rates within a redd is to find out how many dead eggs/alevins remain under the gravel. Thus, after emergence is expected to have occurred, redds can be excavated and fine material trapped in fine mesh netting as it drifts downstream. The major drawback to this otherwise simple approach, is the decomposition of eggs and fry. In some environments, especially cold upland streams (where embryo survival is least likely to be a problem anyway), decomposition may be relatively slow, but this cannot be guaranteed. Likewise, it also depends when mortality occurs. If it is early on, then the likelihood of decomposition will be greater. If significant numbers of dead eggs/alevins are to be found, then it may be concluded that survival rates are poor, but if nothing is found then nothing can be concluded.

Redd excavation can also be attempted immediately prior to emergence, to determine how many live alevins to dead alevins/eggs are found. In addition to direct excavation, cores from the redd can be removed by freeze-coring (Everest *et al.* 1982, Carling and Crompton 1988). This entails pushing a hollow metal probe into the redd and pouring liquid nitrogen or carbon dioxide into it. The surrounding gravels are frozen onto the probe which can then be removed from the gravel by means of a lifting apparatus. This technique has the advantage that the structure of a sample of the redd can be observed, unlike the more destructive previous technique, and little material is lost. This means that if sedimentation of redds is a problem it will be readily identified.

If it is assumed that the samples are representative and lost dead eggs/alevins can be accounted for, these excavation techniques can be used to estimate survival without prior knowledge of the egg deposition. In order to account for the loss of dead eggs correction factors could be computed (Hausle and Coble, 1976). This involves burying mesh receptacles containing dead eggs within redds and retrieving them on excavation.

Planting known numbers of eggs

Rubin (1995) considered that the best way of assessing intra-gravel survival rates is to insert a known number of fertilized eggs into an egg pocket in a natural redd in a sealed mesh container. On retrieving the container at the time emergence would be expected, survival rates can be assessed. Rubin (1995) also describes containers placed in the gravel which are connected to surface holding boxes by means of a pipe up which the fry can "emerge". The important factors in this approach are that the experimental egg containers should be placed within an actual pre-existing egg pocket. Rubin (1995) stressed the importance of exact egg placement, as conditions for incubation can vary within a redd. To place the containers, a hollow pipe with a removable solid metal core was first driven through the gravel into the egg pocket, the core removed, the container pushed down the pipe, and the pipe then removed. A streamlined float on length of string should be attached to the container in order to relocate it.

Potential problems with this approach include the difficulty there may be in ensuring the capsule is actually inserted into the egg pocket. Also, the process of inserting the capsule could result in the death of eggs in the pocket which could become infected with fungus which in turn could infect the eggs in the capsule.

Surveys of abundance of 0+ aged trout

Given that trout do not generally move more than several hundred metres from spawning areas in their first summer (Chapter 3), electrofishing surveys (Section 6.3.4) of 0+ fish during their first summer, can be used to ascertain whether there has been successful spawning or not. Actual survival rates during incubation cannot, of course, be determined by this method, but in environments where there is concern about the potential siltation of redds or problems with acidity, such surveys can point to whether spawning is completely unsuccessful or not. They can also be useful in demonstrating whether or not spawning has occurred in streams where it has not been possible to actually observe redds.

A most important point is that 0+ surveys need to be conducted as soon as is possible in the summer, because the longer the delay, the more mortality and movements will have affected numbers. Trout can be successfully electrofished when they are over about 40 mm, a length which may be achieved by late spring in a warm, productive southern stream but not until late summer in a cool, low-productivity upland stream.

6.3.4 Habitat usage by trout

Introduction

A number of techniques may be used to assess habitat usage by free swimming trout. These include the following.

Direct visual observations of habitat use

Where water clarity allows, it is frequently possible to directly observe trout at feeding stations. Larger trout are most easily identified, but conversely, larger trout may occupy less conspicuous positions. A number of studies report such direct observations. Elliott (1990) and Bozek and Rahel (1991) observed even 0+ trout in shallow water by making a careful approach on the bank. Bachman (1984) made detailed observations on wild brown trout, even to the extent of individually identifying them by their spot patterns, by means of binoculars from a tower on the bank. Underwater observation is also frequently performed with either scuba equipment or snorkelling (e.g. Hankin and Reeves 1988). However, a drawback with direct observation (which cannot always be performed anyway) is that not all of the fish may be visible, and so, this technique is normally used in assessment of microhabitat use rather than for appraising numbers present. Some fish may not hold territories (Elliott 1990) and some may be concealed. If this technique can be employed, it will not provide exact information on overall numbers of trout but it does show which habitats are being used (Hankin and Reeves 1988).

Angling catch-per-unit-effort (CPUE) data.
Angling data can be used to assess numbers of fish in a stream. However, there are a number of important factors to bear in mind in interpreting changes in catches. Catch does not only depend on numbers of fish present, but on the "effort" expended - i.e. the amount of time spent angling plus nebulous factors like angling skill and determination. Other factors like discharge, cover, the weather, food availability, trout feeding behaviour, channel configuration, time of year and so on can influence the susceptibility of trout to capture.

Angling catch data can be corrected for effort to produce an index of Catch-Per-Unit-Effort (CPUE) - e.g. number of fish caught per hour or similar. Anglers should be requested to keep detailed records of what they catch in terms of the size of each fish, whether it was killed or returned and how long they spent fishing. In some types of fishery, anglers may be provided with the requisite paperwork and will provide the data themselves. However, in other instances, difficulties can be experienced in obtaining good data directly from anglers. In such cases "creel surveys" have to be undertaken whereby anglers are actually interviewed on the bank or at some access point as they leave the river.

However, because of the problems over angler behaviour, Ney (1993) states that where angling is intensive, angling CPUE should not be used as an index of fish abundance. Rather, in such a situation, total catch may be a more realistic indicator of fish abundance. This latter can be obtained directly from catch records where these are comprehensive, or where catch records are partially complete, estimated by the procedures outlined by Malvestuto (1983) and Small and Downham (1985).

Up to date information on analysis of catch statistics will be provided in a forthcoming EA research project (Environment Agency 1997).

Quantitative estimates of fish numbers
A number of methods exist whereby numbers of fish in a stream can be estimated quantitatively. These essentially involve some efficient means of catching the fish, the efficiency of which can be estimated.

Two standard methods of estimating fishing efficiency are the "removal" and the "mark and recapture" methods.

Removal method
The removal method involves repeatedly removing fish from a closed length of stream, where the probability of capture must be the same on each occasion (i.e. the removal effort expended is constant, the catchability of the fish does not change and the behaviour of the fish does not

change), the probability of capture of each fish must be independent and all individuals must have the same probability of being captured. The rate at which the catch declines (assuming the probability of capture is high) between successive fishings can be used mathematically to predict the proportion of fish being caught by each fishing and hence the total number of fish present (Wyatt and Lacey 1994). A number of mathematical models have been formulated to perform this task (e.g. Zippin 1956, Seber and Le Cren 1967 and Carle and Strub 1978). The maximum weighted likelihood (MWL) of Carle and Strub (1978) is recommended (Wyatt and Lacey 1994).

MWL estimates can be made from as little as two depletions. However, the accuracy of the estimation increases with the number of depletions and the capture efficiency (Bohlin *et al.* 1990, Riley and Fausch 1992). Biologists frequently use two passes in order to reduce what is a time-consuming exercise, but Riley and Fausch (1992) considered that unless calibration is attempted in the particular stream in question (i.e. by conducting four or more removals and comparing the result with the result which would have been obtained if only two had been used), then at least three fishings should be performed. To be valid, the total population should amount to over 30 fish (Riley and Fausch 1995), otherwise the total number caught has to be used and no error terms are available. This is an easily overlooked consideration, because surveys should involve estimates of the abundance of individual year classes (as differentiated on the basis of length frequency distributions and scale analyses). Clearly, it is important to sample a sufficiently long section to catch enough fish.

Mark and recapture

Mark and recapture essentially involves liberating a known number of marked fish (usually obtained prior from the place where they are reintroduced) into a stream. The stream is then fished, and the ratio of unmarked to marked fish when multiplied by the number of marked fish liberated provides an estimate of the total number of number of unmarked fish present. A number of requirements are that marked fish are randomly distributed amongst unmarked fish, marking must not influence the subsequent likelihood of recapture, mark retention is 100% or can be corrected for and there is no additional mortality on introduced fish. Readers seeking to employ this technique are advised to consult Cormack (1968, 1972) for further details on the statistical procedures involved, methods of error estimation and potential biases.

Electrofishing and seine netting

The two methods which are generally employed for actually catching the trout with the removal method or with mark and recapture are either electrofishing or seine netting. Electrofishing is generally employed in streams or small rivers or shallow reaches of large rivers because the electric field has a limited range and stunned fish have to be manually collected. Seine netting is generally employed in large rivers. Seine netting requires a river bed which is free from obstructions and is frequently used in lowland rivers to assess cyprinid populations. Its value for assessing trout populations is likely to be less because many salmonid streams contain obstructions and snags which make seine netting impossible.

The technique which is most applicable to trout stream appraisal is, therefore, electrofishing. Nowadays, the removal method, is normally always employed with electrofishing rather than mark-recapture. A number of potential problems and biases with electrofishing are discussed in Bohlin *et al.* (1990), Bohlin and Cowx (1990) and Riley and Fausch (1992).

Sampling protocol

When conducting an electrofishing survey (and even more so with seine netting) it is frequently impossible to survey an entire stream. Thus, if comparisons are to be made across space and time, then sample sections of manageable length must be appraised. In order to be representative, a number of sampling sites may be necessary in a given stream in order to overcome spatial variation in fish numbers according to differences in habitat quality etc. Further details on how to calculate how many sub-sections are required and how these should be distributed can be found in Bohlin (1990) and Wyatt and Lacey (1994).

Interpretation of electrofishing data

The whole purpose of the preliminary electrofishing surveys is to corroborate hypotheses regarding the quality of the habitat for different life-stages based on habitat surveys. However, the next question which arises is whether the data obtained are indicative of numbers which may be expected in a good habitat or a bad habitat. As a guide, it is recommended that the EA's National Fisheries Classification for trout (Mainstone *et al.* 1994) is used. The Fisheries Classification for salmonids is based on data from 672 sites throughout England and Wales. There are two elements to the classification - the Absolute Classification and the Relative Classification. With the former, densities of trout (separated into 0+ or >0+ categories) from the entire database were ranked, and on the basis of 20% divisions, classes of abundance were computed (Box 6.5). With the Relative Classification, classes of abundance are based on streams within specific stream width/gradient bands.

Box 6.5 The Absolute Fisheries Classification

The values (in numbers per 100 m^2) represent the lower class boundaries.

	Class					
	A	B	C	D	E	F
0+ trout	38	17	8	3	>0	0
>0+ trout	21	12	5	2	>0	0

On electrofishing a stream, the observed densities of 0+ and older trout should be assigned to their respective class within the Absolute Fisheries Classification, and these can be used as a guide to how high or low numbers are first of all. However, for better detail according to stream type, the relative classification should be used. This requires the use of the EA computer package.

6.4 Limiting Factor Identification

6.4.1 Introduction

After performing the habitat survey and subsequently performing corroborative fisheries surveys, the quantities and distribution of habitats for particular life-stages within the stream/catchment will have been determined. The next problem is to identify the lack of which habitats may be limiting the overall population and where these habitats are located. These considerations are especially important as they will determine which type of restoration work needs to be performed and where it will be carried out.

Identification of limiting factors is not an easy or exact process. Although it is widely stressed, there is little guidance on the subject in the literature (e.g. White and Brynildson 1967, Hunter 1991). The procedure outlined here is essentially one of elimination.

6.4.2 Procedure

Absent habitats
The easiest type of limiting factor to identify is where streams completely lack habitat for one particular life-stage (for example there may be no spawning gravel), then that obviously will be a limiting factor. Therefore, it is firstly necessary to identify whether particular habitat types are completely absent, or whether a habitat feature which would benefit all life stages is completely missing (for example, if bankside cover was being eaten by livestock or being shaded out by trees).

Habitat juxtaposition
The next step is to analyze the distribution of the different habitats. As described in Chapter 3, different habitats are not independent. For example, good spawning habitat will be of little value if there is no good fry habitat in the vicinity. Spawning habitat, fry habitat and juvenile habitat all need to exist in close proximity and these should occur repeatedly. If they do not, then another limiting factor may have been identified.

However, a major knowledge gap is knowing exactly how much of these different habitat types is required and how these should be distributed to optimize the population. In the absence of better information, most restoration studies have merely tried to recreate what may be considered a natural sequence of pools and riffles (Mann and Winfield 1992, Hunt 1993). At any rate, it would not be expected in a "natural" river system that an "optimum" mix of habitats would ever occur over any great distance. Nursery habitat should be more abundant than adult habitat in tributaries and then there will be a progressive change going downstream until only adult habitat is present in the main stem.

Use of fishery survey data
Data on actual trout numbers can provide useful information in identifying limiting habitats. Essentially, the later in the life-history the population is constrained, the more informative a survey will be.

For example, in a shallow gravelly stream, the habitat survey may suggest that adult habitat is lacking and an electrofishing survey may indeed prove there are few adult fish. If the survey also shows there are high numbers of juvenile trout, then it may be concluded that adult habitat is the problem and a main bottleneck has been identified. However, if few juveniles are found it may mean that the spawning habitat is also unsuitable or, alternatively, there are too few spawners because of the lack of adult habitat, and so on. To further disentangle such a problem, it would be necessary to artificially stock the stream with a high density of fry to see if the habitat could actually hold juveniles. In another example, a stream may be deep and contain few shallow areas. A survey may reveal that there are few fry or juveniles, but a greater number of adults. This would indicate that spawning/juvenile habitat is limited but it does not necessarily mean that the habitat is first class for adults, given that recruitment may be insufficient to stock the available adult habitat.

Conclusion

In concluding this section, it must be said that current knowledge does not always readily permit detailed appraisal of habitat potential. If a stream appears to contain some mixture of different habitat types it may be difficult to say just how good it is. Only by progressively removing potential bottlenecks, starting from spawning habitat, can the existence of bottlenecks at older life-stages can be identified. Thus, as stated in Chapter 5, limiting factor analysis is really an ongoing process, continually being improved as more information becomes available. However, on a more practical note, habitat deficiencies are all too frequently glaringly obvious.

7. SCHEME APPRAISAL

7.1 Introduction

As stated in Chapter 5, a fundamental aspect of a restoration project which should be considered from the outset is how any such project should be appraised, both in terms of physical effects on the stream and on the trout population. The chosen method of appraisal will depend on the scale of the scheme and its objectives. Options are now described.

7.2 Identification of strategy

7.2.1 The design of experiments to demonstrate effects of habitat improvement on trout populations

Before appraisal methods can be described, there are several difficulties involved with appraising the effects of restoration work on fish populations which must be considered.

Time-scale of habitat and population response
An important requirement to assess the full impact of a restoration scheme is the continuation of monitoring for several years after the treatment. Firstly, the evolution of the restored habitat could carry on for many years. Any increase in juvenile survival or improvement in spawning habitat will take a few years to feed through to the adult population and this could further benefit from a corresponding increase in egg deposition. For example, Hunt (1976) found that it took five to seven years for the brook trout population he was studying to stabilize and considered that appraisal need not have commenced until three years after the restoration.

Background variation in trout numbers
A major problem is background variation in fish numbers. Many workers have stressed that salmonid numbers in a stream can vary markedly over time (e.g. Platts and Nelson 1988). This frequently occurs because of changing year class strength due to fluctuating environmental conditions (Elliott 1994). Where it exists, variation may mask any change which may occur in a trout population in a restored stream. As a consequence, from a strictly statistical point of view, it is not considered sufficient to merely restore a stream and conclude an impact has occurred from a single year of appraisal before and after, unless control sites are involved (see below).

There are basically three experimental approaches which can be used to overcome this problem.

The extended study
This involves long-term monitoring of fish populations on a long stream section before restoration, to include years of widely-ranging flows, followed by a similarly long phase of post-restoration monitoring so that long term average population levels can be assessed.

This approach was used by Hunt (1976) to appraise the effects of improving a brook trout stream. He conducted an appraisal for three years before restoration and then found that it took a further six years for the improvement to fully show through. The long-term element is important but adds to the cost and requires long-term planning and resource commitment. Moreover, it is not possible to separate out a treatment effect from a natural long term change. Not surprisingly, little of this type of appraisal has been done.

Paired design within a stream
Pairs of similar stream sections, one of which is to be restored and the other left as a control, are subject to surveys pre- and post-restoration. Analyses are made on the basis of a null hypothesis of no difference between experimental and control stream sections. This design has the advantage in that it does not necessarily require extended surveys to demonstrate a treatment effect (though the effect may not necessarily be the long-term one when the population stabilizes). An adjacent, especially upstream, untreated zone may be expected to share in common many of the causes of variation with the zone to be treated and so the problem of variation is easily overcome (Platts and Nelson 1988). A preliminary survey is a means of checking that the paired experimental and control sections are not different before restoration. This is to be recommended, although not strictly necessary. However, despite its appeal, surprisingly few studies have adopted this approach (Mann and Winfield 1992).

Potential problems with this approach are that the experimental section may affect the control one (for example the migration of fish from the control section to the treated section, as considered below), and that a pair can affect another pair downstream.

Paired streams
This approach is essentially the same as the previous design, except that similar adjacent streams are compared, rather than sections within the same stream. A problem with this approach is that different streams need to be comparable. Therefore, at the least, a preliminary survey should be carried out to show that pairs of streams are not different in terms of fish, although Rinne (1988) considered there was a need for detailed physical, chemical and biotic surveys as well. Consequently, more work may be generated than even with the long-term approach. On the other hand, this approach benefits over the paired approach because the pairs are likely to be truly independent.

Replication
Most comparisons between treated streams/stream sections and controls generally consist of perhaps a single improved section and a control (e.g. Rinne 1988). As such, these provide a comparison but do not allow the use of inferential statistics to demonstrate treatment effects as against the possibility of some unforeseen variation. Hurlbert (1984), in a good practical exposition of the design and interpretation of the results of experiments, states that for paired comparisons, at least six replicates are required to demonstrate an effect using a Wilcoxon signed-rank test. However, if streams over a sufficiently wide area were deemed similar enough to be compared at random instead of in pairs, a minimum of four treated and four untreated streams would be necessary for a Mann-Whitney U test. These minimum recommendations could be further reduced to four pairs if a paired *t* test were used, and three treated and three untreated streams for an ordinary *t* test, assuming the other requirements of the test are fulfilled (Sokal and Rohlf 1981). The only study in the literature which claims to have attempted replication like this is a very recent one by Riley and Fausch (1995). A common mistake to avoid, is to treat subsamples within a treatment and control zone as experimental replicates. That does not constitute replication of treatments, but is known as

pseudoreplication (Hurlbert 1984).

This basic type of design to test the effect of some treatment is not only applicable to fish numbers, but also to other impacts - for example, the effects of gravel treatment on egg survival rates.

Increased production or redistribution?
Interpreting why a change in trout numbers has come about may be difficult. Mann and Winfield (1992) point out that, locally, fish numbers can increase as a result of increased survival at some stage in the life-cycle but also through a geographic redistribution without there necessarily being any increase in overall numbers. For example, a restoration scheme which causes adult trout to settle in a particular area and abandon the one which they may have previously used, may appear successful on a local scale, but may actually be detrimental to other areas. Another example may be where new spawning areas are created and the fish use these in preference to the old areas, with a resulting change in the distribution of juveniles in the stream.

It is not easy to disentangle the effects of migration and survival. The only studies which have attempted to do so are those of Hunt (1976) and Riley and Fausch (1995). Accurate measures of mortality are required in both untreated and treated sections or before a treatment and after. This requires a marking system with very high mark retention rates and an intensive survey system that is guaranteed to find marked fish that are still alive, wherever they may have moved. One possibility is to have an extensive study area which will encompass the home range of all marked fish for life (Riley and Fausch 1995).

Conclusions
Detailed appraisals are effectively in the realm of scientific research and out-with the scope of many practical stream restorers - hence the reason so little has been done. However, the fact that a thorough appraisal of the overall impact of stream restoration is difficult, should not prevent some appraisal, for it may be much simpler to appraise some of the specific aims of restoration using the designs outlined above.

7.2.2 Practical appraisal in the context of specific aims

The specific aim of a restoration scheme may be to restore some particular element of habitat which is holding back the entire trout population, the increase of which may be the overall aim. For example, the specific aim may be to create new spawning habitat. It is easier to determine whether new spawning habitat has been successfully created, rather than whether the entire population of fish has increased. The success of spawning habitat creation will be apparent from numbers of fish which actually spawn on new areas, relative to previously used areas. Likewise, in a scheme which creates better conditions for holding adult trout, irrespective of whether an increase results from increased production or geographic redistribution, any increase in fish numbers means that the specific aim of improving adult habitat has been successful.

Therefore, whilst the overall aim of scheme appraisal should be to demonstrate changes in the overall population, in reality, the immediate issue for the stream restorer is whether he can actually create the type of habitat intended. The overall effect of habitat restoration will be immaterial if the actual attempt at creating a specific habitat fails. It is most important, therefore, that the specific aims are appraised. So, even if overall effects cannot be fully appraised, the specific aims should be.

To appraise a specific aim, any restoration should incorporate treatment and control sites, preferably paired and with a sufficient number of true replicates. Ideally, some pre-scheme assessment should take place on all sites. Such a design at least obviates the requirement of a long-term commitment, which few organisations are able to make.

Even if a thorough appraisal is not possible, some degree of appraisal should always be conducted. For example, if no replication of a treatment is possible, pre- and post treatment surveys should still be conducted on the treated area and on a control area. Any change which occurs on the treated area relative to the control area may well result from the treatment, but the possibility of some other unforeseen factor cannot be discounted. In such a situation, a stream restorer, faced with a knowledge of local conditions, must satisfy him or herself whether the treatment is likely to be responsible. It should be remembered that the more such individual appraisals are performed, the greater the probability that some complication will have played a part. However, this situation is preferable to having no appraisal at all.

7.3 Habitat Appraisal

7.3.1 Introduction

In addition to appraising effects on the trout population, it is also important to show whether treatments really do change the stream in the manner envisaged or otherwise. This involves firstly producing detailed measurements of the physical habitat before the work is carried out. This survey will often be additional to the pre-scheme limiting factors survey and may involve even more detailed data collection. After the work has been carried out, another survey employing the same methodology must be conducted. In fact surveys may need to be conducted for several years as the stream moves to a new equilibrium.

Depending on the exact nature of the restoration different methods of appraisal are required. All involve obtaining detailed systematic measurements, though the level of detail can vary.

7.3.2 Walk-over survey

The simplest level of detail which may be used are the measurements taken on the walk-over survey which is described in detail in Section 6.2.2. Where really major changes in the habitat are envisaged over long stretches of stream and precision is not considered important, this technique may be perfectly adequate, and indeed, may be the most practicable.

7.3.3 Transects

A more rigorous form of data collection than the walk-over survey is by the transect method (Orth 1983). Basically, point readings are taken at intervals across a cross-section (transect) of the stream at regular distances along the stream. The spacing between transects depends on the width of the stream and the degree to which the width varies, and may be expected to vary after restoration. Intervals between sampling points on a transect should also be of a distance which will be representative. For example, they should be closer together in a stream with an undulating bed than if the bed is even. As described in Chapter 6, depths, current velocities and substrate types are ascertained at each sampling point. Quantities of overhead cover must also be measured.

With these data, it is possible to demonstrate changes in stream width, degree of cover, water depth and substrate type. However, it is not possible to demonstrate changes in the actual level of the bed, the level of the water surface or its gradient, the position of each particular bank or bank height. These require the establishment of a fixed base-line as now described.

7.3.4 Permanent transects

Permanent transects can be marked out by fixing permanent pegs on the same level on the bank at each end of the transect. A surveyor's level will be required to fix the height of the pegs (see Section 7.3.5). By stretching a taut string across the stream, a reference level is created for each transect which can always be referred to. By measuring the vertical height downwards from the string, it is possible to detect changes in the actual bed level and stream surface level. By measuring horizontal distances, the position of the bank is also fixed.

7.3.5 Levelling

A better method for performing a physical survey involves the use of a surveyor's level and staff. Firstly, a fixed reference point should be established on the bank (preferably related to the Ordnance Datum). From this point, the level is used in conjunction with the transect method to ascertain the level of the streambed and water surface at each point.

7.3.6 Theodolite survey

The best, but most time consuming survey method involves the use of a theodolite or modern electronic surveying equipment. This enables each point surveyed to actually be plotted in space so that both changes in the bed level and bank position can be determined.

7.3.7 Choice of method

The choice of these different survey methods will depend on whether the operator has access to all the methods, financial and time constraints, and the questions which need to be answered. For example, if cover is being restored on long stretches of stream, then all that may be required is a simple measure of change in stream width and degree of cover. This may even be satisfied by the walk-over survey described in the previous chapter. However, if a new spawning riffle were to be created by the addition of gravel, then a detailed survey may be needed to determine its effects on depths and current speeds and its long term stability.

7.4 Models of Habitat Quality

7.4.1 Introduction

One method which may be employed to directly appraise a change in "habitat" quality, is to use a habitat model. This approach has been little used in the context of appraising restoration work, but it clearly has potential.

7.4.2 HABSCORE

In Section 6.2.3 the empirical HABSCORE model, which is widely used by the EA, was described. On streams which are comparable with those on which HABSCORE is calibrated, a reach may be appraised before restoration work takes place and then afterwards. This could demonstrate a change in habitat quality. HABSCORE is calibrated for different life-stages, so the effects of the restoration work could be appraised at this level.

7.4.3 PHABSIM

The Physical Habitat Simulation System is a model developed in the USA specifically to relate habitat quality to different levels of flow in a stream (Bovee 1982). It is currently being used in Britain for similar applications (Johnson *et al.* 1993). The basis of the model is similar to that of the Habitat Suitability Index model described in Section 6.2.3. That is, it provides a theoretical index of habitat quality for trout of a particular life-stage within a stretch of stream based on available depths, current speeds, substrates and cover. Commonly, this index is expressed as the Weighted Useable Area (WUA), a theoretical measure of the amount of suitable habitat.

The usual application of PHABSIM has been to predict the effects of different flows on WUA in issues relating to water resource developments (e.g. Johnson *et al.* 1995), but it has been used to calculate WUA before and after habitat restoration to demonstrate a change in habitat quality (Shuler and Nehring 1994). However, this is a complex technique and its use in the context of appraising habitat restoration is still in development.

7.5 Cost-Benefit Analysis and Reporting

7.5.1 Introduction

Many of the techniques used in trout stream restoration can entail considerable expense, especially if long stretches of stream are involved. It is important, therefore, that the benefits of restoration schemes outweigh the expense. However, cost-benefit analysis is a complex subject, as will now be outlined. It involves the conversion of both costs and benefits into monetary units (National Rivers Authority 1993), but in a situation like habitat restoration it can be very difficult to arrive at monetary values. The types of data which must be considered include the following.

7.5.2 Costs

Unlike some other values, the costs of habitat improvement are relatively easy to ascertain. These are the actual costs of materials and work performed, whether actual monetary costs or work in kind. Cost data should always be documented for all restoration schemes. There is no excuse for not obtaining cost data.

7.5.3 Benefits

Types of benefit

While the costs of habitat restoration are evident, some of the benefits really are hard to quantify. The benefits of trout habitat restoration can take several forms. For example, an increase in angling catch, numbers of anglers fishing, the value of the fishery or public amenity are all obvious benefits in themselves. These are considered to be "use-related" benefits. However, habitat restoration also produces "non-use-related" benefits. These benefits are not necessarily enjoyed directly by users, but may be perceived as important by the public at large. These may include such things as an increase in trout numbers in itself, an increase in the numbers of some uncommon genetic strain of trout or an improvement in the overall ecological status of the river.

Identifying benefits

As there are many different types of benefits which may be expected, a wide range of data must be collected to identify any benefits which may accrue from habitat restoration. Earlier in this chapter, the difficulties in ascribing increases in trout numbers to habitat improvements were described. These difficulties may be multiplied up when the various use and non-use related benefits have also to be shown to have resulted from the habitat improvements! Thus, identifying the benefits can be very difficult, before any values are even assigned to them.

Assigning values to benefits

Some of the use-related benefits derived from trout habitat restoration have a direct monetary value. These include an increase in fishery revenue or the capital value of the fishings or the money saved by not having to stock farm-reared trout. Assigning values to non-use related benefits and some other use-related benefits (e.g. increased recreational opportunity or amenity value) is complicated and beyond the scope of this manual. Instead, the *Economic Appraisal Manual* (National Rivers Authority 1993) should be consulted.

It must be accepted that, at the present time, undertaking a complete cost-benefit analysis will be beyond many restoration projects. However, even if this is the case, it is important that as much information should be collected as possible. Even if it is not possible to put a financial value on all benefits, the non financial aspects of a restoration (e.g. merely increasing trout numbers or improving a fishery) may be regarded as an end of expenditure in itself by some promoters.

7.5.4 Cost-effectiveness

Another consideration which is slightly different from cost-benefit, is the concept of cost-effectiveness. With cost-effectiveness it is not necessary to put a monetary value on benefits but merely to identify what the benefits are. The costs of different restoration techniques are then compared to see which ones provide the best value for money. The type of index used to do this could be the cost per trout of a certain size produced, or something similar.

7.5.5 Summary of cost-benefit procedure

Cost-benefit analysis is a complicated area and some of the procedures will be beyond the scope of most people involved in habitat restoration. However, the following are the steps which can and should always be undertaken by all schemes.

- All costs incurred, whether monetary or in kind, must be noted.
- The qualitative benefits should be recorded (for example, "numbers of fish have increased", or "the fishing has improved" etc.).
- Quantify all the benefits which can be quantified (e.g. how many more fish are there, by how much has fishery value increased etc.).
- Use the above information to produce an assessment of cost-effectiveness.
- Cost-benefit appraisal involving non-use related benefits is a developing area and specialist advice should be sought.

7.5.6 Reporting

A final consideration is that once a scheme has been fully appraised in terms of effects on trout, the general habitat and costs and benefits, this information must be reported. This is a most important consideration as it permits the exchange of experiences which is necessary if the discipline of stream restoration is to develop.

8. HABITAT RESTORATION TECHNIQUES

8.1 The Approach to Habitat Restoration

Having decided that a stream is in need of restoration, and the habitat deficiencies identified, the next problem is how to treat them. This chapter details the various methods which may be applied to overcome specific habitat problems.

As stated earlier, there are different approaches to habitat restoration. If a problem is ongoing, it may be possible to treat the actual causes at the catchment level, but it may also be possible to ameliorate the symptoms by physical alteration of the channel. However, the latter course can involve either "soft engineering" (the use of natural sedimentary processes allied to the ability of vegetation to trap and stabilize sediment) or "hard engineering", where direct action is taken to modify a channel.

The essential philosophy taken in this manual is to influence the physical and biological processes which create the stream environment, if this is at all possible. Therefore, methods of habitat improvement are considered firstly at the catchment scale. Although it is appreciated that it is most difficult to influence catchment scale management, it needs to be considered, as catchment management should be the long-term overall ambition. In-stream works which may be applied on a more local basis, essentially to treat symptoms, are described last.

Where direct instream works are necessary, the soft engineering approach is promoted where possible. This is because soft engineering may often be performed by people who have no knowledge of engineering as such. Many habitat problems have relatively simple causes (e.g. dredging, overgrazing and bank damage, overshading by trees) and the solutions to many of these problems are often equally simple, though maybe requiring a great deal of physical labour. Therefore, people lacking in engineering expertise need not feel daunted by the task. It should be stressed that habitat management is fundamentally an ecological exercise, rather than an engineering one. Another benefit of the soft engineering approach is that the stream will create the desired habitat itself and will, therefore, be stable. However, hard engineering often involves a degree of 'straight-jacketing' the channel and if the design is not correct costly failures can result. For example, the physical alteration of a channel can cause water velocities to increase and if these are unduly high, scouring of the bed can ensue, eventually leading to the collapse of the works.

Some restoration techniques do involve highly complex technical methods which are beyond the scope of anyone lacking a specialist engineering and geomorphological knowledge. Some techniques (e.g. meander reinstatement) require a multi-disciplinary specialist input and approach.

It is appreciated that many of the hard engineering options may be of greatest application to most individual fishery managers, given that the response of the habitat is quick, but a genuine need for them should always be established. Trout stream restoration should not automatically be thought of as building structures in the river. Not that structures do not have their place, but undue reliance should not be placed on them for restoration schemes in general.

8.2 Catchment Management

8.2.1 Introduction

Many problems affecting streams stem from the wider catchment. These include inputs of sediment, nutrients and other chemical pollutants. Increased sediment loads, especially when combined with increased in-stream plant growth, can affect trout spawning habitat, physically change rearing habitat and overall channel shape. Dredging is often found necessary to "restore" channel capacity, causing even further damage. In this all too common scenario, the best solution is to remove the problem, if possible, as it may be difficult to offset the recurring symptoms. Restoration work which seeks only to treat the symptoms of stream degradation may provide only a short-term remedy but catchment scale solutions will provide long term benefits.

The reduction of inputs from the wider catchment may not be easy to achieve but there are several possible approaches which can be adopted. These include stopping erosion at source, stopping the products of erosion entering watercourses or, if the former are not possible, removing the products of erosion from the stream itself. These options are now considered.

8.2.2 Land use

Introduction
The most fundamental and sustainable method of preventing erosion from the catchment is for land use practices to be adopted which prevent erosion occurring in the first place. Reeves *et al.* (1991) note that the most successful method of habitat rehabilitation has been watershed protection.

Benefits
By reducing inputs of fine sediment into streams habitat conditions will be improved for all life-stages of trout. The extent of spawning habitat will increase as gravels are uncovered and incubation success will increase. A reduction in the degree of embeddedness of habitat features will also create more habitat for fry and deeper pools will improve the habitat for adult trout.

Implementation
Catchment management can only really be achieved through the formulation of land use policies and catchment planning strategies by Government and related agencies, land owners and land users. Whilst it is appreciated that catchment management is not directly under the control of Environment Agency fisheries departments or other fisheries interests and that the detailed description of methods is not warranted in this manual, it should be appreciated that catchment management is a fundamental issue which must be tackled in the long term.

Many forestry practices can have damaging impacts on water courses, especially in fragile upland systems. Official guidelines have already been drawn up by the Forestry Commission (Anon 1993) and these detail those practices which should be adopted to minimize impacts on fresh waters. These include the adoption of shallow ploughing and the draining of furrows onto vegetated surfaces and silt traps rather than into water courses.

Comprehensive official policies or guidelines do not exist yet in the UK on sympathetic agricultural practices in the context of catchment management, partly because the practical and political situation with regard to agriculture is much more complex than with forestry. However, the Ministry of Agriculture, Fisheries and Food has published a *Code of good agricultural practice for the protection of soil* (MAFF 1993) which addresses some of the issues. This largely focuses on point sources rather than diffuse sources but guidelines for the prevention of diffuse soil erosion are currently the subject of research and development by the Environment Agency and these will be published in the near future. Similar guidelines which have been applied in parts of the USA include contour ploughing, strip planting, "conservation tillage" (i.e. planting without turning over the soil) and the planting of permanently vegetated strips in areas where overland flow is concentrated (Waters 1995).

The above considerations relate to prevention of erosion at source. Catchment management can also be used to reduce the rates at which sediment is transported from the source areas to watercourses. This is considered more fully in Section 8.2.4.

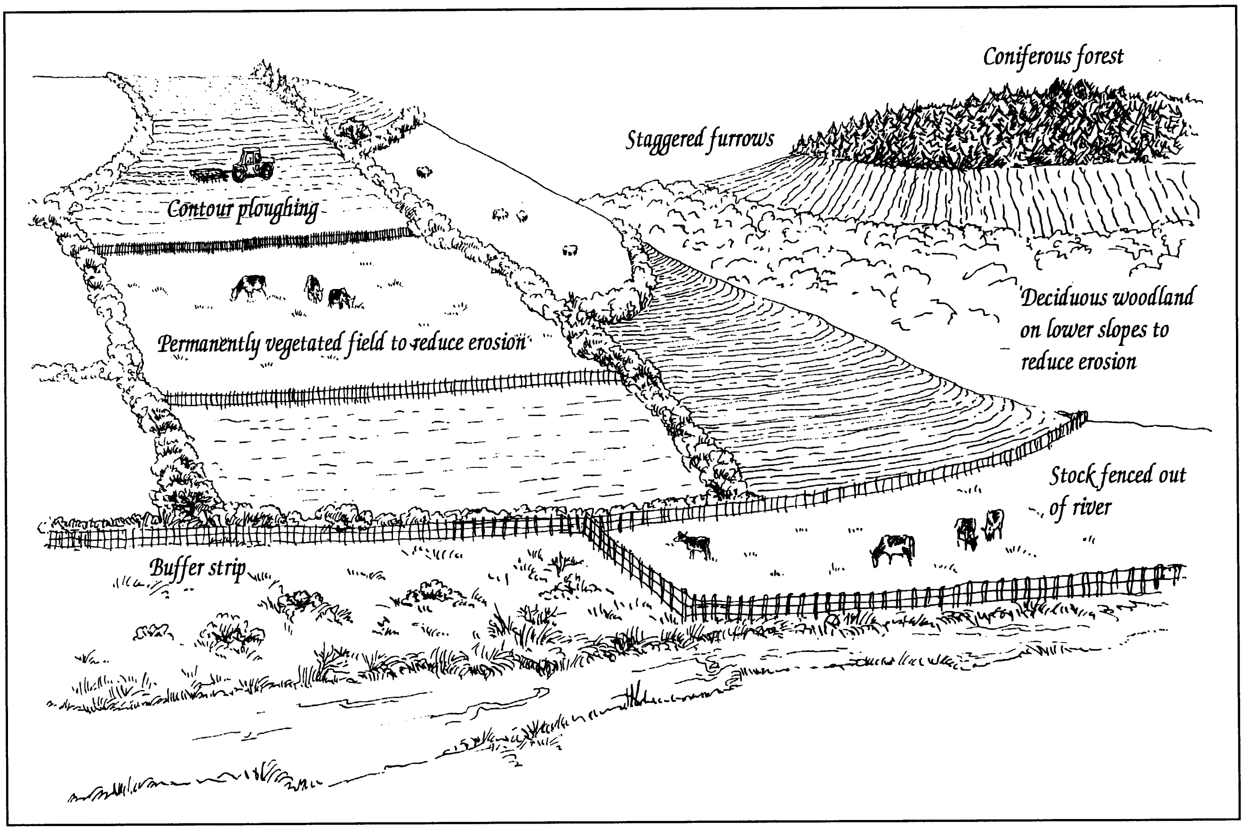


Figure 8.1 Sympathetic land use

Further information

Further information on the effects of land use on freshwaters can be found in National Rivers Authority (1992a) and Waters (1995). The latter text is especially recommended for information on ameliorative measures.

8.2.3 River Flow Regimes

Introduction

The sustainable management of a catchment requires water resources to be balanced between the needs of abstractors and instream uses such as fisheries and the wider environment. The demands to regulate river flows are considerable and include direct abstraction for domestic, industrial and agricultural purposes, hydropower etc. The EA has statutory duties and responsibilities to conserve, redistribute, augment and secure proper use of water resources. Although this manual cannot focus on such a large subject in detail, this section highlights its importance to fisheries habitat management and provides guidance to further information.

The link between flow, habitat and stream ecology

The inter-relationships between hydrology (study of the water cycle) and stream ecology are important and complex and the study of these, termed "hydro-ecology", is still developing. As discussed in Chapter 2, the stream environment is largely determined by catchment scale factors such as climate, geology, land use etc. The structure and functioning of stream systems must be viewed at this scale to understand the factors important in relation to more local management issues such as habitat restoration.

Flow regime is of great importance to the functioning and health of a stream system. A key aspect of this is that the flow regime has a fundamental link with the geomorphological processes (e.g. sediment erosion, transport and deposition) which determine the channel and floodplain morphology. In addition, the flow regime has a strong relationship with the physical habitat factors within the determined channel such as depth, flow velocity, etc. The flow regime of a stream therefore has a fundamental role in determining and maintaining instream habitat which in turn helps to determine the ecology.

The importance of flow regime for trout

The habitat requirements of the different life stages of trout are discussed in Chapter 3. This section provides a brief link between habitat requirements and flow regime.

The survival of eggs and alevins can be reduced by the dewatering of redds in low flow conditions (Frost and Brown 1967) and the reduction in the supply of oxygenated water (especially in gravel of poor permeability). Studies on salmonids have reported significant positive relationships between winter discharge and survival to fry (Gibson and Myers 1988). Very high flows may also decrease survival by destruction of redds.

The survival of fry and parr can be reduced by a number of mechanisms. The preferred habitat of these life stages may be reduced in area by reductions in flow and induce behavioural changes and use of less preferred pool habitat (Campbell and Scott 1984). The positive relationship between flow at the time of emergence and 0+ trout densities has been reported by Solomon and Paterson (1980) with possible mechanisms being increase in suitable habitat and a decrease in the area of the territory defended by individuals. The long term study by Elliott (1985) also indicates decreased survival and growth of 0+ and 1+ trout in years with summer droughts. Other mechanisms relating flow to decreased survival include stranding as a result of rapid decreases in flow (Hvidsten, 1985) and high elevated water temperatures during low summer flows.

The survival of sea trout smolt may also be positively related to flow. Studies on Atlantic salmon have shown that smolt survival is dependent upon the time they enter the sea and that delay to downstream migration due to low flows results in reduced returns. It has been suggested that high flows during downstream migration is beneficial to smolt due to reduced predation, reduced entrainment into abstraction intakes and more effective orientation.

The survival of adult trout and upstream migration of adult sea trout may also be related to flow. Studies have shown that flow is one of the most important environmental factors inducing salmonids to enter freshwater and migrate upstream (Banks, 1969). Flow is also related to the availability and distribution of adult trout habitat. The connectivity of this habitat is particularly important in relation to spawning migrations which are important to enable effective distribution and use of spawning and juvenile habitat. Spawning habitat may be reduced at low flows due to reduced water depth and water velocities.

Ecologically Acceptable Flow Regimes

It is clear from the preceding sections that flow regime is of fundamental importance to stream systems and influences both the habitat and the ecology on all scales from channel and floodplain structure to the microhabitat of specific life stages of trout. The flow requirements to maintain a healthy and sustainable ecosystem are clearly complex and vary with respect to timing, magnitude and location. An ecologically acceptable flow regime (EAFR) will be specific to each sub catchment.

The requirements of an EAFR will include identification of a suite of flow targets (Petts *et al.*, 1996). High flows are important in relation to stream processes which determine and maintain the physical habitat diversity of the instream and floodplain environment. Varying annual flow regimes are also important to maintain important ecological integrity and seasonal target flows related to specific ecological targets are required. Specific ecological targets must be identified and may include seasonal and quantified flow targets relating to adult trout migration , provision of spawning habitat, fry habitat maintenance etc.

The identification of the flow quantity and frequency required to meet these suite of targets is a complex and developing area. In relation to trout, specific targets can be identified using a range of methods including behavioural studies (fish tracking and counters) for adult migration, long term fish population studies for a range of life stages and habitat models for habitat management and protection.

The successful implementation of an EAFR requires consideration of balancing conflicting demands for instream and out of stream uses. Consultation, negotiation and regulation form part of this process with recent EA R&D projects assessing issues such as River Flow Objectives (Petts *et al.*, 1996) and the Instream Flow Incremental Methodology (IFIM) (Johnson *et al.*, 1993).

Further Information

Further information on this complex subject can be found in Gordon *et al.* (1992), Aprahamian (1993), Petts and Maddock (1994), Petts *et al.* (1995), Stalnaker *et al.* (1995), Petts (1996) and Petts *et al.* (1996).

8.2.4 Buffer strips

Introduction
Whilst land-use management in its broadest sense may be difficult to implement, a more practical solution is the use of "buffer strips" alongside watercourses. These are strips of land immediately adjacent to watercourses which are removed from agriculture and are managed to maintain specific forms of semi-natural vegetation which assimilate particular types of water-borne pollutants.

Benefits
Buffer strips can filter sediment particles and pollutants attached to these from overland flow and prevent them entering streams. They can also assimilate nutrients in solution through plant growth and remove nitrates from solution by a chemical process called denitrification which occurs in waterlogged organic rich soils (Environment Agency 1996a).

This will bring benefits to all life stages of trout. Reducing sediment loads will improve conditions for incubating eggs and uncover habitat features for older trout. There are also many wider conservation, landscape and amenity benefits associated with the buffer strip itself.

Design considerations
The design of buffer strips depends on whether they are primarily to filter sediments from overland flow or assimilate nutrients. With the former, the soil needs to be freely drained and the vegetation cover dense, but with the latter, the soil needs to be waterlogged and rich in organic matter (Environment Agency 1996a). Therefore, the types of pollutants to be removed need careful identification. Sediment and pollutant pathways also need to be identified, as these may be concentrated in particular areas. Specialist advice may be required with some of these aspects.

The dimensions and siting of a buffer to trap sediments will depend on the mode of sediment delivery. If suspended sediments are to be removed from uniform sheet flow (e.g. at the bottom of a steep ploughed field), a buffer strip of dense grasses need only be a few metres wide, but continuing along the entire channel. Where sediment delivery is concentrated in rills an extensive grassed area may be required to soak up the discharge. However, by targeting point sources, there may not be a need for buffering the entire channel length.

For successful nutrient uptake, buffer strips may need to be much wider than sediment trapping. Large and Petts (1992) recommended that minimum effective buffer zone widths are one to two metres for small ditches, ten metres for small upland streams and 100 m for large floodplain rivers. The land should not be underdrained, otherwise drainage water will bypass the buffer. Denitrification is also most effective where soils are waterlogged. Harvesting of the vegetation may also be necessary to prevent nutrient recycling.

Applicable stream types
The application of buffer strips is not constrained by stream type and, in principle, their widespread adoption is encouraged. However, a need for them must exist, and the soil/drainage characteristics of the valley floor must be of an appropriate type to be effective. For maximum benefit, buffer strips need to be applied to the whole catchment above any

specific point of interest. This includes buffering even the smallest ditches.

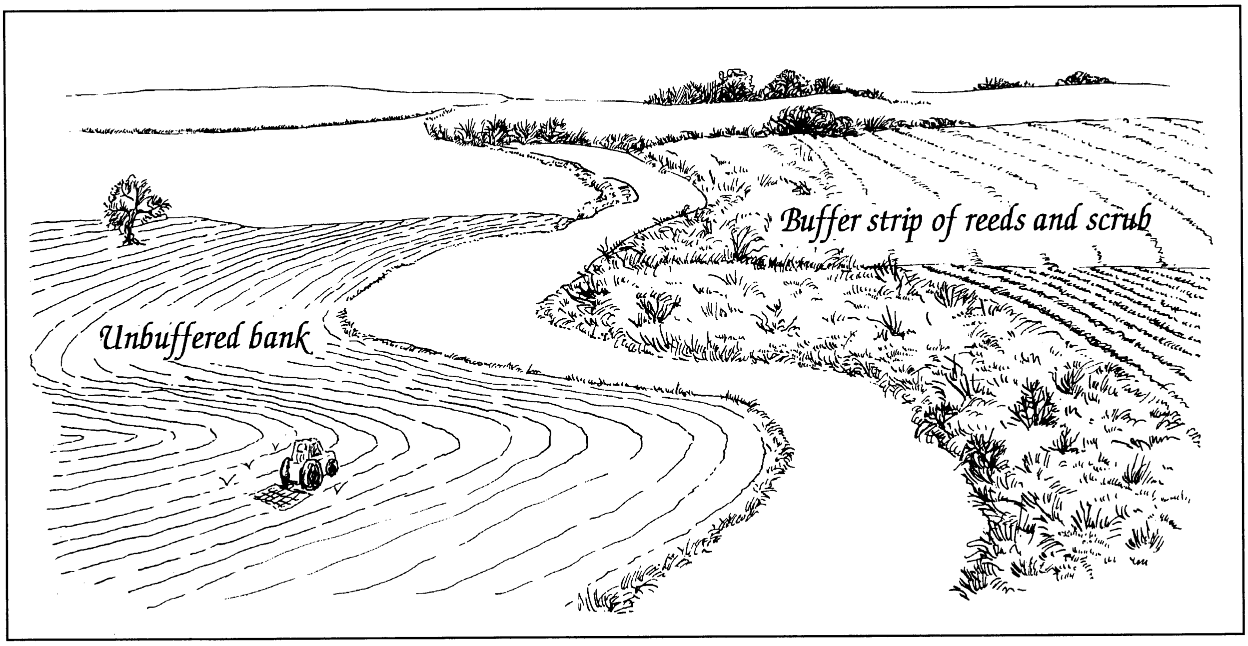


Figure 8.2 Buffered and unbuffered riverbanks

Drawbacks
Buffer strips are generally beneficial with no bad side effects on trout habitat quality. However, they do require management to prevent excessive bankside tree growth which, by shading, can negate some of the benefits which may arise.

Effectiveness
No specific studies have been found which demonstrate effects of buffer strips on trout habitat specifically. However, a number of studies reviewed by Muscutt *et al.* (1993) have demonstrated their effectiveness in reducing sediment and nutrient concentrations in receiving watercourses.

Cost considerations
The costs involved are mainly those of taking agricultural land out of production and any effects on neighbouring land. Additional costs will be incurred if fencing is required (see Section 8.3.4). Lesser costs may be involved in periodic management, that is cutting back the vegetation. Currently, several types of grant aid are available for farmers who wish to create buffer strips and information on these can be obtained from the EA and MAFF.

Further information
Many aspects of buffer strip performance, are not completely understood but knowledge is fast developing, especially with regard to differences in buffer types and locations relative to pollutant pathways. A good overview is provided by Environment Agency (1996a) and comprehensive details on buffer strips and matters arising can be found in Large and Petts (1992, 1994), Muscutt *et al.* (1993), Waters (1995) and Haycock *et al.* (1997). As this is a developing area it is advised that professional advice is sought for any major intended schemes.

8.2.5 Sediment trap

Introduction

Whilst it is preferable that sediment be prevented from entering streams in the first place, where this is not possible, it may be trapped, removed and thus prevented from having a deleterious effect on habitat further downstream. A sediment trap consists of a reach of slow flowing water where, in even the largest spate, fine sediment will settle out. As the trap gradually fills up, it is emptied periodically to maintain trapping efficiency.

Benefits

By removing fine sediments, conditions for incubating eggs are improved, buried spawning gravels may be exposed and more cover becomes available for free-swimming fish as the level of embeddedness of habitat features is reduced.

Design considerations

Sediment traps could be constructed to trap any size of sediment particles, but in practice, removal of anything smaller than sand is very impractical. Details on the dimensions of trap necessary to trap different sizes of particles are found in Hansen (1973).

A sediment trap should be constructed in a straight reach with a low gradient, the lower the gradient the better. A simple guide is to locate a straight reach where fine sand already accumulates on the bed. A trap should not be constructed on a bend as the turbulence generated hinders sediment deposition.

A sediment trap should be of uniform width, tapering down gradually at either end to the width of the inflowing and outflowing channels. This helps to reduce turbulence and so aids the deposition of sediment. The banks should be sloped so that they maintain stability when machinery is operating. Traps need to be sited where there is good access for an excavator and the banks must be firm enough to take its weight.

A major consideration is disposal of the spoil. Ideally, waste land should be available in close proximity to spread the material on.

Applicable stream types

Sediment traps are most likely to be effective in relatively low gradient streams which carry high loads of sand. Sediment trapping is not a practical proposition on streams which have high loads of silts and clays. To remove really fine sediments a trap would have to be very large and cleaning costs would be high.

Drawbacks

Depending on how great sediment loads are, sediment trapping may be expensive. Initial excavation and periodic cleaning are not the problem, it is the disposal of the spoil. Double handling of the spoil is inevitable since it cannot be left on a flood plain. If it has to be transported by road off the site, costs will rise considerably.

Care should also be exercised if gravels are actively being transported, as the stream may be starved of gravel downstream. A sediment trap should only remove "surplus" sediment which has resulted from human interference upstream. Removal of all sediment can result in unforeseen scouring of the bed and banks downstream.

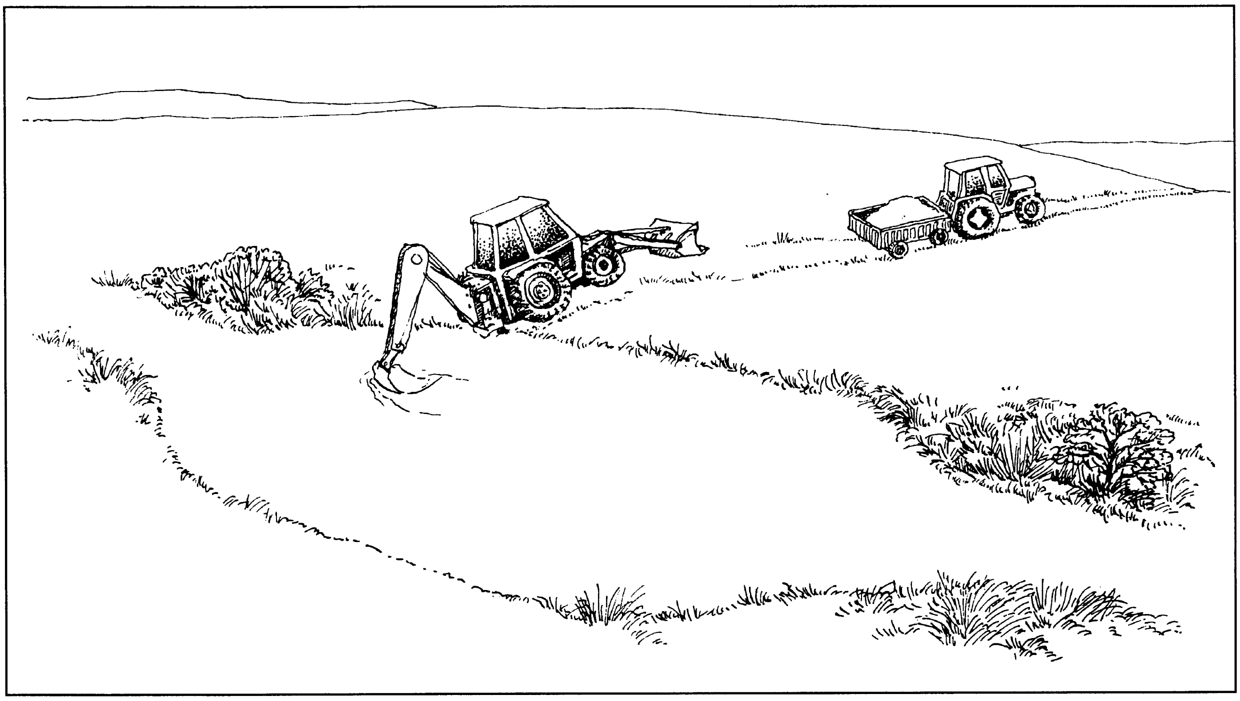


Figure 8.3 Cleaning a sediment trap

Effectiveness

Alexander and Hansen (1983) and Hansen *et al.* (1983) describe sand removal from a small stream in Michigan which had a catchment area of 32 km^2 and a sand load of 725 tonnes per year. A sediment basin approximately 50 m long by 7.5 m wide and 1.2 m deep was excavated. Half the depth was required for storage, equating to a volume of over 200 m^3. The trap was cleaned out by dragline on average every five months (14 times over six years) with the removal of about 2000 m^3 of sand. Sediment samples from above and below the trap showed a 71% average reduction in sand, whilst clays and silts remained unaffected. A 28% increase in trout production also followed.

Cost considerations

The main costs involved are those of periodic cleaning. An excavator will be required to remove sand and some form of transport will be required to transport it to a disposal site. The exact costs of any scheme will depend greatly on the size of the stream, sediment loading and how close a disposal site can be found.

Further information

Details on the construction and design of this technique, including the specifications for removing different sizes of sediment can be found in Hansen (1973), Alexander and Hansen (1983), Hansen *et al.* (1983), Iversen *et al.* (1993), Waters (1995) and Sear (1996).

8.2.6 Fish passage

Introduction

As described in Section 3.8, trout may make extensive movements within a catchment. Therefore, the issue of fish passage is an important consideration and must be viewed on the catchment scale. Although this manual is not intended to describe in detail methods of improving fish passage, important issues are briefly detailed here along with sources of further information.

Benefits

Improving fish passage is of benefit to all life-stages of trout. If adult fish cannot reach the spawning grounds, then no production will result.

Procedures

Access to ascending trout can be denied in several common ways and, depending on the type of the problem, different courses of action are required.

A first consideration is that many forms of obstruction to fish passage are related to flow. Some obstructions may be passable at high flows but not at low flows. Indeed, passage through an unobstructed channel may even be aided by increased flows (Section 3.8). Therefore, as outlined in Section 8.2.3, maintenance of an adequate flow is a necessity, especially in the period before trout may be expected to spawn.

The simplest type of physical obstruction to overcome is that of complete debris jams. These frequently occur in small wooded streams. These normally only block passage under conditions of low flow. This problem can be overcome by removing part of the obstruction (Reeves *et al.* 1991).

Fish passage can be denied by man-made weirs and dams. Preferably, such obstructions should be removed entirely if possible. However, if this is not possible, some form of fish-pass must be constructed. Details on fish-pass design can be found in the references cited below.

In addition to upstream passage, downstream passage can also pose dangers for descending juveniles, sea trout smolts and kelts. Danger points include intakes for surface water abstraction, fish farms, hydro-electric turbines and irrigation. The need for screening such sites has been described by Solomon (1992).

A final form of obstruction is that of areas of low water quality. This is especially a problem for sea trout which require passage through an entire river system. Water quality is relatively low in the lower reaches of a number of rivers where good habitat for juvenile trout exists in the headwaters.

Effectiveness

Providing access for spawning trout, where it is limited, may be one of the most effective techniques for increasing populations. In many river systems, large areas of spawning ground can be opened up in this way. For example, recently, action on this front on the River Tweed has resulted in opening up around 300 km of tributary streams where obstructions, mainly weirs, existed (Anon 1995). The effectiveness of cleaning up estuarine pollution is well illustrated on the River Tyne, where the annual sea trout rod catch rose from almost nothing in the 1950s to around 1000 in the late 1980s (Anon 1991).

Cost considerations

Many types of obstruction can be removed at little cost, although fish-pass construction may involve considerable capital expenditure. However, even then, fish-passes may still be very cost-effective. To spend tens of thousands of pounds allowing fish passage up a lengthy stream with good habitat, may be a much better option than trying to restore a similar length of stream which has been badly degraded but where access is good.

Further information

Further information on this subject can be found in Beach (1984), Reeves *et al.* (1991), Solomon (1992), Clay (1995), Komura (1995) and Carling and Dobson (1996).

8.3 Prevention of Streambank Erosion

8.3.1 Introduction

Accelerated streambank erosion is frequently damaging to trout habitat. Less bankside cover results and streams become wider and shallower. It can also be a major source of sediments which may have a damaging effect on trout habitat downstream. A good overview of the problems is provided by Waters (1995).

To a degree, streambank erosion occurs naturally in most environments. Indeed, without it, pools, riffles and meanders would never form. While erosion is sometimes seen as a "natural" phenomenon, Thorne *et al.* (1996) state that accelerated erosion (for example where bank protection has been removed by dredging or overgrazing) really does cause problems. Accelerated erosion should be rectified as far as possible.

Several factors govern the susceptibility of banks to erosion. One major factor is the nature of riparian vegetation. It is important that vegetative cover which prevents erosion be encouraged and that vegetation types or land use practices which result in erosion should be discouraged - i.e. this involves firstly removing the cause of any accelerated erosion if it is still ongoing. If this is insufficient to cure the problem or restore it to a former state, it is also possible to reduce erosion and re-instate the bank using hard engineering options. These include rock revetments, gabions, planking, geotextile fabrics etc. Indeed, in some situations, hard engineering may be the only realistic option. However, hard engineering should only really be considered as a last resort when other options are not appropriate. Further information on the principles of erosion prevention can be found in National Rivers Authority (1995) and Thorne *et al.* (1996).

Options for reducing erosion are now considered.

8.3.2 Erosion control with grasses

Introduction
From the point of view of preventing erosion, a thick growth of coarse grasses is a necessity on any streambank. They play an extremely valuable role in reducing erosion.

Benefits
Streambanks are subject to erosion in two dimensions, on the upper surface and on the bank face. Coarse grasses form the most effective protection against erosion on a flat or sloping soil surface by binding the soil with their roots and providing physical protection of the surface. However, grasses are more limited in preventing active erosion of steep bank faces as their roots cannot effectively bind sediment more than about 30 cm deep.

By helping to maintain narrow channels, grasses increase velocities and depths which help provide habitats for all life stages by keeping spawning riffles scoured clean of fine sediment and maintaining deeper pools for adults. Reduced sediment inputs also benefit all life stages.

Species and management

Different types of grass are necessary according to the function they need to fulfil. To maintain shallow depositing fringes on the insides of bends, large grass species such as common (Norfolk) reed (*Phragmites australis*), reed canary-grass (*Phalaris arundinacea*), reedmace (*Typha latifolia*) and reed sweet-grass (*Glyceria maxima*) all have the ability to absorb current energy, bind bank soils and to collect and consolidate silts to generate natural channel narrowing and improved habitats. Local conditions dictate the best species to use. Note that *Phragmites* is notoriously difficult to establish unless it is planted in wet soil adjacent to the river edge and then spreads its rhizomes into the water-logged soils at its own speed.

For protection of drier upper surfaces, wholly terrestrial grass species are appropriate. However, for the edge of overhanging banks *Phalaris* is a suitable species. It can grow either as an emergent or on a dry bank where it sends its roots down to the water table. Its long stems allow it to drape over a bank face and protect the bank.

For stabilizing eroding bank faces, most grasses are most suitable in low power streams which have banks less than 50 cm high.

Practices which damage bankside swards should be avoided. A major problem in Britain which prevents the establishment of riverbank swards is that of stock grazing, the control of which is described in Section 8.3.4. Control of trampling by people can also be necessary. In such instances, people need to be directed away from bank edges or walkways should be provided. Bankside trees also need to be maintained to prevent shading of surrounding grasses (see Section 8.3.3).

Figure 8.4 A dense grass sward binding a bank

Applicable stream types
A thick sward is appropriate to prevent erosion on upper bank surfaces in all types of stream. The only exceptions would be upland streams where there is no true soil on the bank.

Drawbacks
Promoting the growth of a riparian grasses has few obvious drawbacks for trout habitat quality. As with many other techniques, some loss in channel capacity may result with a risk of upstream impoundment.

Effectiveness
As an example of the ability of grasses to prevent erosion, Smith (1976) found that root free silt eroded at a rate of 160 cm/hour whilst the presence of roots reduced this to 0.02 cm/hour.

Cost considerations
Costs involved in maintaining riparian grasses include fencing, if necessary, and the labour involved in periodic trimming of any trees which become established.

Further information
Information on grass species and techniques of establishment are described in Adams and Whyte (1990) and Ward *et al.* (1994).

8.3.3 Erosion control with trees

Introduction

Whilst grasses are most efficient at protecting flat or sloping bank surfaces the protection they offer to steep banks liable to undercutting is limited. Where grasses are not suitable, trees are often still very effective.

Benefits

Tree roots penetrate further than grass roots and are much stronger and erosion resistant. Consequently, they can make a most efficient buttress along an eroding stream bank where trees are planted close together and the roots can form an intertwining mass. The roots both bind the bank together, and when exposed, provide direct physical protection to the bank face. As with grasses, all life stages of trout can benefit from this form of protection.

Design considerations

The species of tree most appropriate for riverbank stabilisation purposes are willow for shallow banks and alder for higher banks. These are very easily propagated, grow rapidly, and like wet conditions. A branch several centimetres in diameter is cut off an existing tree in late autumn or early spring. A section about 50 cm long is cut from this and side shoots trimmed off. This is pushed into the soil so far as to reach the summer water table but leaving some buds protruding above ground level. The branch will take root by itself and new shoots will grow that summer. The shoots should be pruned back during the winter and in the second summer, vigorous new growth will ensue. With willows, the new shoots may well reach in excess of two metres.

Where the height of an eroding bank is less than about half a metre from the stream bed, alders can be planted on top of the bank far enough back from the edge so that the roots become properly established before the bank erodes out to them. When the bank eventually erodes to the root mass, the bank will hold together and the myriad of hollows which will be formed between underwater roots are excellent cover for trout. However, it is fundamentally important that root boles from neighbouring trees are close enough to intertwine.

Where there are steep banks over half a metre high, it is necessary to reprofile the bank before planting. Vertical banks need to be cut away at an angle above normal water level and the lower terrace, so formed, planted out with pre-rooted alders or willows. Thin willow branches (‘withies’) can be woven amongst the stems, and if partially buried, these will take root and produce a robust, long-lasting, living bank protector. It is recommended to use a variety of willow species to enhance the visual and conservation values of the scheme. Such work should be performed in spring just before growth commences. This will ensure the maximum amount of time possible for the scar to be revegetated before the next winter floods.

Another technique, known as “spiling” (Ward *et al.* 1994), involves driving willow stakes into the bed of a stream along the toe of the bank. Withies are then woven between these stakes to create a solid lattice work. Aggregate is then backfilled behind the barrier (more examples of retaining barriers are given in Section 8.3.6) and the stakes will take root and grow. However, this particular technique may be inappropriate where strong scouring velocities are likely to be experienced before the bank is consolidated.

In preventing erosion, it is the roots of the tree which are important. Trees used for bank protection should be managed to maintain a large root system but not to cause shading of the understory. There are several techniques whereby this may be achieved.

Coppicing entails the cyclical (three to six year) winter cutting of vigorously-growing side shoots back to the base. Alder, willow and hazel all coppice well, increasing the longevity of the trees. The decline early this century of traditional coppicing of riverside trees has led to many overgrown alders and willows falling into rivers and causing serious bank erosion and flooding problems. Coppicing keeps growth low and vigorous, and poses little retardation of flood waters.

Pollarding entails cutting back the crown of a tree at around two metres height (the grazing height of cattle) at regular intervals. Whilst coppice requires protection from grazing livestock, pollards, once established, are too high to be damaged. Old willow pollards become very valuable habitats for a wide range of wildlife including fish (roots), breeding birds, insects, mammals and plants. However, they need careful treatment, with the retention of one or more main boughs after pollarding to maintain growth. Severe cutting back can kill old willow pollards.

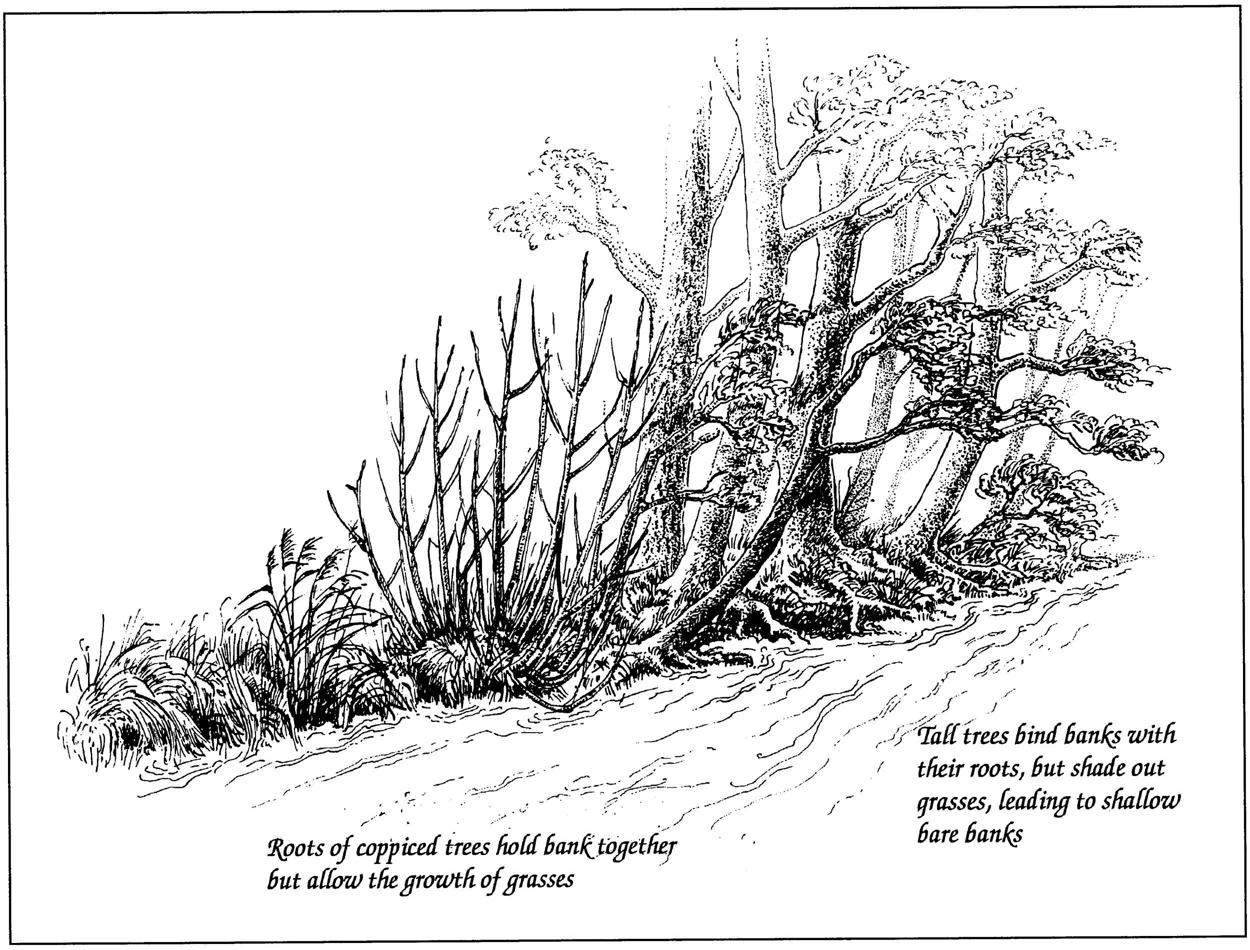


Figure 8.5 The effects of tree management in preventing erosion

Appropriate stream types

Trees are effective in stemming erosion in practically any type of stream so long as the eroding bank provides a suitable rooting medium. Whilst grasses may be an alternative in low power streams, there is no alternative to trees on moderate gradient alluvial streams where rapid bank erosion occurs.

Trees are more suitable in the south of Britain/lowland areas where conditions for growth are good and benefits can be seen within a few years of planting. Growth may be slow in exposed upland and coastal areas and other methods of erosion control may be appropriate.

Drawbacks

If trees are allowed to shade smaller plants they can increase erosion rates out with the immediate vicinity of their roots (Section 2.3.2). If the roots of adjacent trees do not intertwine, embayments may result between trees. In extreme cases, this results in erosion taking place right round the tree, leaving it stranded within the stream. Bankside trees have, therefore, to be managed (see above) to prevent the growth of a shading canopy. This enables both lower growing plants to survive and trees to grow in close proximity to each other.

Effectiveness

The effectiveness of trees in stemming erosion is shown by North American studies cited by Dawson and Kern-Hansen (1979) where erosion rates were cut between 85% and 95% on the establishment of trees.

Cost considerations

Relative to other methods which will be described, tree planting is a cheap form of riverbank protection in terms of capital and labour costs (Orth and White 1993). Cuttings can be obtained for nothing, the main costs being that of paring back the banks and manpower for planting and subsequent maintenance. The real cost relative to hard engineering options is that of the time taken for the revetment to mature.

Further information

Detailed information on erosion control and bank reinstatement through tree planting can be found in Henderson (1986), Hemphill and Bramley (1989), Adams and Whyte (1990), Coppin and Richards (1990), Ward *et al.* (1994), National Rivers Authority (1995) and Thorne *et al.* (1995).

8.3.4 Fencing to protect streambanks

Introduction

Grazing by livestock is a major factor which prevents the establishment of dense riparian vegetation, which is very important in protecting banks. In addition, mechanical damage by the animals themselves can directly cause erosion. To prevent erosion, livestock should only be permitted on stream banks at low densities or on a strict management rotation where grazing is only allowed for short periods. However, it is difficult to define what an acceptable density is because animals often gravitate to streams. The most certain option is to exclude them from the stream entirely. In most instances this will entail fencing.

Benefits

By fencing stock away from streambanks, erosion rates are reduced and inputs of fine sediment fall. This improves conditions for spawning by exposing smothered gravel and improving conditions for incubating eggs. The narrowing of the channel which results from the encroachment of vegetation creates deeper and faster water for adult trout along with increased cover.

Design considerations

A number of factors need to be considered when erecting fences alongside streams. The fence line should be at least on the crest of the bank. Having the fence as high as possible will reduce the likelihood of debris being caught up during floods. Debris on fences can be a flood hazard and also damages the fence. Also, by keeping the fence several metres away from the stream allows the development of a good width riparian buffer, together with adequate angler access. It should also be remembered that a cow can stretch its neck and head up to a metre beyond a fence line.

It is easier and cheaper to construct a straight fence than one with many corners requiring heavy strainer posts. Therefore, instead of following a winding river channel the fence should be set back as far as possible from the bank to minimize the number of corners. Also, by running fences parallel with the meander belt poses less of a flood risk. The amount of grazing land which may be sacrificed needs to be balanced against the extra costs of complicated fencing.

The type of fencing required depends on the type of livestock to be excluded. Dairy cattle may be excluded by as little as two strands of barbed wire, but where cattle of different ages are likely to be grazed, at least four strands are necessary. With sheep, wire mesh is required, and with both sheep and cattle, mesh and two strands of barbed wire at the top are necessary. Good quality treated posts should be used because they are less prone to rotting on damp streambanks. Fences need to be made of the best and strongest materials so that they will last. It should also be remembered that regenerating streamside vegetation can prove very attractive to livestock during dry periods and, if they gain entry, a great deal of damage can be done over a short period.

Where fences are erected, provision must be made for livestock to have access to the stream at certain points to drink. Embayments must be fenced off and the bed preferably lined with rubble to prevent excessive poaching of the soil. Bays must be wide enough for several cattle to drink at a time so that the fence will not be damaged by them jostling.

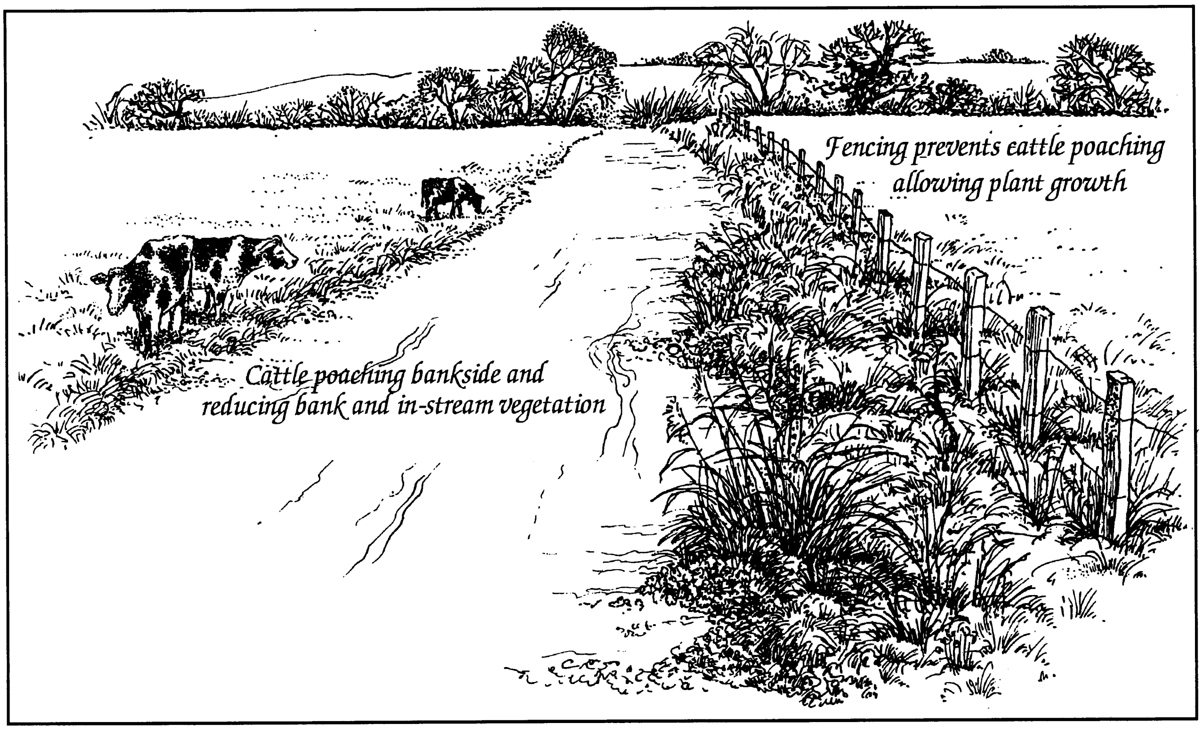


Figure 8.6 The effects of fencing on riparian vegetation

Where cattle must cross the stream, special consideration must given to the construction of fords. In small streams where water levels rarely reach the lowest wire, a fence line can merely be erected across the stream. However, with larger streams, fences can trap debris during floods, causing both a flood hazard and damaging the fence. One option to overcome this is to install gates across a stream (see Fig 8.7) which float on their sides during floods and allow debris to pass. Such gates need to be anchored very securely to strong posts on the bank with considerable tension so that cattle will not push through them. A much more simple technique which is appropriate in streams where livestock are likely to removed during wetter parts of the year is to string wires lightly across a stream so that on trapping debris they will break but can easily be restrung. A final consideration again is that a ford should be sited in a shallow stretch with a hard armoured bed if possible. If such substrates do not exist, then rubble ought to be laid on the bed to prevent erosion.

After fences are constructed they need to be periodically inspected and repaired. This is especially important after flood events. The erection of fencing also entails a commitment to long-term management of the regenerating riparian vegetation (see Section 8.3.3). If trees are considered unnecessary then they should be removed as soon as they appear. Likewise, if coppiced trees are desired, coppicing should commence early. It is much easier to manage trees if it is done from the start rather than having to cut back and dispose of many years growth. However, if trees are not managed and overshading results, many of the benefits of fencing may be lost.

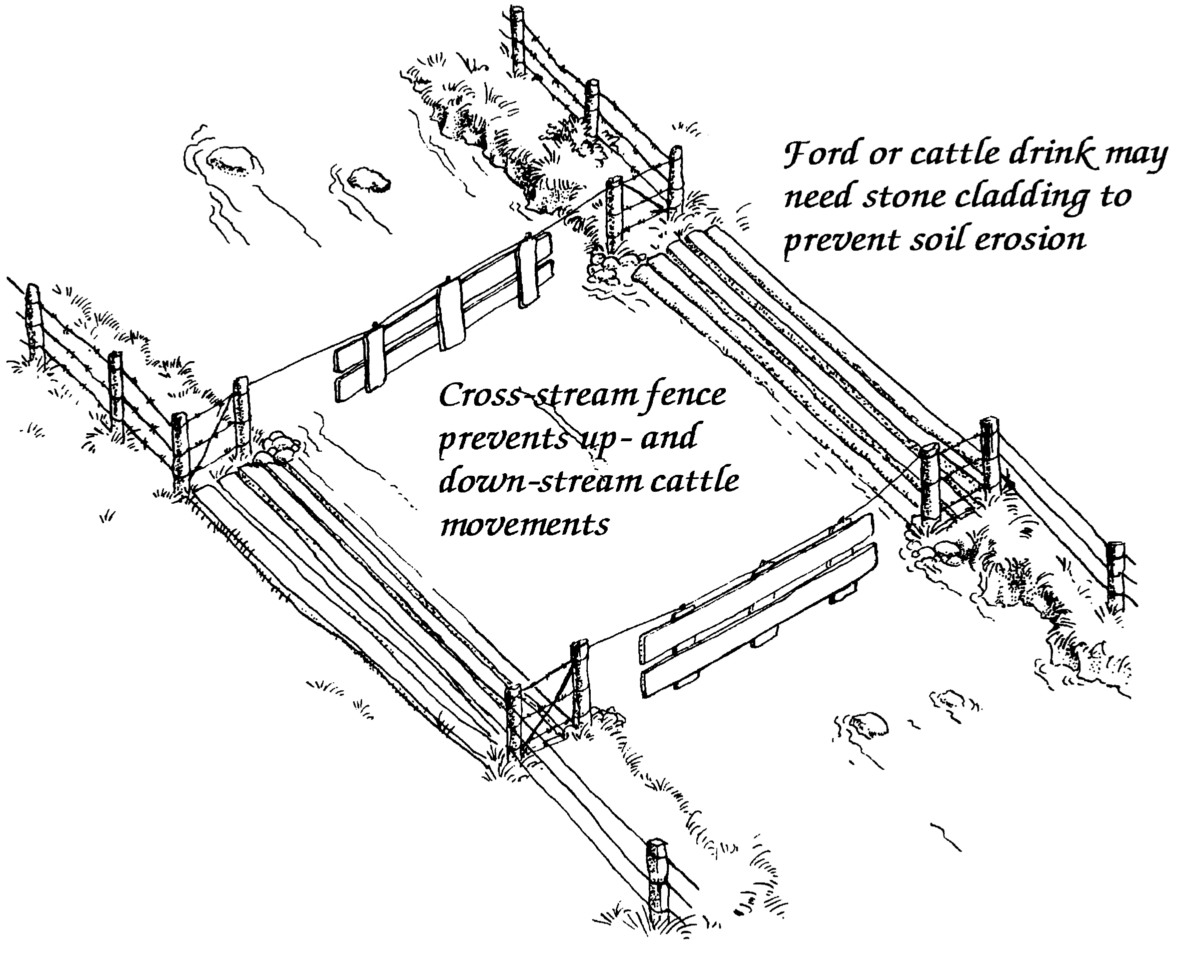


Figure 8.7 Fencing considerations at fords (Adapted from Hunter (1991))

Applicable stream types

Fencing is a necessity on practically all streams from a trout habitat point of view. These include, lowland streams where cattle grazing tends to be dominant to upland streams where sheep dominate. In fact, the only type of stream in which fencing is unlikely to benefit trout habitat is in steep upland streams with bedrock channels where vegetation can never become established.

Drawbacks

Fencing can pose an increased flood risk in rivers which experience overbank floods and carry debris. Likewise, in unstable streams they can collapse if the banks are undercut and become both a flood hazard and a hazard to river users. Fencing can indirectly lead to increased upstream flood risk and impoundment of the flow as the channel capacity is reduced with recovering vegetation. In some cases fencing may be regarded as aesthetically unattractive.

Effectiveness

A number of North American studies have considered the impact of fencing out stock on bank stability. For example, Rinne (1988) found that, in one stream, the banks were totally stable in a section where cattle had been fenced out and vegetation allowed to regenerate, but 64% of the bank was actively eroding where cattle still had access. However, there was no demonstrable increase in numbers of fish because a lot of eroded sediment still entered the improved reach from degraded areas upstream.

Dahlem (1979) reported a 20% increase in the amount of stable bank in a stream in Nevada within two years after stock removal and the regrowth of herbaceous vegetation. The percentage of silt on the bed reduced from 27% to 11%, and spawning gravels increased from 52% to 70%.

Platts (1979) cited two unpublished studies in Utah where streambank stability was found to increase between 100% to 740% as a result of stock exclusion.

Cost considerations

A three strand barbed wire fence with treated posts every four metres costs £4 to £5 (1996 price) per metre single bank, including labour, although unit costs may drop by up to 25% for large projects. Platts and Wagstaff (1984) found that maintenance costs amounted to less than 5% of installation costs. Erection of fences, rather than maintenance is, therefore, a major expenditure. In Britain, fencing the thousands of kilometres of unfenced trout streams would run into tens of millions of pounds.

Further information

A large number of American studies have shown the great value of excluding stock from trout streams with readily erodible banks. Reviews are given in White and Brynildson (1967), Keller and Burnham (1982), Wesche (1985), Elmore and Beschta (1987), Hunt (1988, 1993), Adams and Whyte (1990), Hunter (1991) and Waters (1995). Adams and Whyte (1990) provide clear instructions on fence construction techniques and valuable guidelines for practical siting and installation parameters. Platts (1991) describes in detail the impacts of different fencing and livestock rotation regimes.

8.3.5 Bank reinforcement: rock revetment

Introduction
Vegetation management is not always the most desirable or effective way of controlling erosion. Firstly, in any environment, trees take time to grow and in some environments tree growth may be very slow due to exposure or the infertility of the soil. In badly degraded upland streams there may even be no real soil at all. Also, trees are not always desirable on riverbanks from the perspective of some riverbank users (e.g. anglers), even when well coppiced. One option is to protect banks with rocks.

Benefits
Rock revetments, sometimes referred to as "rip-rap", can form very durable bank protection which can be created quickly. Their primary benefit is in maintaining steep stable banks on the outside of a bend which creates deeper water for adult trout than can be maintained with an eroding bank.

Design considerations
If the bed is very stable, a vertical facing can be created by placing rocks like a drystone wall. This can create a very strong bank. However, the height to which a vertical face can be built is limited and will be greater with larger rocks. Ideally the face should not be smooth but should plenty of deep crevices and protruding rocks and spurs which create more cover for fish (Brookes *et al.* 1996).

Where the water is deeper than about two or three rock diameters and there may be some risk of subsidence, rocks must be placed in at an angle. A bank with a shallow angle does not provide such good adult trout habitat as does a vertical bank with overhanging cover, so this must be compensated for by creating an irregular edge with protruding rocks to provide cover.

The main purpose of a revetment is to protect the toe (i.e. the base) of the bank rather than the upper part. It is not necessary to continue a revetment much above normal water level. High steep banks should be pared back at an angle a little above summer water level and planted with vegetation. The upper surface of the revetment should be filled in with soil and turfed so that vegetation can grow and mellow the appearance. Vegetation, once established, will drape over the face of the revetment and it will be obscured from view.

Angular quarried boulders of dense rock are best because they tend to lock-together more than smooth weathered field or streambed stone. However, large enough rocks are not readily available in all environments, so alternatives may be considered. Heavy duty weldmesh baskets filled with rubble (gabions) are commonly used. They are economical and readily obtained, the stones can move around to accommodate small degrees of subsidence and a degree of flow percolates through the structure. Willow branches can be woven through the gabions, and when these take root will further bind the gabions together.

Applicable stream types
Rock is a widely applicable material for bank protection. It is the most appropriate form of protection in high energy streams where banks are prone to crumbling but beds offer a stable foundation. However, although other techniques described in Section 8.3.6 are suitable for low power streams, rocks are equally effective. The only real constraint against the use of rock

is if the bed is composed of soft material (e.g. sand or silt) which offers no foundation.

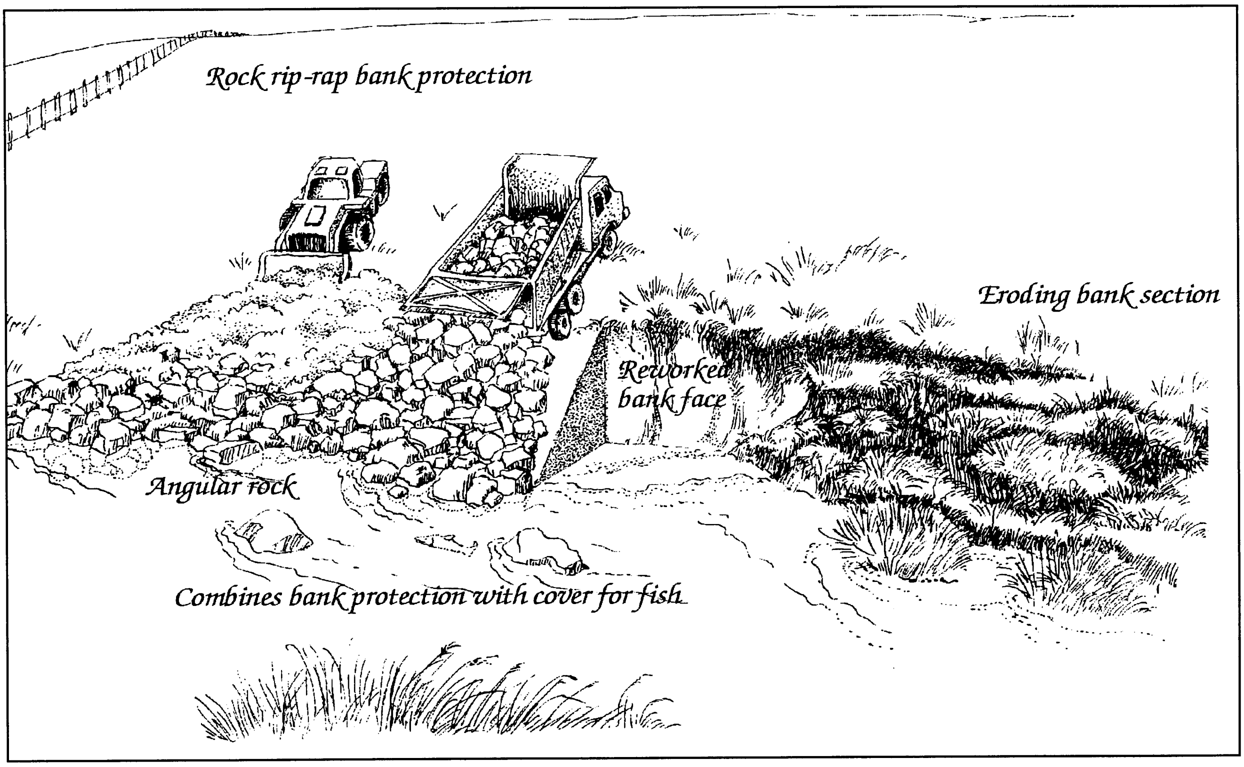


Figure 8.8 Constructing a rock revetment along an eroding bank (Adapted from Hunt (1993))

Drawbacks

In lowland streams where rocks do not normally occur, revetments may look out of place if every effort is not made to make them unobtrusive as possible. This is especially so with gabion baskets. However, when vegetation establishes on top of rocks they can blend in really well. Gabions should only be used underwater or if buried under a turf bank with a fringe of draping vegetation.

A further drawback with gabions is that when the metal corrodes, sharp protruding wires can be both unsightly and dangerous to river users and to wildlife. Plastic coated gabions last longest, and this can be in excess of fifteen years (Wesche 1985). When gabions do eventually fail they have to be replaced. If a rock revetment collapses for whatever reason, the rock can always be drawn back and re-used.

A fundamental criticism of rock revetments, or any artificial bank stabilisation, is that by limiting the ability of the channel to change shape, changes in the river regime may have unforeseen consequences like increased bed scouring. Professional help should be sought if long reaches of revetment are contemplated.

Effectiveness

Rock revetments have been widely used in fisheries restoration schemes. However, they have mainly been used in conjunction with other techniques. Few studies appear to have appraised the effectiveness of revetment alone. For example, bare rock revetments and rock weir construction was used by Hvidsten and Johnsen (1992) to compensate for salmon and trout habitat damage caused by a channelization programme on the River Soya, Norway; densities of both species increased after rock placement.

Hunt (1988) appraised two examples of rip-rapped bank and found that brown trout numbers increased by over 25% in one and over 50% in the other.

Revetment with large (70 cm diameter) rocks is thought to have contributed considerably to the effectiveness of a range of brook trout habitat improvement measures on Beaver Creek, Wyoming (Moreau 1984).

Finnigan *et al.* (1980) report that fry of Pacific salmon species use walls of jumbled rock in artificial rearing channels.

Cost considerations
The cost of rock varies greatly depending on locality within Britain. In south-eastern England suitable rocks are practically unobtainable. There, flint filled gabions are the only option. Elsewhere, quarried rock may cost in excess of £10 per tonne. At the other extreme, in upland environments, rock may be obtained on site for the cost of moving it. The greatest costs normally include carriage (approximately £20 per hour lorry hire) and placement (approximately £150 per day excavator hire). If, for example, rock is available at £5 per tonne from a quarry within one hour round trip, the cost per metre of bank of a one metre high by one metre wide revetment will be about £15.

Further information
Fuller details on revetment design and construction can be found in White and Brynildson (1967), Hemphill and Bramley (1989), Adams and Whyte (1990), Hunt (1993), Ward *et al.* (1994), National Rivers Authority (1995), Thorne *et al.* (1995), Waters (1995) and Brookes *et al.* (1996).

8.3.6 Bank reinforcement: retaining barriers

Introduction
Another method of bank reinforcement is to erect a supported retaining barrier along a bank face which can both protect the bank face from erosion and physically prevent a steep bank from slumping or being undercut.

Benefits
As with rock revetments, retaining barriers maintain steep banks adjacent to deep water which is most important in maintaining habitat for adult trout. They are most frequently used in relation to channel narrowing which has other benefits (Section 8.6.2).

Design considerations
There are many possible forms of barrier construction. Planking ("camp sheeting") or logs held up by stakes is one option. This was commonly used in the past before the advent of machinery which made the installation of rock revetments easier. Another option is a revetment of logs piled vertically into a soft substrate. Living barriers can be created by willow "spiling" (see Section 8.3.3), that is pushing willow stakes into the bed and weaving thinner branches around them which then take root.

A major design concern with barriers is that of undercutting which can lead to material being washed out from underneath, especially if the fill material is fine. Barriers need to be well sealed at the ends, between the planks/logs and at the toe. It is important, therefore, that the toe be embedded well into the substrate. Scouring will occur alongside the new face so the toe must be deep enough down not to be undercut. With a soft substrate, it may not be possible to bury the base deeply enough. Accordingly, an apron of geotextile fabric should be attached behind the barrier and then backfilled.

An alternative option is to construct a barrier entirely of apron type material. One type of geotextile - sold under the trade name of Nicospan - is designed for this purpose. Nicospan has tubular pockets woven into it at intervals along its length. It is held up by supporting stakes driven into the bed which fit into the pockets. The surplus Nicospan is bent over to form an apron (see Fig. 8.9) and then backfilled.

Applicable stream types
Retaining barriers are most suitable in low power streams and are most commonly used in lowland areas where rock is not readily available. They are used primarily on the outsides of bends to create vertical banks with overhanging vegetation on top. They are especially applicable where banks lack the cohesive strength to remain vertical.

Drawbacks
Barriers require maintenance. Wooden stakes and wooden barriers rot with time. There may be a considerable outward pressure exerted on the stakes by the bank fill and so bank failure may result when the stakes rot. Metal stakes can be used to overcome this problem. Barriers can look artificial if they are exposed so it important that they do not extend far above normal water level and can be obscured by draping vegetation.

A sheer vertical barrier will not undercut and, so, provides few niches for fish to hide. Other means of cover installation should be incorporated along with barrier creation (Section 8.7).

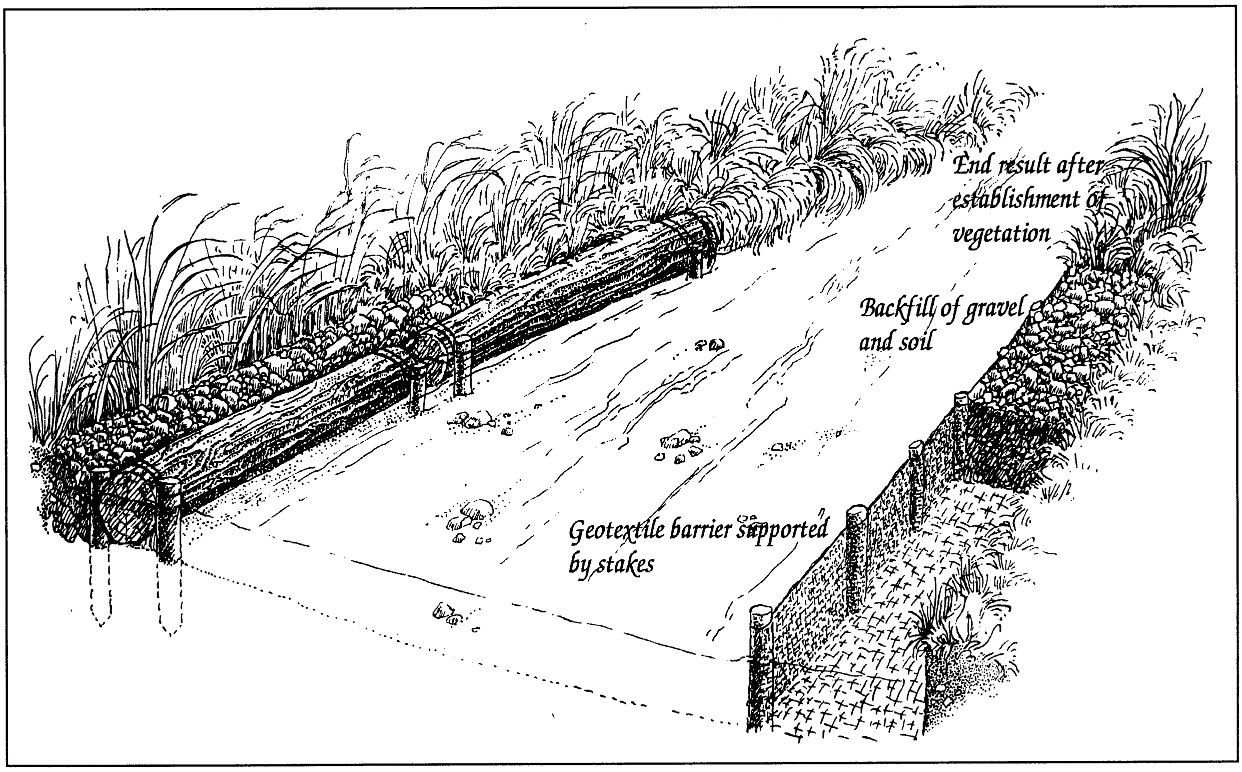


Figure 8.9 Bank protection with logs and geotextile fabric

Effectiveness

This type of revetment is not widely reported in fisheries literature in the context of trout habitat restoration. No quantitative evidence has been found of benefits, or otherwise, to trout habitat. White and Brynildson (1967) show an example of a wooden barrier in an unsuitable stream which is shallow and rocky with high banks.

Cost considerations

Costs are incurred in obtaining barrier material, but most of the cost involves the erection of barriers and in backfilling the barrier. These are dependent on the height of the barrier and the amount and availability of backfill material. If backfill material has to be transported to the site costs will rise considerably.

Further information

Examples of the construction of retaining barriers and further details can be found in Hemphill and Bramley (1989), National Rivers Authority (1992b) and Ward *et al.* (1994).

8.4 Spawning Habitat Improvement

8.4.1 Overview of problems and solutions

Spawning habitat may be deficient for many reasons. Consequently, there are several methods by which spawning habitat may be created or improved. This section describes the various options. Solutions which need to be applied to specific problems are shown in Box 8.1.

Box 8.1

Problem	**Solution**
Lack of spawning gravel	Gravel planting - most suitable where gradients are low and there is little gravel in the stream (8.4.2)
	Gravel traps - appropriate in higher gradient channels where mobile gravel does not accumulate (8.4.3)
	Gravel traps plus gravel planting - appropriate in higher gradient streams where gravel would not accumulate but there is no gravel.
	Scouring structures - most suitable where gravels buried under fine deposits need to be exposed or riffles need to be created (8.5.4)
Compacted/sedimented gravels	Gravel cleaning (8.4.4)
	Gravel loosening (8.4.5)
Gravel bound by plants	Plant removal/shading (8.4.6)
Lack of suitable tributaries	Spawning channels (8.4.7)

The various techniques are now described in turn.

8.4.2 Gravel planting

Introduction

Where spawning gravels have been removed from a stream, or in some cases may never have existed, it is possible in certain circumstances to create spawning habitat by placing deposits of gravel on the bed.

Benefits

By introducing gravel it may be possible to create habitat with suitable hydraulic conditions for adult brown trout to spawn. If siltation is not a problem successful incubation may also occur.

Design considerations

Before gravel planting is considered, preliminary investigations need to be performed to ensure hydraulic conditions are suitable. Firstly it is necessary to determine mean flood velocities by using the Manning equation (Box 8.2) or alternatively by direct measurement during flood conditions. Then, by multiplying the mean velocity by the cross-sectional area of the channel, the discharge is calculated. By changing the cross-sectional area term in the equation in accordance with a proposed reduction in channel depth, the new mean stream velocity necessary to accommodate the same flood discharge can be roughly determined. This velocity is then compared with critical entrainment velocities for different sizes of sediment (Box 8.3) to see if the gravel will remain stable. These computations should also be done to ensure that velocities will be high enough to prevent the accumulation of silt and sand which could bury any planted gravel. More detailed information on design velocities etc. can be found in Shields (1996).

For trout spawning, gravels have generally been reported to range from less than 5 mm to over 50 mm in diameter, with some in excess of 100 mm (Section 3.3). The maximum size of gravel which will be moveable by trout will depend on the current velocity, and so will vary from stream to stream. Therefore, when assessing which size of gravel to introduce, the best guide is the size of gravels which are already present in the stream on any suitable areas of spawning habitat. Uniform quarry graded gravel should not be used. Instead ungraded mixed size gravels have more stability than uniform gravels and are less easily infiltrated with fines.

Gravels should be placed on the stream bed to form deposits approximately every six times the width of the channel. The length of each deposit should be about three times the width of the channel. This will result in the creation of riffles and pools (see Section 8.5.3) with a variation in bed level necessary to promote downwelling and upwelling flows within the gravel.

Applicable stream types

The effect of introducing new substrate is to raise the level of the bed. As the level rises, the water velocity increases and, so, the hydraulic and physical conditions necessary for spawning may be created. Above a certain equilibrium bed level, velocities will become high enough to scour away any further gravel. The applicability of this technique really depends on flood velocities not being too high to prevent the accumulation of a sufficient depth of gravel which will maintain adequate conditions for spawning.

Gravel planting is, therefore, most appropriate in deep slow reaches (low Froude numbers - see Box 8.2 for definition), which if characterized by silts and sands, will indicate that velocities are not high enough to move gravel. Streams which have been overdeepened and widened by dredging are especially appropriate - i.e. gravel placement effectively restores the bed to its former level. Hydraulic conditions suitable for gravel planting may be created in steeper streams if a structure to reduce water surface gradient (a gravel trap - Section 8.4.3) is constructed in the stream. Alternatively, a stream may be widened to reduce velocities, or a pre-existing coarse substrate may be removed and replaced with gravel.

Box 8.2

The Manning equation estimates mean stream velocities in reaches of uniform depth, slope and velocity.

$$V = (S^{1/2} R^{2/3}) / n$$

Where V is the mean velocity (m/s), S is the water surface slope, R is the hydraulic radius (m) and *n* is a dimentionless coefficient of channel resistance.

R = Cross sectional area / length of wetted perimeter

Values of Manning's *n* vary according to the shape of a channel, size and shape of roughness elements in it and water depth relative to the size of the roughness elements. Where depths are much greater than the height of roughness elements, as they would be at flood discharge in a channel where gravel planting is to be carried out, the following are typical values - from Richards (1982).

Channel type	*n*
Excavated channel, earth	0.022
Excavated channel, gravel	0.025
Natural channel <30 m wide, clean, regular	0.030
Natural channel <30 m wide, some weeds, stones	0.035
Natural channel <30 m wide, sluggish weedy pools	0.070
Mountain streams, cobbles and boulders	0.050
Major streams >30 m, clean regular	0.025

Further details on the estimation of *n* can be found in Chow (1959)

The Froude number is a dimensionless index from 0 to just over 1 which is related to the specific energy of flowing water (Richards 1982). It is calculated as follows.

$Fr = v / \sqrt{(dg)}$ were v is the mean current velocity (m/s), d is the depth (m) and g is gravitational acceleration (9.81 m/s^2).

Gravel planting is not appropriate in an alluvial channel with pre-existing gravel riffles as the riffles are likely to be at their equilibrium height and any gravel introduced may be unstable. Also, it should not be performed in streams where siltation will be a problem.

Box 8.3

Bed substrate materials and typical entrainment current velocities (from White and Brynildson 1967).

Stream bed material	Mean current velocity
Silt (<0.05 mm)	20 cm/s
Fine sand (<0.25 mm)	30
Medium sand (<1.0 mm)	55
Coarse sand (< 2.5 mm)	65
Fine gravel (<5.0 mm)	80
Medium gravel (<10 mm)	100
Coarse gravel (<15 mm)	120
Fine pebbles (<25 mm)	140
Medium pebbles (<40 mm)	180
Coarse pebbles (<75 mm)	240
Small cobbles (<100 mm)	270
Large cobbles (<150 mm)	330

Drawbacks

A major consideration with gravel planting is that, by raising bed levels, a degree of upstream impoundment will result. This may have a detrimental effect on habitats immediately upstream. Depths will increase, velocities will be slowed and fine sediments deposited. It is necessary to consider the habitat value of the surrounding stream for other life stages before gravel planting is performed.

Impoundment will also affect land drainage upstream. The reason in many cases why the original gravel beds were removed in the first place may have been to increase channel capacity. It is imperative to consider impacts on neighbouring land use at the outset when considering this technique. Where, the impact is likely to be detrimental a compensatory increase in channel capacity by creating a two-stage channel (Section 8.6.3) will be required.

Effectiveness

Compared with other methods of gravel reinstatement, relatively few studies have appraised the introduction of gravel without the aid of a retaining structure, i.e. a gravel trap. However, Wesche (1985) notes that by excavating large cobbles and replacing them with correctly-sized gravels a 4100% increase in spawning activity occurred on a tributary of the Snake River, Wyoming. Adams and Whyte (1990) reported salmonids spawning on placed gravels in a lake outlet. Reeves *et al.* (1991) reported that in an Oregon stream, 10,000 m^3 of dredged gravel and rock were replaced by gravel and spawning activity of chinook salmon increased over five-fold. Solomon (1983) cites a study in Wyoming where pools were excavated in the bed of a stream and the gravelly spoil was deposited on the bed just downstream of each pool. Coarse material was removed and used to stabilize the downstream face. Over ten years, numbers of spawning cutthroat trout increased from six to 250. Significant, though smaller, improvements were also observed in other streams.

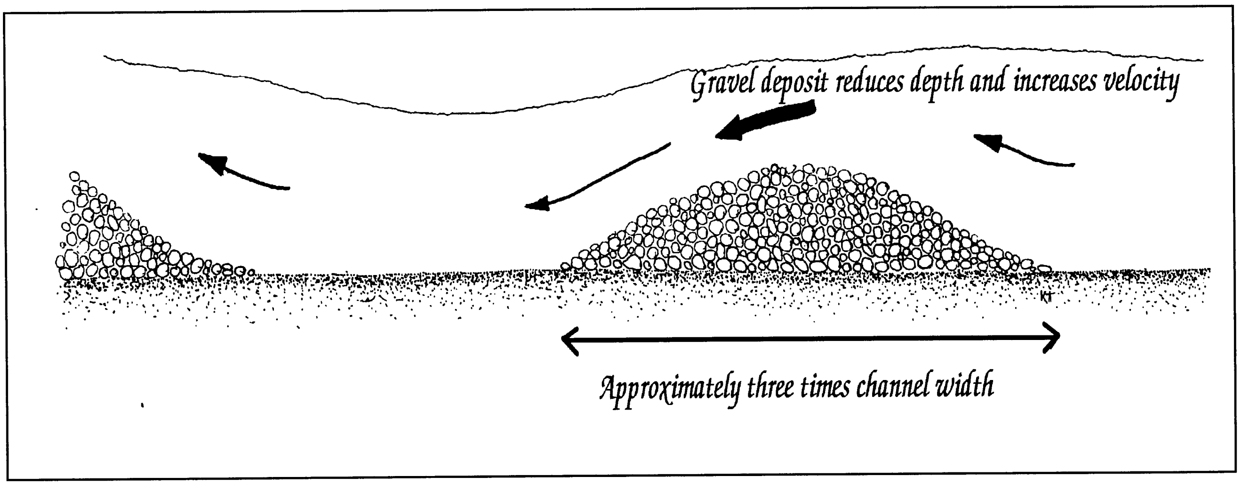


Figure 8.10 Gravel deposited on a streambed to create spawning riffles

In England, gravel planting has been performed by the EA in formerly dredged reaches of the rivers Coln and Windrush in the Cotswolds and trout do regularly spawn in these areas (V. Lewis pers. comm.). It has also been tried by the EA on the River Test, again with fish choosing to spawn on the planted gravel (L. Talks pers. comm.).

Cost considerations

Costs of gravel planting involve the cost of gravel, carriage and the cost of hiring a machine, unless the stream is small enough for gravel to be planted by hand. Gravel costs less than £15 a tonne and lorry hire about £20 per hour. A 15 tonne load of gravel (about 7 m^3) on a one hour round trip from a quarry would cost less than £250. One load would equate to one 50 cm thick spawning riffle in a stream two metres wide. An excavator to place the gravel will cost at maximum £150 per day and could place a number of such riffles in one day.

Further information

Further information on gravel planting criteria in Denmark, where this technique has been extensively used can be found in Nielsen (1996). Gravel planted in the River Ock is illustrated in Ward *et al.* (1994). Useful information is also provided by Adams and Whyte (1990).

8.4.3 Gravel trap

Introduction
In some streams which lack spawning gravel, hydraulic conditions are not suitable for gravel to remain stable. This problem may be overcome with a gravel trap.

Benefits
A gravel trap basically is a control structure built in a stream which reduces the water surface gradient upstream and causes the stream's energy to be dissipated over a step. The reduced water velocities upstream allows the deposition and accumulation of gravel above the structure. If the structure itself is porous, the difference in water level across the structure will promote downwelling of water into the gravel which will promote egg incubation. In high gradient streams, gravel traps play a similar role to fallen trees which are characteristic of mature forests.

Design considerations
To be most effective, a gravel trap consists of a V shaped weir with the apex pointing downstream. There should be a 1% slope from the bank to the centre. This is the opposite form of design to weirs designed for scouring pools below (Section 8.5.8). Gravel traps are intended to dissipate the stream's energy rather than concentrating it. Traps can be built in pairs, with the current being dissipated over the upper step and gravel accumulating more effectively above the lower step.

Gravel traps should be sited in straight reaches with a gradient of less than 2%. The substrate and banks should be stable. Basically, in a high gradient stream, the lowest gradient and widest stretches should be selected. Stretches where the stream is widening should also be selected, especially for the upper trap. The stream may even be widened to further increase energy dissipation. The height of the sill of a lower trap should be level with the base of the upper trap.

If the bed immediately upstream of a trap is "armoured" with coarse material the larger cobbles can be removed to only leave gravel which is of a size suitable for spawning.

A weir should be designed so that it does not become a barrier to migrating fish. Where weirs are designed to scour pools, the deep water immediately downstream provides depth from which a fish can jump, but with a gravel trap no such depth may exist. Therefore, the height of a sill should not be more than 30 cm.

Whilst a series of V shaped sills are best, other weir designs will also trap gravel upstream in suitable circumstances. These include straight weirs built at right angles to the flow or diagonally across the stream. It is usual for weirs designed for pool scouring on their downstream side (Sections 8.5) to also act as gravel traps.

Gabion baskets have been widely recommended as being ideal for the construction of gravel traps. Loosely packed gabions, if unlined, permit a good throughflow of water which encourages downwelling into the gravel above. If the bed is composed of stable material, gabions can be placed directly on the bed, embedding them slightly. They should be placed end to end and wired together. Steel bars driven into the bed should be used to anchor the gabions in place and further stability can be ensured by threading a steel cable through the gabions before they are filled and the two ends are securely anchored by steel pins driven deeply into the bank. Gravel is then raked in behind the structure.

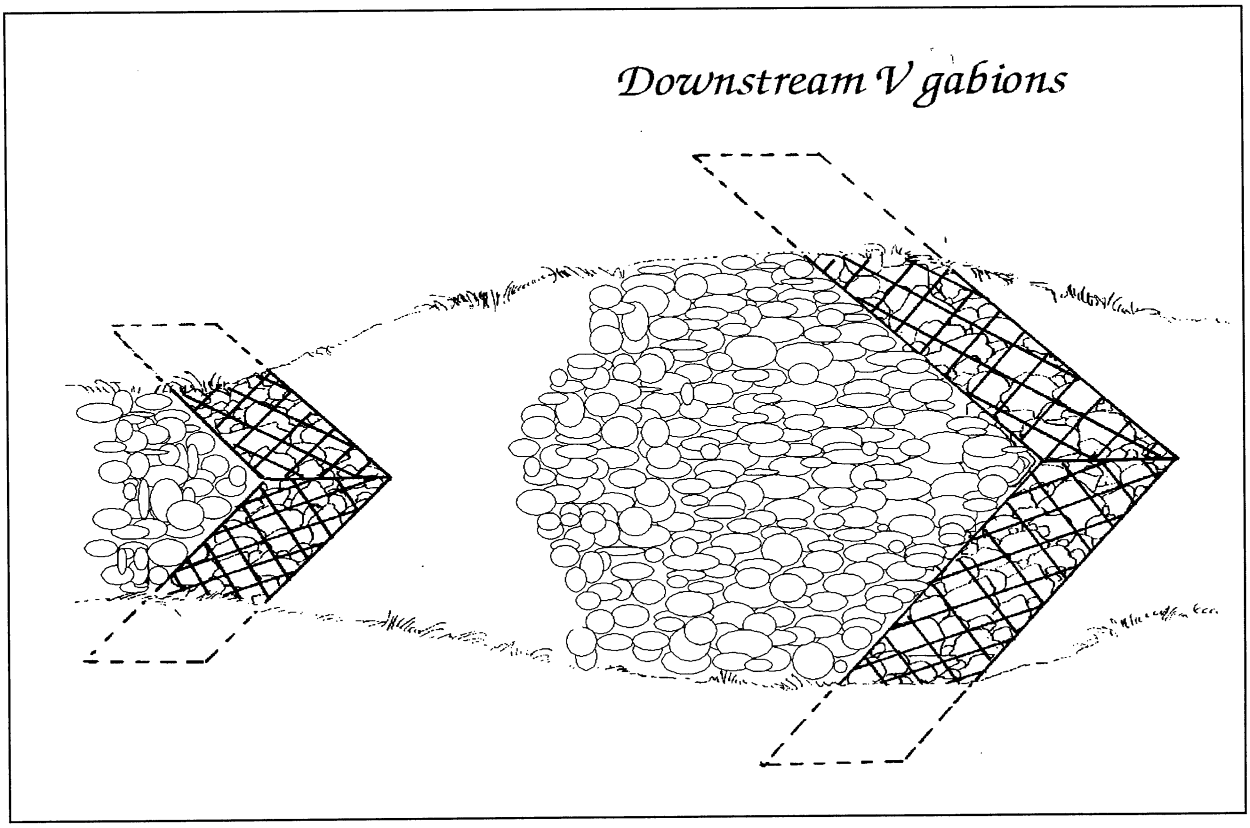


Figure 8.11 Downstream pointing V gabions to dissipate the flow and trap gravel (Adapted from Reeves *et al.* (1991))

If the bed is really stable, large boulders can also be used to construct a weir. Boulders which are large enough to withstand likely flood velocities should be embedded slightly in the bed and smaller boulders keyed in between.

Where a bed is not highly stable (for example where there is a thin deposit of gravel on top of sand) the structure should not rely on the streambed for a foundation. One option is to bury a broad foundation gabion in a trench so that its upper surface is flush with the bed. The weir, made of a narrower gabion, is fixed on top at the upstream edge. Water falling over the weir dissipates its energy on the lower gabion rather than on the soft bed.

If a stream is narrow, a log can be placed across it and the ends keyed into the banks and protected with cobbles and boulders, and so does not rely on the bed for a foundation. If the bed is erodible, water must be prevented from flowing under the log, otherwise a hole will be scoured underneath. An apron of wire mesh or geotextile fabric should be stapled to the upstream face of the log and extend several metres upstream. Cobbles under gravel should be used to bury the apron and thus seal the weir. To prevent scouring under the base of the weir, heavy flat slabs should be laid on the bed immediately downstream to break the impact of cascading water.

Where streams are too wide to allow a single span of a soft bedded stream, a sill can be created from logs or planks which are fixed by stakes driven into the bed. Wooden stakes are most suitable in terms of aesthetics, but it is frequently impossible to drive them into a stream bed. Steel reinforcing rods are thinner, so are more easy to drive and are stronger. Rods, if driven deeply into the bed, will remain in place even if some undercutting of the structure does occur.

A further refinement of this basic theme is to bury perforated pipes under the gravel above a lower trap. By continuing the pipes up to the level of the sill of the upper trap, the resulting head difference produces a flow through the pipes and out into the gravel. If the upwelling current so generated is strong enough, the gravel can be kept permanently free of fine sediment. However, in reality, such a head difference is required that this technique will rarely be applicable. Further details and specifications can be found in Kelso and Hartig (1995)

Applicable stream types

Gravel traps are necessary in streams where gradients, and consequently velocities, are too high to permit the accumulation of spawning gravel. Examples are high gradient upland streams or even in moderate gradient channelized streams from which gravel has been removed. As described in Chapter 2, channelized streams tend to have higher gradients than the meandering channels they replace. Furthermore, the beds of channelized streams are often composed of coarse lag sediments which are not easily re-sculpted into riffles and pools. Theoretically, a gravel trap could be constructed over a wide range of stream gradients, the main consideration being that it must be constructed high enough to sufficiently reduce the gradient to trap gravel.

Drawbacks

Gabion weirs, though suitable for the purpose, are aesthetically detracting and need to be carefully made. Like all forms of impoundment, gravel traps may have a detrimental effect on habitat for older trout on its upstream side. Downstream V weirs may also result in erosion of the banks downstream.

Effectiveness

Gravel traps have been used widely in North America. Initially, stability of the structures was often a problem but more recently, designs have improved. Reeves *et al.* (1991) describe this evolution in great detail and describe many successful schemes. A good example of a successful scheme was that of House and Boehne (1985). They found that a number of species of North American salmonids, including cutthroat trout, preferred to spawn above gravel traps over natural spawning areas. Cutthroat trout, especially sought out gravels in the middle of the V. In Britain, Bowker and Brassington (1995) describe a scheme where gravel trap creation contributed to an increase in trout numbers.

Cost considerations

The cost of constructing a gravel trap essentially entails the cost of building a weir, outlined in Section 8.5.9. If gravel has to be introduced that will be an added cost. As an example, in a stream averaging about ten metres wide, House and Boehne (1985) found that a team of four to six men and a digger could install one to two gabion structures in a day. At the time this worked out at about $60 per metre of gabion or an average of $1200 per structure.

Many brown trout spawning streams in the UK are much smaller than the above example and costs will be less. Morrison and Collen (1992) found that installing a straight log weir across a stream four to five metres wide, took two men and a digger less than one hour. Though not specifically designed as a gravel trap the procedure was essentially the same.

Hunter (1991) describes a scheme where three men and a digger completed two or three downstream pointing V log sills per day.

Further Information

Finnigan *et al.* (1980), Wesche (1985), Adams and Whyte (1990), Hunter (1991), Reeves *et al.* (1991) and Jones and Milner (1992) are recommended for descriptions of gravel trap design and construction.

8.4.4 Gravel jetting

Introduction
A number of techniques have been devised to clean spawning gravels of fine sediment. Some techniques developed in North America are highly sophisticated and involve machines which dredge up gravel, wash it and replace it. However, such costly technologies are not really justified for brown trout which spawn in much lower densities than some Pacific salmon species. The most applicable technique is that of manual water jetting.

Benefits
By gravel jetting, fine sediments, lime concretion and plant roots are purged from amongst riverbed gravels leaving them loose and permitting a good throughflow of water. This can improve spawning habitat by allowing fish to spawn where gravels may otherwise be too hard and by improving the throughflow of water to improve conditions for incubating eggs.

Procedure
Water jetting involves directing a jet of water at the streambed which forces fines out of the gravel into suspension in the water column. Jetting commences at the upstream end of the area of gravel which is to be cleaned. The jet is then directed at the bed, and by a combination of jetting and levering with the pipe a hollow will form. By extending the hollow, a trench between 20 cm and 30 cm deep should be created across the width of the area to be cleaned. Then, by jetting the downstream face of the trench, coarse material is blown into the trench and the fine sediment entrained in the water column is washed downstream. By working back and forth across the downstream face, effectively like ploughing the bed, the gravel can be turned over and cleaned.

Gravel jetting should be performed shortly before trout commence spawning so that the maximum benefit can be derived from the cleaning.

The authors have performed water jetting with several types of water pump and have found a petrol driven pump with a delivery rate of 250 litres per minute with an outlet pipe diameter of 3.75 cm satisfactory. It is important that the width of the pipes be as wide as possible for the power of the pump. This ensures the highest pressure of the jet. A strong metal pipe (about 1.5 m long) should be inserted on the end of the outlet pipe to direct the jet and act as a probe. The metal pipe ideally should be of a wide diameter and should be flattened at the end to produce a high pressure jet. Talks (1992) found that a high pressure pump (3000 psi) which delivered 16 to 30 litres per minute was good at breaking up the gravel but not for purging silt.

Applicable stream types
Gravel jetting is likely to be necessary in streams which have high loads of fine sediments, problems of lime concretion and plant growth. Chalk streams and lowland limestone streams are probably worst affected. It is not likely to be generally necessary in upland streams.

Drawbacks
Care needs to be paid to the sites where jetting is carried out. By purging fine sediments, the level of the bed can fall, and the flow can be drawn into this lower zone. By altering the flow pattern, it is possible to de-water other spawning areas and deflect the current unintentionally. More seriously, resultant increased velocities over jetted areas, combined with a loosened

gravel surface, may result in erosion of the gravel surface. Gravel jetting ought not to be performed right over the head of a riffle bar but only as patches on either the upstream or downstream face of a riffle bar, or preferably on a level gravel reach. Jetting is most suitable in relatively low power streams like chalk streams. Dangers of washout are higher in spate rivers.

Jetting should not be attempted once spawning commences as the fine sediments generated may choke any redds which may have been cut downstream.

The fine sediment generated by jetting constitutes a form of pollution so permission should be sought from the EA before commencing any jetting. Due consideration should be made with regard to impacts on fish habitat downstream.

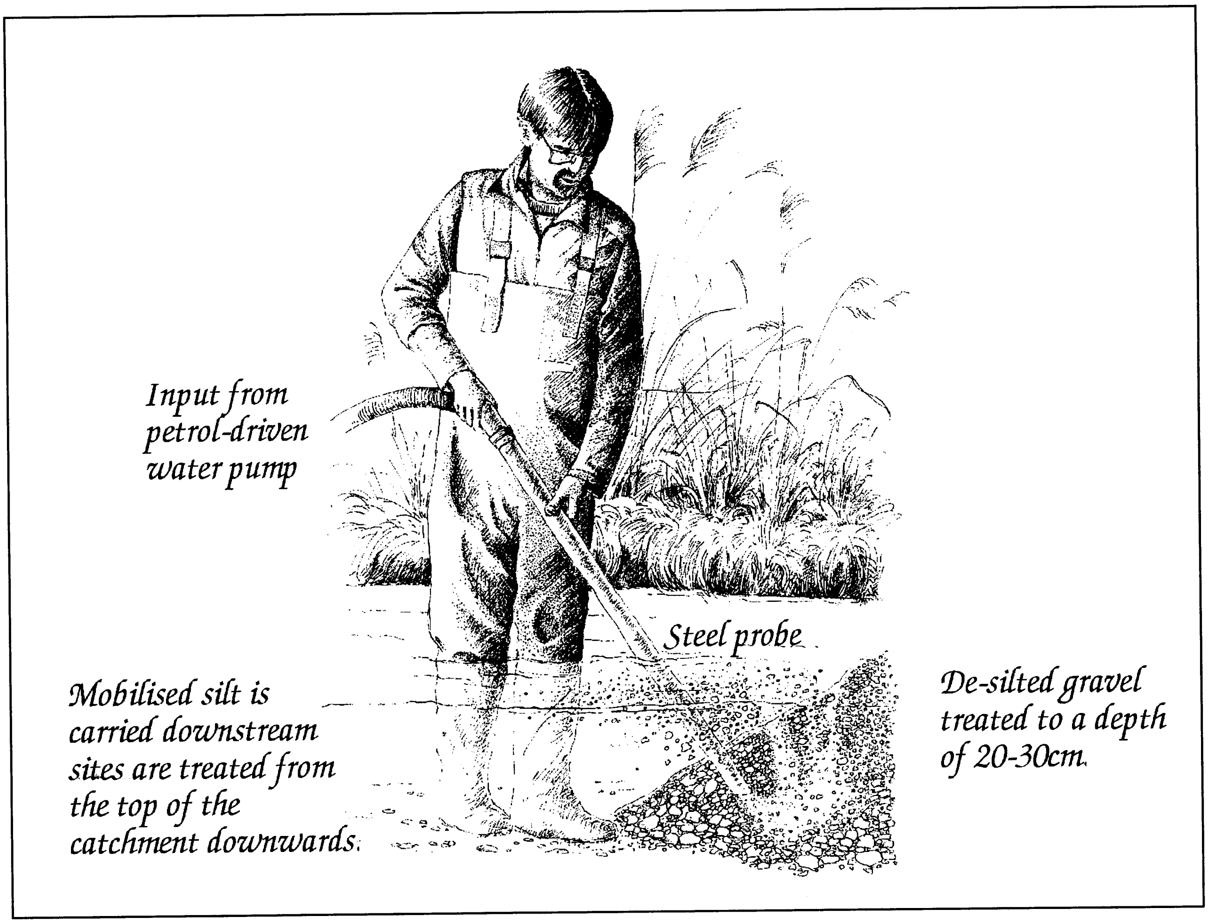


Figure 8.12 Gravel jetting

Effectiveness

Gravel jetting is now a widely used technique in southern chalk streams. A number of studies have looked at its effectiveness jetting on egg survival in both chalk and limestone streams. For example, several studies have demonstrated that gravel jetting significantly reduces the percentage of fine sediments within the gravel (Beaumont *et al.* 1992, Shackle 1995). Other studies have indicated that gravel jetting has a beneficial effect on egg survival, although insufficient replicates and the use of inappropriate statistical methods has prevented a thorough appraisal in most cases. For example, Scott (1994) showed that survival of planted eggs was higher in some artificial redds on cleaned gravel than on uncleaned gravel on the River Itchen. Shackle (1995) similarly found in streams in Oxfordshire that survival rates of planted eggs tended to be higher on areas washed with a high volume pump, though not with a high pressure, low volume pump. However, the eggs were not planted into redds which may have very different conditions for egg incubation than the surrounding substrate. Summers and Giles (1995) found that survival rates of salmon eggs planted in artificial redds tended to be higher, though this was not statistically significant, on cleaned gravel in the River Avon, Hampshire.

An important consideration is how long the benefits of gravel jetting last for. Clean gravel can rapidly silt up, depending on the gravel type, sediment size and hydraulic characteristics of the site (Carling 1984, Sear 1993). Beaumont *et al.* (1992) found that cleaned gravel in the River Itchen still had a lower percentage of fines after four months. However, caution may need to be sounded with regard to apparently promising results. For example, it is frequently observed that the bed level falls after gravel jetting in chalk streams. This indicates that substrate is to some degree supported by the matrix of fines rather than supported by a framework of gravel. In such an instance, purging the fine sediment will actually reduce the amount of void space within the substrate, meaning there is less room for fine sediment. Unless gravel is reworked by spates, it is to be expected that such cleaned gravel will continue to have a lower percentage of fines than uncleaned gravel, even though the void space may be as filled with fine sediment as uncleaned gravel. Further information is required on this subject.

Another potential complication is that because the effect of gravel cleaning is to improve throughflow in the overall substrate, if the main problem is infiltration of fine sediment into a redd post-spawning, gravel cleaning may not be effective. This issue also needs to be clarified before the effectiveness of gravel jetting is fully known.

Cost considerations

A portable gravel-jetter comprising a small petrol-driven water pump with a jetted wide-bore outlet pipe can be constructed for around £300 and should give many seasons service, if well maintained. Talks (1992) found that between 7.4 m^2 and 8.7 m^2 of bed could be cleaned by a single operator in one hour in a chalk stream. Most of the cost is therefore, manpower.

Further information

Detailed descriptions of gravel jetting procedure and its effect on the substrate can be found in Semple (1987) and Talks (1992). The wider range of gravel cleaning techniques are described by Solomon (1983), Pott and Schellhaass (1986), Adams and Whyte (1990) and Waters (1995).

8.4.5 Gravel loosening

Introduction

Gravel loosening, as opposed to gravel cleaning, involves breaking up the surface layers of gravel in a stream where they are compacted or bound by fine sediments, lime concretion or plants. While some loosened fine sediment may be washed from the gravel, gravel cleaning is not the primary objective.

Benefits

By breaking up a hard gravel surface, fish may be allowed to be physically able to spawn. In some cases, improvements in the throughflow of water may result because of reduced compaction.

Procedure

In small shallow streams, forking over the gravel to break it up followed by raking to completely loosen it is adequate. In larger streams where the area to be cleaned is greater and the gravels coarser, more powerful techniques may be used. Heavy harrows dragged across the bed by a tractor on the bank or even horse teams within the stream have been used. Where the gravel is really compacted a tractor and rotovator may be used or the bed raked with the bucket toes on large mechanical excavator.

Appropriate stream types

Gravel loosening is probably most required on silty lowland streams where the bed is bound by fine sediment or where calcareous or manganese deposits or plants completely bind the surface. Chalk streams are especially prone to these problems, though with the exception of lime concretion, they are by no means unique to chalk streams. Loosening may also be necessary in higher gradient streams where gravels are mixed with coarse cobbles which trout cannot move.

Drawbacks

In streams where there is a high loading of fine sediments, gravel loosening may not result in successful spawning if the eggs subsequently die because of siltation. As with gravel jetting, care must be taken in loosening gravels on riffles as they may be washed away.

Effectiveness

A number of studies have demonstrated that fish will spawn on loosened gravel. For example Solomon and Templeton (1976) found that brown trout preferred to spawn in a stretch of chalk stream which was ploughed each year to suppress plant growth. Data presented by Wheeler (1993) show that on the rivers Test and Itchen, trout and salmon exhibited no overall preference for raked gravel but did spawn on it. Reeves *et al.* (1991) describe a four-fold increase in egg to fry survival of sockeye salmon was recorded in a small Alaskan stream after hand-digging spawning gravels and then flushing out silt with an artificial freshet. They also reported that chinook salmon spawning activity increased on a Californian river after gravels were loosened by bulldozer. Pott and Schellhaass (1986) describe how on the Big Qualicum River, Vancouver Island, British Columbia, the heavy silt load necessitates annual bulldozing to improve spawning conditions for Pacific salmon species and steelhead trout. (*Oncorhynchus mykiss*).

Shackle (1995) appraised the effectiveness of loosening streambeds with a tractor and rotovator. No change occurred in the substrate composition but, at some sites, increased survival of planted eggs was found.

Talks (1992) appraised the effectiveness of different methods of gravel loosening on English chalk streams in terms of how well the gravels were loosened. By hand forking and raking one operator could loosen between 2.2 m^2 and 5.8 m^2 in one hour depending on the degree of concretion. In gravel which was completely concreted this method was not possible. By towing a harrow with a four wheel drive vehicle on the bank, 11.2 m^2 to 16.2 m^2 could be loosened per man hour. Four people were required for this operation, two of whom stood on the harrow to give it extra weight. To be effective the gravel had to be harrowed four times, but even then it was ineffective on concreted gravel. An excavator could rake 378 m^2 in an hour. However, it only loosened gravel down to 10 cm. This method was only justifiable where a big area had to be loosened.

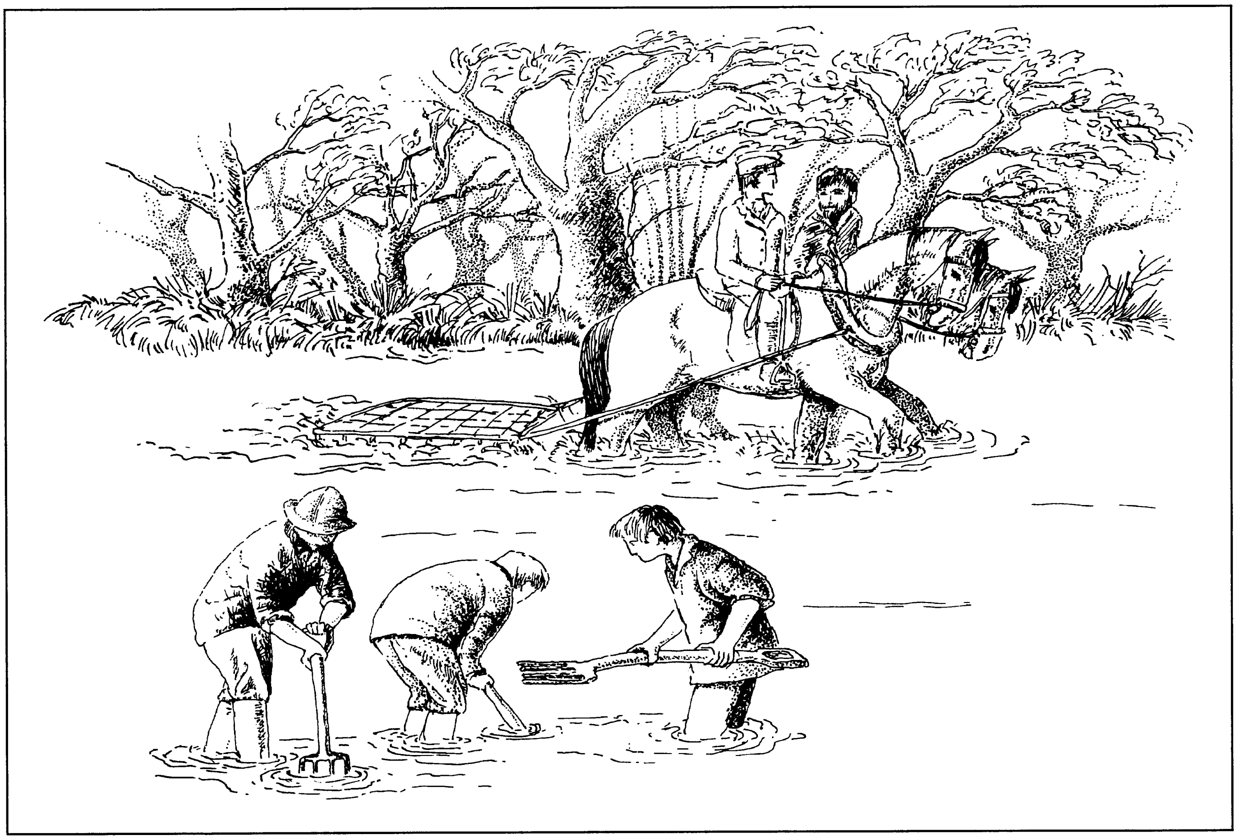


Figure 8.13 Loosening spawning gravel by raking and harrowing

Cost considerations

With hand raking and harrowing with a vehicle the main costs involved are manpower and an indication of this can be gained from the examples above.

Further information

Further information on these techniques can be found in Adams and Whyte (1990), Talks (1992) and Shackle (1995).

8.4.6 Plant control

Introduction
In-stream plants can have a major influence on trout spawning habitat. It is important therefore, that on riffle heads where trout are likely to spawn, plant growth should be controlled.

Benefits
By controlling plant growth on riffle heads, gravels remain exposed and available for fish to spawn on. Plants can physically cover gravels, bind them with their roots, trap sediment and reduce velocities meaning that fish cannot dislodge the gravel so easily.

Procedure
Gravel loosening and cleaning techniques described in Sections 8.4.4 and 8.4.5 can be used to control plant growth. However, over extensive areas this may involve a prohibitive amount of work and gravel loosening may not be appropriate where the surface gravel layer is thin or liable to washing away.

Instead of loosening the gravel, plants can be more quickly cut with a scythe. Cutting by machine is not appropriate because they must be cut right to the base on spawning riffles and the areas cut are very specific. Cutting should take place shortly before spawning commences as weed may grow back quickly. However, cutting does not remove the roots which still bind the gravel.

In-stream plant growth can be suppressed by shading. In Chapter 2 the influence of tree shading on streams is discussed. Tree shading is detrimental to many elements of trout habitat but may be beneficial for spawning habitat.

On spawning areas, trees prevent plant growth and encroachment of emergent vegetation, thus helping to maintain a wide channel - the conditions necessary for the deposition of gravel. It is important in this instance that shade is provided on both stream banks to prevent the deposition and consolidation of material on the point bar.

While tree shading may take years to develop, temporary shading in the form of well anchored dark gas permeable sheeting on the bed will produce quick results. The sheeting should be placed for a period of some months prior to the spawning season to kill off the plant growth and then removed. One such type of sheeting is sold under the brand name of Typar (Dawson 1989).

Applicable stream types
The necessity for plant control may be considered to be highest in rich lowland streams, most especially chalk streams. However, plant growth can be dense in a wide range of other environments. As a consequence of nutrient enrichment, plant growth is now more widespread than in the past.

Drawbacks
While plants can ruin spawning habitat they may provide important cover for fry and juvenile trout. It is important, therefore, that plant growth is only checked on areas where fish will

spawn and weedy areas should be maintained immediately downstream for the fry when they emerge from the gravel.

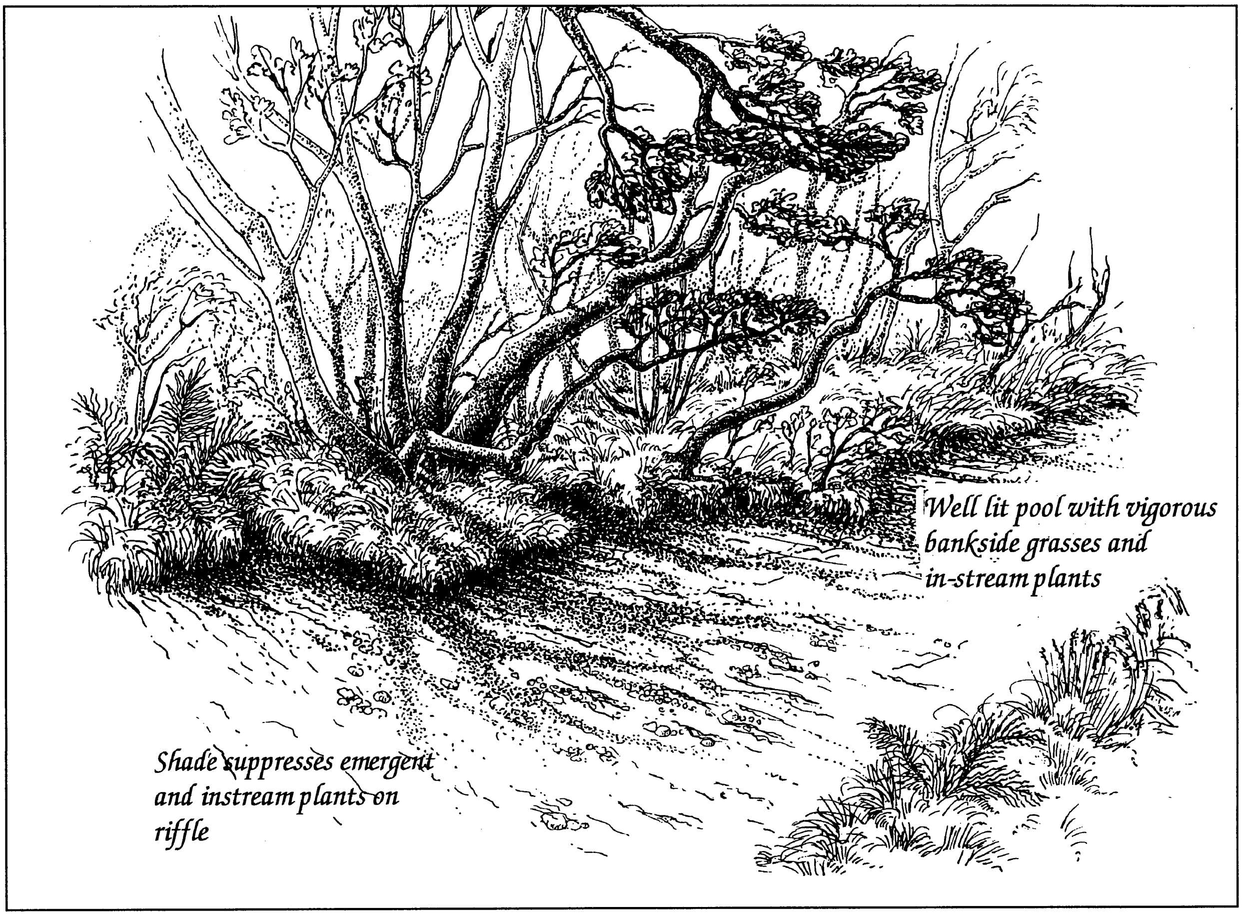


Figure 8.14 The use of trees to suppress plant growth on a spawning riffle

Effectiveness

There is little scientific information available to assess the effectiveness of these simple practices on trout spawning success. Solomon and Templeton (1976) reported trout preferentially using an area of chalk stream where plants were ploughed out. Talks (1992) reported that on gravel raking on a chalk stream, flannels of weed were left between strips of cleaned gravel to provide cover for fry, to concentrate the current over spawning areas and to minimise visual contact between adult males at spawning time. However, no information is provided as to whether leaving the plants did actually have these effects.

Cost considerations

Costs incurred in gravel loosening and weed cutting amount to manpower. Tree shading is very cheap in that once planted the work does not have to be repeated each year.

Further information

No information has been found specifically on plant control to improve trout spawning habitat. However, more general information on the control of in-stream plants can be found in Dawson and Kern-Hansen (1979), Dawson (1989), Wade (1994) and Ward *et al.* (1994).

8.4.7 Spawning channels

Introduction

The preceding techniques in this section involve the creation of spawning habitat within an existing channel. However, in some channel types it may be completely impossible to successfully use any if the techniques described. For example, the river may be too big and velocities too fast, or the gradient may be too steep. To overcome this problem it is possible to create a completely new, side channel, with spawning habitat incorporated, which is of a suitable size and has the required hydraulic conditions for spawning. This is, therefore, the ultimate option within a range of different techniques for the creation of spawning habitat.

Benefits

Spawning channels could provide spawning and nursery habitat adjacent to larger streams and rivers which would be underpopulated if dependent on recruitment from far upstream.

Design considerations

The siting, design and construction of a spawning channel involves complicated procedures. Specialist knowledge should be sought at the design stage. Considerations relating to the design of a stable channel are summarized in Section 8.6.4. Specific considerations are that the levels should be higher than the main river to avoid backwatering when the main river is in spate. Engineering advice is also required on intake design to ensure an adequate flow.

Applicable stream types

Spawning channels are most appropriate alongside larger rivers where there is surplus flow which can be utilized and little existing spawning habitat.

Drawbacks

A major drawback with this approach is that the sedimentary characteristics of a lower river spawning channel will be different from a tributary of the same size, and so, lower egg survival rates may occur. Also, it should be considered that there will be effects on the ecology of the main river by drawing off some of the flow, especially during times of drought.

Effectiveness

Spawning channels have largely been used in North America for Pacific salmon (Solomon 1983). No details have been found on their specific construction for brown trout. However, the extensive water meadow “carrier” systems found on many chalk streams in southern England effectively employ the same principle, and these frequently do provide spawning habitat for trout as has been evidenced on many occasions by the authors. This technique can undoubtedly work if correctly designed.

Cost considerations

Spawning channels are costly to construct. Unless disused channels (e.g. a mill leat) can be restored, costs are involved in design, major excavation works and removal of the spoil. For this reason, little of this work has been done.

Further information

Further information on the use of spawning channels in North America can be found in Solomon (1983), Adams and Whyte (1990) and Environment Agency (1996b).

8.5 Creation of Within Channel Diversity

8.5.1 Introduction

A most important element of trout habitat is that there ought to be a diversity of depths and velocities within the stream. This is expressed as a succession of pools and riffles in alluvial streams, and as pools and steps in high gradient streams. As described in Chapters 2 and 3, a succession of pools and riffles is a widespread feature of natural streams and provides a mixture of habitats required for trout of different life stages.

A great problem is that many streams have lost their former pool-riffle diversity because of dredging and bank damage. Frequently, they have also been channelized, so a full restoration could involve complete channel reconstruction (Section 8.6). Ideally, it is desirable to restore streams to a complete pre-channelized condition. However, in Britain, many streams have been so altered that a return to a natural planform is a practical impossibility. In such instances, and where only in-channel diversity has been lost, the techniques described in this section can be used to restore this diversity. In many instances this does require the use of artificial structures, which may not be the ideal, but can still have the desired effect. In fact, Brookes and Shields (1996b) and Brookes *et al.* (1996) considered that there is often no alternative to the use of such structures. Given the relative costs, they considered that extensive improvements could realistically be achieved in this way.

Different techniques are applicable under different conditions. These range from re-creating self-sustaining pools and riffles to the installation of various types of current deflectors and weirs. The biggest problem is deciding which technique to use in a given circumstance as they all have slightly different effects (Brookes pers. comm.). One approach to overcoming this problem - the “cook book” approach (Orth and White 1993) - has been to provide a very detailed classification of stream types and recommend appropriate tested measures for each (e.g. Rosgen and Fittante 1986). This approach can lead to success, but there have been examples where it has not (Brookes and Shields 1996b, Kondolf and Downs 1996).

Another approach, stressed by Orth and White (1993) is that it is fundamental to understand why a technique creates a habitat, and so schemes can be designed according to local conditions. The desired product is to construct wide riffles and narrow deep pools, and so, different techniques are a means to this end and not a necessity in themselves. Natural stream forming processes should always be invoked where possible and if a simple technique will suffice, it should be used.

The approach taken in this manual is to describe various techniques as alternatives to be considered in the light of conditions particular to individual streams. It is important to understand the functioning of the different techniques so sources of further information are provided. By understanding why different techniques structures work, the reader will recognize those conditions under which a particular structure is most appropriate. It is also strongly stressed that professional advice should be sought when necessary.

8.5.2 Creation of alluvial pools and riffles: excavation of pools

Introduction

Natural gravel riffles are effectively very broad low profile weirs which are spaced regularly along the channel (Chapter 2). It is possible to create such features in an even bedded stream by either excavating the pools, introducing material to form riffles (Section 8.5.3), or a combination of both. This section describes the excavation of pools and the following section the introduction of riffles.

Benefits

By excavating pools, habitat can be created for all life stages. Adult trout especially will benefit from the deeper water, but downwelling currents may be induced in the riffle above each pool, improving the overall quality of spawning habitat.

Design considerations

Each excavation should be about three channel widths long with similar lengths of unexcavated bed in between. At low gradients the lengths of the pools could be extended further, as it has been found that pool to pool spacing can be up to 10 channel widths in length in such streams (Shields 1996). In practice, the distance between excavations need not be rigid but should follow pre-existing features. For example, at the foot of a break of slope or on a corner where secondary circulation will maintain the scour. At bends, the excavation should be concentrated on the outside half of the channel. The deepest part of the excavation should be about one channel width from the upstream end of the excavation and should gradually slope up to the downstream end. The depth of an excavation is dictated by substrate stability. A more stable substrate means a deeper excavation is possible as the risk of bank slumping is less.

Once a pool is excavated, the water surface level over the upper part of the pool will fall slightly. The increased head difference between the upstream riffle and the new pool head will cause velocities to increase at the pool head whilst velocities will decrease at the pool tail. If hydraulic conditions are suitable, this velocity difference created will help maintain the form of the bed by keeping pools scoured clean and depositing material on the riffles as in natural pools and riffles (Chapter 2).

Pools should not be excavated in the centre of the stream. The deepest part of the excavation should always be skewed towards one of the banks with intervening riffles set diagonally across the stream. By thus alternating the thalweg between different sides of the stream secondary circulation may be encouraged which will further enhance the pools.

Appropriate stream types

Excavation of pools is appropriate in uniform shallow streams consisting of continuous riffle. This type of stream frequently results from channelization in moderate gradient areas. Ideally the bed should be composed of stable sediments. It is unlikely to be successful in fine gravel because the upstream pool edges may not remain stable. The stability of the pools is dependent on the overall stream gradient - fine sediments will remain more stable where there are lower gradients. The stability of the upstream face of a pool is a critical aspect and where conditions are unsuitable, weirs may have to be constructed to give stability (Section 8.5.6).

This technique will also fail in low gradient streams carrying high sediment loads. Current velocities need to be high enough to prevent sediment from accumulating in the excavated pools. Essentially, the stretches of stream between the pools are to become riffles/glides, so if they do not fit this description, the stream is unsuitable.

It is recognized that this is a difficult subject, and so advice from a geomorphologist ought to be obtained if much of this work is contemplated.

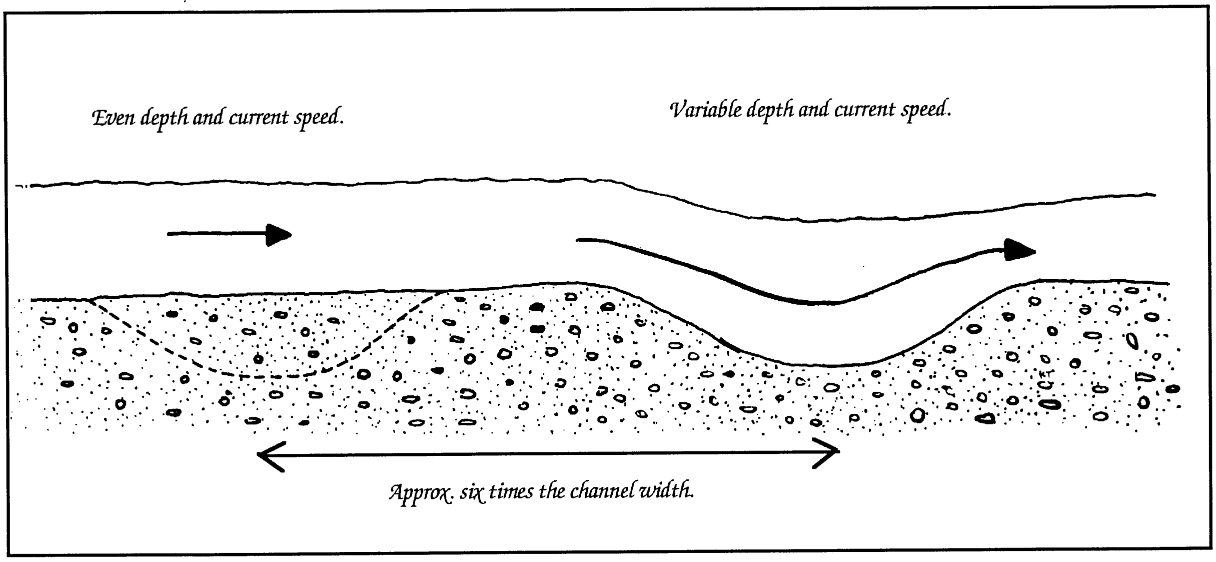


Figure 8.15 The excavation of pools in a shallow stream

Drawbacks

If conditions are not appropriate for this technique it will fail. The pool-riffle harmonics must be right according to the substrate type and stream power for a self perpetuating system to be set up. If the upstream face of the excavation is not stable it may erode resulting in the infilling of the pool. Likewise, if scouring velocities are not high enough, deposition of fine sediment may occur resulting in the infilling of the pool. However, in the favour of this technique, where it is successful it is to be recommended as it requires no artificial structures.

In some environments (e.g. chalk streams) the groundwater table can dip below the level of the stream in places and at particular times of year. Excavation may break through the "seal" in such perched reaches and allow water to leak to ground, leading to a reduction in discharge. This technique should not be used in such areas.

Effectiveness

Few studies have appraised this technique in the literature. Brookes (1990) makes reference to excavation of the bed at points where flows are convergent (e.g. on bends) and states that such restoration work seems to be successful in streams with a medium power. Under higher stream powers the bed tends toward instability and under lower powers aggradation of fine sediment can occur.

Pool excavation on bends was performed by Wessex Water Authority on the River Piddle in Dorset as part of a dredging programme in the late 1970s. Most of these pools still remain stable, and electrofishing by the authors has shown them to be very important habitats for adult trout.

Cost considerations
Compared to most techniques for creating pools and riffles, direct excavation is the cheapest. The major costs involved are the hire of an excavator (about £150 per day) and removal of the spoil from the site. Also if self perpetuating pools and riffles can be created maintenance costs are low.

Further information
A number of references described the use of this technique, normally in conjunction within the wider field of total channel reconstruction (Section 8.6). These include Brookes (1990), Hey (1994), Brookes and Sear (1996) and Shields (1996).

8.5.3 Creation of alluvial pools and riffles: introduction of riffles

Introduction

The previous section described how pools and riffles can be created by lowering the bed level at intervals. Equally, similar features can be created by treating the existing bed level as the pool bed and raising the bed level at intervals to create riffles by the introduction of material to the stream.

Benefits

As in the previous section, the introduction of riffles results in the creation of both adult habitat (in the pools between the riffles) and where conditions are suitable to introduce spawning gravels, spawning habitat.

Design considerations

Riffle introduction employs practically the same principles as gravel planting (Section 8.4.2) and the procedures described in that section for deciding on the applicability of gravel planting are also appropriate. Where gradients are suitable, planted gravel can be used to create a riffle and so creates both spawning habitat and pool habitat for adults between riffles. However, to create a riffle which is not intended as spawning habitat, coarser material unsuitable for spawning may also be used. Such riffles may be planted in velocities which would wash away gravel.

As with gravel planting, coarse substrate material should be introduced about every six times the channel width. The deposits should form a cone with the highest points being spaced at six times the channel width but the base of the cone should extend one to two channel widths on either side of the apex (i.e. the total width of the deposit will amount to about three times the channel width, running from the upstream to the downstream edge of the material). The same criteria with regard to siting and stability of the deposit apply as in gravel planting (Section 8.4.2).

It is important to perform a levelling survey whilst planting riffles. There should be an even fall over each riffle and the height of each riffle needs to be tailored to local variations in streambed height.

As with pool excavation, it is important that other forms of feature should be incorporated. For example, riffles should be formed diagonally as in natural streams to cause the current to alternate from bank to bank. Pools should be located on bends and riffles in straight reaches.

As with excavation, it is advisable to obtain geomorphological advice with this technique.

Appropriate stream types

Whilst excavation of pools is appropriate in streams which are effectively riffle, riffle introduction is appropriate in streams which are effectively all "pool". These are deep slow reaches with low Froude numbers. It is a technique especially applicable to lowland streams which have been over-deepened by dredging.

Unlike pool excavation, riffle planting is appropriate where there are perched water tables.

Drawbacks

The greatest drawbacks with riffle planting are expense and upstream impoundment. Riffle planting often seeks to reinstate part of the reason why riffle removal was done in the first place - i.e. to improve land drainage. Impoundment can also affect other habitat upstream. However, it is possible to reach a compromise. Riffle heights need to be designed to create an acceptable level of impoundment. There are standard computer models available to compute backwater effects (Shields 1983). Another compromise may be to construct a two stage channel which will accommodate floodwaters, though not necessarily lowering the water table (Section 8.6.3).

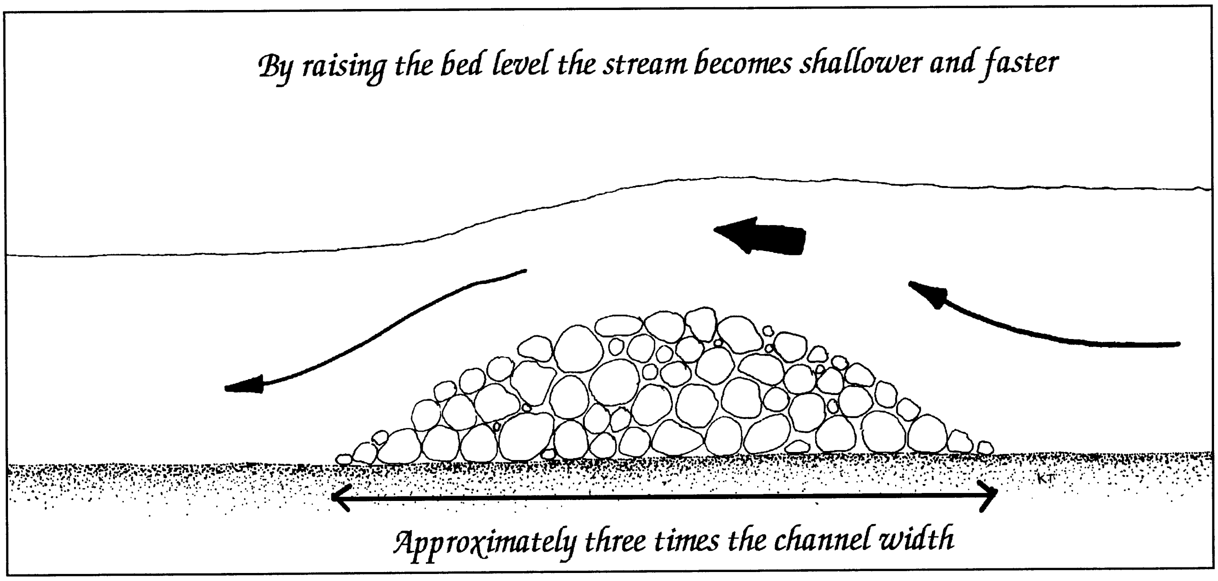


Figure 8.16 A deposit of boulders forming a riffle in a deep slow channel

Effectiveness

Few studies have been found which appraise the effectiveness of riffle planting. Smith *et al.* (1995) found that riffles introduced into a lowland stream were stable on the most part and functioned as intended although there were some failures which were ascribed to unsuitable siting. O' Grady *et al.* (1991) placed boulder mats to create riffles in a deep slow reach of the River Boyne, Ireland, and demonstrated an increase in numbers of salmonids using the site.

Cost considerations

The biggest cost of riffle introduction is that of material and transporting it to the site unless material can be found on site. Rocks vary greatly in price depending on availability (see Section 8.8.1). The other major cost is an excavator (about £150 per day). As an example, Smith *et al.* (1995) found gravel for a riffle 0.5 m high by 7 m to 8 m long in a 2 m to 3 m wide stream cost £100 including delivery plus the cost of an excavator to place the gravel.

Further information

Further information on the theory of riffle introduction can be found in Hey (1991, 1994), Smith *et al.* (1995) and Brookes and Sear (1996). Other examples are provided in Ward *et al.* (1994).

8.5.4 Current deflectors - the principle

Introduction
Current deflectors are widely used and effective structures designed to concentrate the flow of a stream. By narrowing the stream, the deflector itself creates a deeper and faster flow whilst the increased velocities cause scouring of the bed downstream.

Benefits
The scour pools created by deflectors, if combined with good cover, make excellent adult trout habitat. Furthermore, increased velocities at the head of the pool increase feeding potential of the site for trout. By increasing velocities, fine sediments are also scoured from the tails of the pools, exposing spawning habitat.

Hydraulic considerations
A commonly used form of deflector is a simple jetty, often referred to as a groyne or croy, which extends at a downstream angle into a stream. This design operates as intended during low flows, but under high flows - when streams do most of their scouring work - these have the opposite effect. Water flowing over a submerged object tends to flow off at right angles, so a downstream pointing croy causes the current to be deflected towards the near bank under high flows. This results in dissipation rather than concentration of the stream's energy and sometimes erosion of the nearside bank. Downstream pointing croys are not, therefore, recommended, unless they are high enough never to be submerged.

The remedy is to use a triangular shaped structure which will deflect the current at all water heights. Under low flows the current is deflected as with the simple croy, but at high flows, the current is deflected off the downstream edge in the desired direction (White and Brynildson 1967).

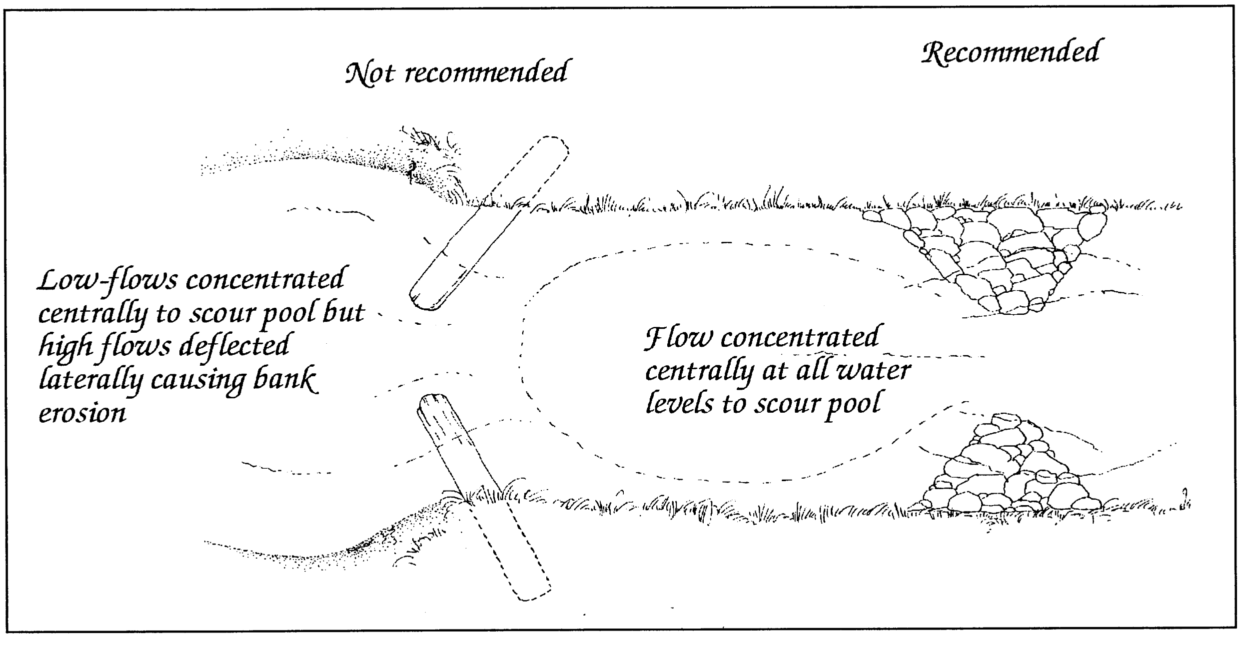


Figure 8.17 Differences in scouring effects between downstream pointing groynes and triangular "wing" deflectors. (Adapted from Orth and White (1993))

8.5.5 Current deflectors - wing deflectors

Introduction

In the previous section the broad principle of the wing deflector was described. In the fisheries literature many variants on the wing deflector theme can be found. These are referred to as single wing deflectors, double wing deflectors, channel constrictors etc. This section describes the principles of the wing deflector in greater detail.

Benefits

Wing deflectors effectively function as point bars which narrow the stream and re-direct the flow. The scouring effect of a deflector can be created by other means, e.g. by planting a riffle (Section 8.5.3) or installing some form of submerged weir (Sections 8.5.6 - 8.5.8). However, these techniques increase velocities by raising the bed and create a shallower and faster flow over the structure. In trout stream restoration, it is not always desirable to create fast shallow water. For example, a stream may contain more than ample spawning habitat and lack adult habitat. Deflectors, by narrowing the stream instead of raising the bed, create deeper and faster water alongside them rather than shallower and faster water. Thus, deflectors produce habitat for juvenile and adult trout in the scour zone but can also create spawning habitat on the tail of the scour pool.

Design considerations

Deflectors must be designed to concentrate normal flows but not to impede high flows. For this end, the height of the apex of the deflector should be just above the level of average summer flows. The upper surface of the deflector should slope upwards towards the bank so that water continues to be deflected at higher water levels. The height of the deflector at the bank should not be greater than one third of bankfull depth.

By deflecting the current away from the nearside bank, fine sediments are deposited in the lee of the deflector allowing the bank to become consolidated, leading to a narrower pool. By placing deflectors alternately on either bank at a spacing of about six channel widths, channel diversity can be further increased. An isolated deflector can be used to scour a pool and deposit spawning gravel below that pool.

Wing deflectors should be built below riffles at pool heads, where alluvial point bars are sited. However, care must be taken that by raising the water level, the upstream riffle is not drowned out. Deflectors are much less effective in really low gradient, deep slow silty streams. In such streams the bed level needs to be raised by riffle planting (Section 8.5.3).

In practice, most published examples show deflectors as somewhat angular structures, but though more difficult to construct, a deflector ideally should be a rounded whaleback structure with the sides sloping rather than vertical. Such a structure will deflect the current more efficiently as there are fewer sharp corners to create turbulence which dissipates the stream's energy. Deflectors are intended to guide the flow, rather than damming it and should not have protrusions which collect floating debris.

There is no set rule for the angle or distance a deflector projects into the current. In the literature an angle of 45° is often stated but this really depends on the circumstances of the site. Cooper and Wesche (1976) experimented with temporary plank and sandbag deflectors to achieve the channel pattern they required before using more durable materials.

Wing deflectors can be constructed from many different types of material. They essentially consist of erosion resistant faces and can be infilled with gravel, rubble, chalk etc. The exact materials chosen depend on how stable the bed and banks are, the current velocities likely to be experienced, readily available materials and aesthetic considerations.

Where the bed is stable and offers a good foundation, boulders stacked like a drystone wall or rock-filled gabion baskets make a good facing material. In lowland environments where rock is often unavailable and streams have low power anyway, deflectors may be faced with planking, logs or geotextile fabrics. If foundations are stable, concrete filled sandbags wired together make a good facing material because they can be moulded to form a hydrodynamically efficient whaleback structure. A major drawback of deflector construction is the amount of material which is required, so anything which can be done to simplify a structure is desirable.

An important point when constructing deflectors is to ensure that they will not be undercut by the current which can lead to the escape of the infill material and even the collapse of the structure. This is especially a concern where wood is used as a facing (boulders and gabions can "settle" if undercut) and the bed is made or erodible material. In that instance, the wooden structure must be embedded in to the substrate, anchored in place with steel bars or wooden posts driven deeply (up to a metre) into the bed, and an apron of geotextile fabric placed in behind the facing before backfilling takes place. The ends of deflectors should also be keyed well into the banks and, where necessary, protected with boulders to prevent scouring.

Appropriate stream types

Deflectors work best in streams with a gradient less than 0.5% and certainly no greater than 3% (Wesche 1985). The stream may be of any size, but typically with a high width to depth ratio. The bed needs to be relatively stable so the structure does not undermine with the resultant scouring. They are not suitable for moderate gradient streams where there is a lot of movement of gravels and cobbles. In such streams high flood velocities are encountered and an intrusive structure can be damaged or impede flows. Low gradient streams with high fines loads are also inappropriate as silt accumulations can render the structures ineffective.

Drawbacks

As with any other structure which creates an increase in head height, deflectors can cause upstream impoundment. Also by narrowing and scouring the channel, the accumulated sediments will be displaced downstream affecting habitats there. In fact such a process may not be a one-off occurrence because temporary sediment storage will be reduced, passing the problem on downstream.

Effectiveness

Numerous North American studies have involved the creation of deflectors and demonstrated effects in improving trout numbers. The best examples are those of Hunt (1969, 1971, 1976, 1988), Hunter (1991), and Shuler *et al.* (1994) all describe the successful use of deflectors. In terms of hydraulic performance, Binns (1994) found that after 18 years service, 96% of deflectors were intact.

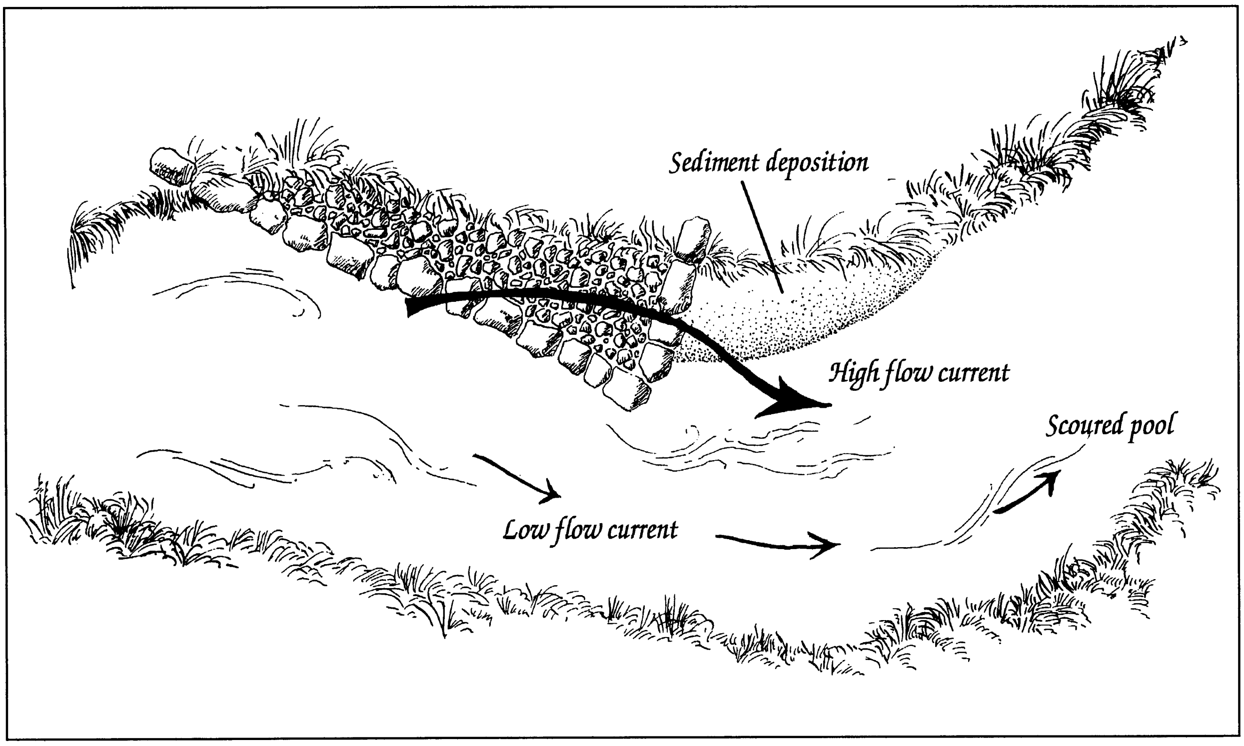


Figure 8.18 A single wing deflector concentrating the current in a corner pool

However, Knox (1985) found that of 23 log deflectors built in the channelized Ten Mile Creek, Colorado, only five appeared to provide any habitat improvement. Lere (1982), working on the St. Regis River Montana, found that rock jetties largely failed to improve habitats, probably because they were spaced too frequently (only two channel widths apart) and because the stream was too steep and confined during flood flows for these structures to work effectively. Moreau (1984) found that deflectors were better at directing flows than at scouring pools.

Cost considerations

Costs involved largely consist of obtaining materials and transporting them to the site and installation. Seehorn (1985) reported that a four-man crew can build three or four wing deflectors on a four to five metre wide stream in an eight hour working day with the aid of a digger. Recent work by the authors found that an excavator (£150 per day) with operator and overseer can build three or four single boulder wing deflectors in a day on a 15 m wide river with a stock pile of rock at hand.

Further information

Detailed descriptions of wing deflectors, construction materials and appropriate sites are found in White and Brynildson (1967), Wesche (1985), Adams and Whyte (1990), Hunter (1991), Hunt (1993), Central Fisheries Board (1995b), Waters (1995) and Brookes *et al.* (1996). Brookes (1992) provides details of general deflector function and siting criteria.

8.5.6 Low profile weirs - the principle

Introduction

In addition to wing deflectors, low profile weirs are the main type of artificial structure used in creating within-channel diversity. As with deflectors, there are many different designs of weir but this section describes the important general principles of how weirs create trout habitat. Section 8.5.7 and 8.5.8 provide specific examples of different designs on a common theme.

Benefits

Weirs, by raising the bed level or by maintaining the existing bed level when the bed level is lowered downstream, increase the water surface gradient and so cause the current to accelerate on flowing over them. Weirs can, therefore, be used to locally speed up the current and scour the bed immediately downstream. Depending also on the configuration of a weir, the direction of the current can be changed, the flow concentrated, and scouring further increased. The pools scoured by weirs provide habitat for adult trout especially, but gravel accumulations above weirs and on the tails of the scoured pools can also provide spawning habitat.

Design considerations

The purpose of a low-profile, or drowned weir, is to speed up and deflect the current immediately downstream to scour the bed and sweep fine material away. It is important that the stream's kinetic energy is transferred over the weir efficiently to the area where work needs to be done. Effectively, a low profile weir performs the same role as a natural alluvial gravel riffle (Chapter 2).

The principle of a low profile weir, is that water should flow over it with minimal turbulence rather than fall over it. To ensure this, the downstream face of a weir should be gently sloping. There should also be no sharp angles to create turbulence. With a steep weir, water cascades over and energy is dissipated on the bed immediately below, creating a backwash which can lead to undercutting and even the collapse of the structure if it does not have a secure foundation (Fig. 8.19).

The efficiency by which energy is transferred over a weir is not only affected by the weir's shape, but by the water level downstream. As the downstream level increases relative to the height of the weir crest, less of a fall results and less energy is lost through turbulence. Since water levels vary with discharge, the crest of a weir should slope across a stream so that during low flows the flow is concentrated at one part and can still flow smoothly over the weir with minimal energy loss.

Appropriate stream types

Low profile weirs are appropriate in shallow streams with a swift current. They are not so much intended to raise the head and increase velocities but to redirect and concentrate the current in streams where velocities are already high. One use of such a weir is to stabilize the upstream face of an excavated pool as described in Section 8.5.2 which would otherwise infill. In such a case the level of the weir would be no higher than the existing substrate and would merely create an erosion resistant sill. A low profile weir may also be constructed in conjunction with riffle planting (Section 8.5.3) or gravel planting (Section 8.4.2) to stabilize the downstream face and act as a grade control structure. In that instance the sill should be the same height as the planted riffle.

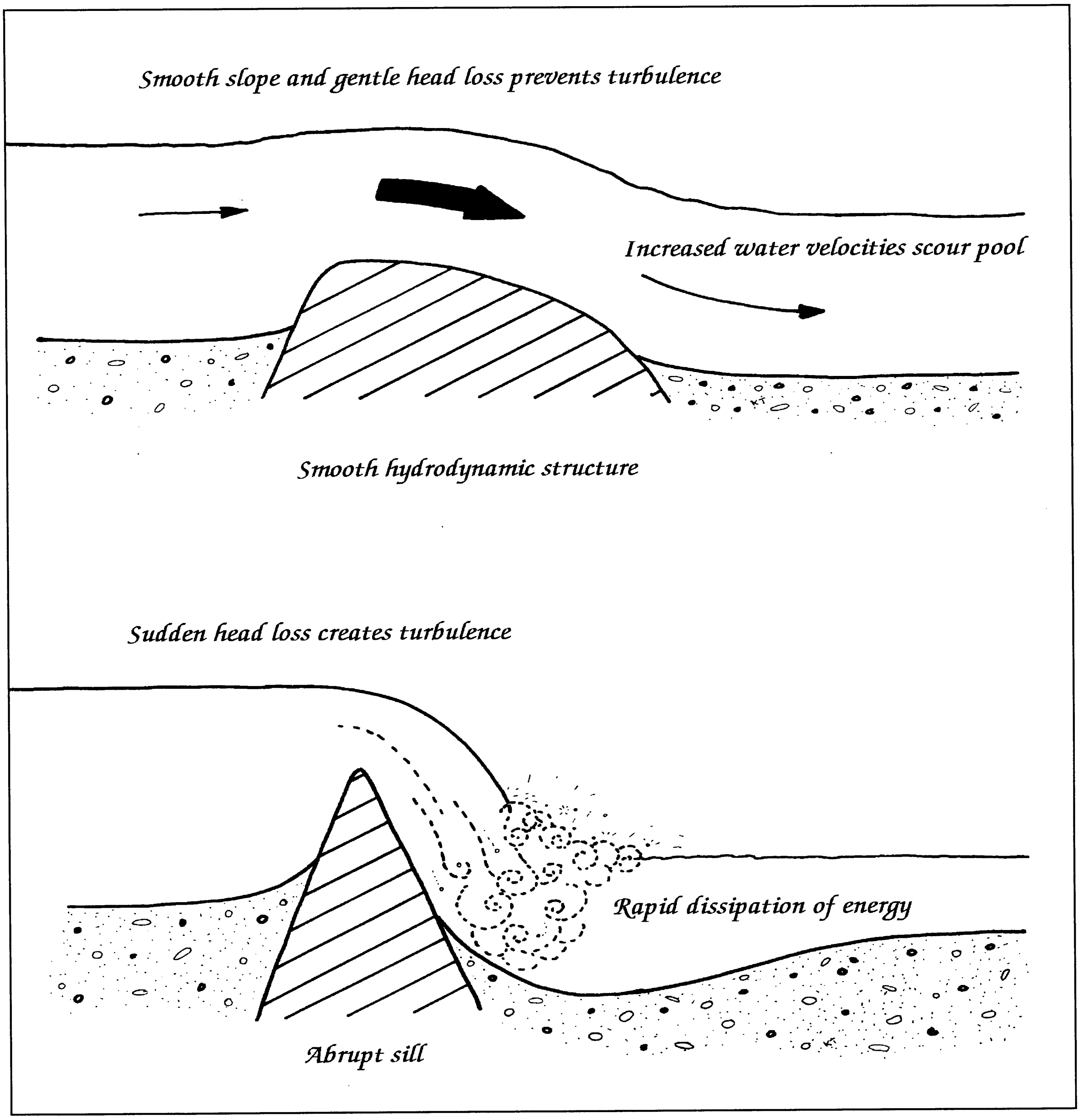


Figure 8.19 Principles of a low profile weir (top), and a drop-over weir (bottom)

Drawbacks
As with other structures placed within a channel, consideration must be taken for the effects of impoundment, both on habitat quality and land drainage. The effects will be greater where gradients are lower.

Further information
Principles of weir design can be found in Shields (1983) and Hey (1994).

8.5.7 Low profile weirs - the diagonal weir

Introduction
In meandering alluvial streams, riffle bars are usually aligned diagonally across the stream and the current is deflected towards one bank where it is concentrated and scours a trench pool (Chapter 2). Similar features can be created by installing a low profile weir diagonally across a stream to deflect the current alongside a reinforced bank.

Benefits
By concentrating the current against a strong bank, a pool may be scoured which will provide habitat for adult trout especially. The resultant deposition at the tail of the pool may also create spawning habitat. A diagonal weir can also be used to create a gravel trap (Section 8.4.3) to create spawning habitat on its upstream side.

Design considerations
The basic design principles for a diagonal weir are described in Section 8.5.6. The main specific design consideration is that a diagonal weir should be angled such that it is lower alongside the bank which the current is to be deflected to. This ensures that at times of low flow the current is concentrated in one part of the channel and maintains scouring velocities. It also ensures that fish will always have free and easy passage at all heights of flow. In effect a diagonal weir operates like a submerged wing deflector. A diagonal weir could be viewed as a low profile wing deflector which is permanently submerged and extends right across the width of the stream.

Diagonal weirs can be constructed from many different types of materials depending on local availability and design specifics.

Rocks and boulders are good weir construction materials because they settle into the bed if undercut and the structure is maintained. This form of construction is appropriate in streams with very stable beds, e.g. rock, cobbles or hard clay. Large boulders should be embedded in the bed to act as keystones to provide compressive strength for the weir when other boulders and placed in between them. Where possible, a structure should be built around existing well-bedded rocks in a stream.

Considerable care must be taken to ensure that rock weirs are well sealed, so that low flows do not flow through, rather than over them. The weir should be composed of various sizes of stones which can be packed into the interstices and then, cobbles and gravels should be packed into the upstream face. Where a good seal is difficult to achieve, a geotextile fabric apron can be incorporated into the weir to prevent finer sediments being washed out. It is important ensure the downstream face is sloped and the downstream toe of the weir may need to be protected with large flat boulders to prevent undercutting by backwash.

In small streams (up to five metres wide) diagonal weirs can be successfully made with logs and this form of construction is described in Section 8.5.8.

Appropriate stream types
Diagonal weirs are appropriate in moderate gradient shallow streams which may experience high spate velocities. In such a stream, a wing deflector may restrict the flow to too great a

degree and be liable to damage. The submerged weir does not so much obstruct the flow but steers it.

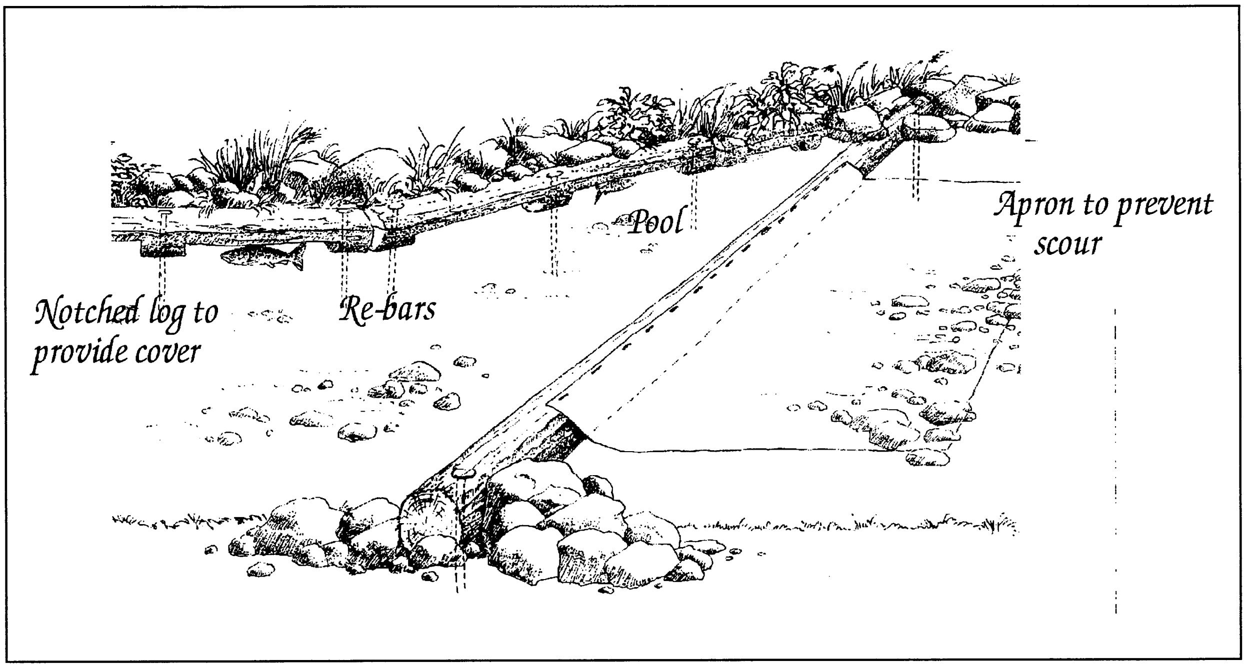


Figure 8.20 Diagonal weir to deflect current against a bank reinforced by logs (Adapted from Hunt 1993)

Drawbacks
As stated in Section 8.5.6 the potential exists with any form of weir creation to create an impoundment upstream which not only increases flooding risks to surrounding land but can damage trout habitat by reducing current velocities and causing sediment deposition.

If the banks are not stable, diagonal weirs can cause erosion of the banks and can initiate meandering.

Effectiveness
No studies have been found which have appraised the effects of diagonal low profile weirs on trout numbers in isolation. However, Hunt (1992) reported that in terms of their hydraulic performance, of eight such structures made of logs, 63% performed to an "excellent" standard and 25% were classed as "good".

Cost considerations
Of all weir designs, diagonal weirs are relatively cheap to construct since they are embedded in the bed and consist of a simple straight structure. Detailed costings on weirs generally are provided in Section 8.5.9.

Further information
Descriptions on the construction of diagonal weirs can be found in White and Brynildson (1967), Wesche (1985), Adams and Whyte (1990), Hunter (1991), White (1991), Hunt (1993) and Hey (1991, 1994).

8.5.8 Low profile weirs - the "V" weir

Introduction

The diagonal weir in Section 8.5.7 creates pool habitat by concentrating the flow against a strong bank. In streams where the banks are composed of soft sediments, bank stability may not be high enough to permit the use of diagonal weirs. However, by constructing an upstream pointing V, the current from each half of the stream is deflected to the middle and so the current is concentrated in the centre of the channel rather than against the banks.

Benefits

As with diagonal weirs, V weirs create pool habitat for adult trout and spawning habitat where the gravel is deposited downstream.

Design considerations

The main design considerations are described in Section 8.5.6 and 7. However, it is important that the structure is lower in the centre than at the banks so the current is concentrated during low flows. It is possible with this design to leave an open gap in the centre so that low flows are not impeded at all. Such a design effectively equates to constructing a wide wing deflector on either side of stream.

Suitable construction materials include boulders, described in the last section (8.5.7), and logs. The diameter of logs required will depend on the degree to which the bed level is to be raised. In practice the larger the log the better, for if it is too big, it can always be partially embedded. If large logs are unobtainable, small logs can be used with one log lashed on top of another or even three logs lashed into a triangle. Logs need not be the only material used. Planking, boards, railway sleepers are alternatives. However, logs are frequently easily obtainable and have a more natural appearance in a stream.

A trench must initially be dug in the stream bed to ensure a sound footing for the weir. After placement the structure must be anchored with wooden posts or steel rods driven deeply into the streambed. The log must be lashed securely with galvanized wire because it may be subject to considerable stress. The upstream face needs sealing at bed level with clay, a geotextile or wire mesh apron and backfilled with cobbles and gravel. It is also important to protect to downstream toe of the weir with a rock/cobble base which can be held together with wire mesh pinned flat.

The ends of logs must be sunk at least one third of a channel width into the bank. Cobbles need to be packed in with the log and the stream edge should be protected with rock.

Applicable stream types

The siting criteria for V weirs are essentially similar to those for diagonal weirs (Section 8.5.7). The main difference being that banks are less stable and the initiation of meandering being avoided.

Drawbacks

A potential problem with a V weir is that if the flow is concentrated to too great a degree, severe back eddies can be generated by the central plume which can cause lateral erosion.

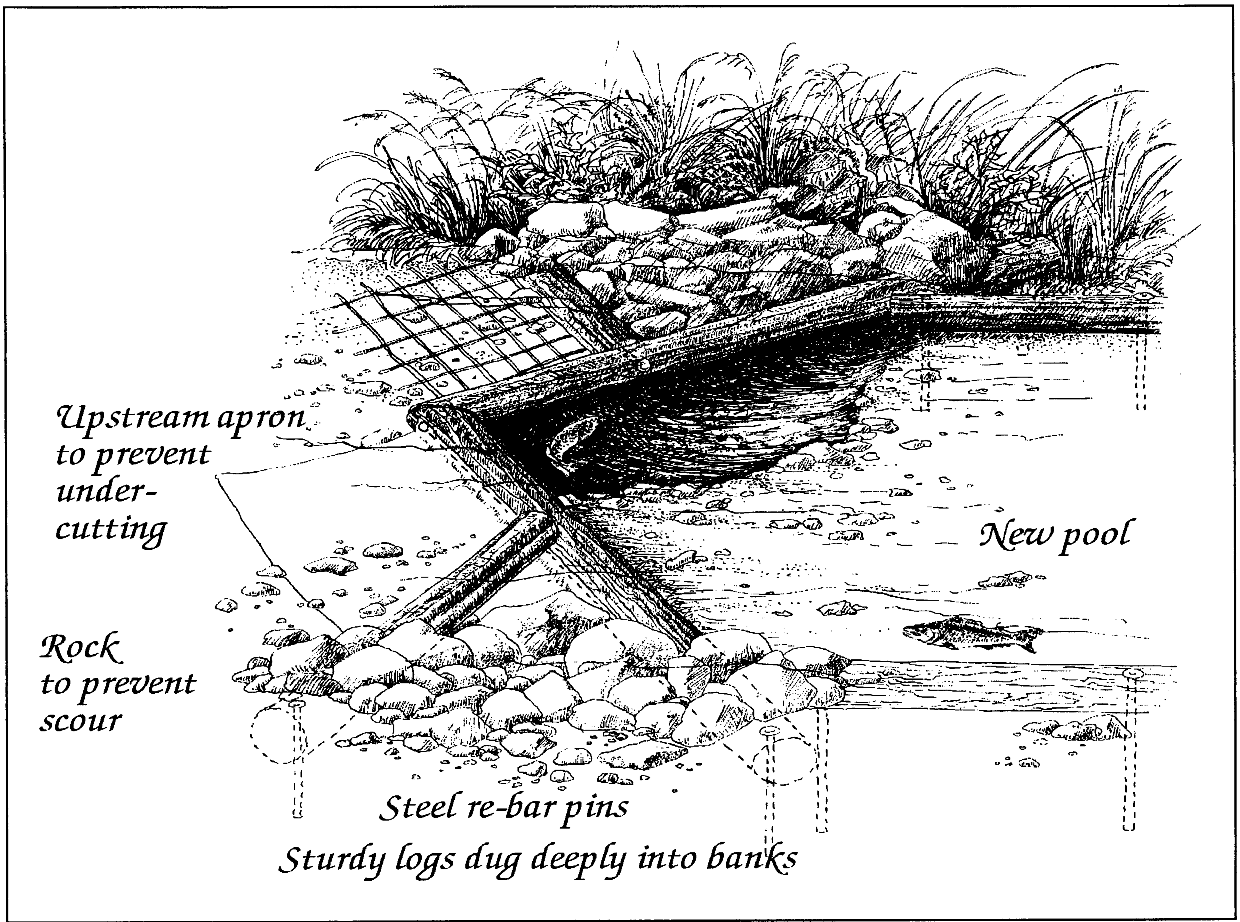


Figure 8.21 Upstream V weir to scour a central pool (Adapted from Hunt (1993))

Effectiveness

No examples of the specific appraisal of the effects of a drowned V weir have been found in the literature, though there are a number for V shaped drop-over weirs (Section 8.5.9). However, the authors recently constructed eight structures of this nature on a four metre wide chalk stream in Dorset which had been badly degraded by cattle grazing. After one year the structures were still fully functional. Combined with regeneration of the riparian vegetation through fencing, a six fold increase in numbers of wild trout present was found (Giles and Summers 1996).

Cost considerations

On a four metre wide stream, the authors found a four man team, plus an excavator to deepen the pools and backfill gravel, could construct four structures in an eight hour day. Materials for each structure, consisting of railway sleepers, a wire apron and steel bars as anchors cost less than £50 (1994 price).

Further information

Detailed descriptions on the construction of this form of weir are provided in Carter-Platts (1930), Wesche (1985), Hunter (1991), Hunt (1993), Central Fisheries Board (1995b) and Shields *et al.* (1995).

8.5.9 Drop-over weirs

Introduction

Unlike low profile weirs, drop-over weirs are designed to create a sharp change in hydraulic head height in a stream. This creates a waterfall rather than allowing the flow to pass smoothly over (Fig. 8.19).

Benefits

Water falling over a weir leads to effective energy dissipation which will create a turbulent pool under the structure. Such a weir is in fact designed to be undercut. The pools created are intended as habitat for juvenile and adult trout.

Design considerations

A drop-over structure consists of a sill which is placed over a stream and does not depend on the bed for a foundation, so it can be undercut without collapsing. A sealed ramp is constructed on the upstream side of the sill so the stream is impounded and flows over the sill rather than under it. Wooden planks or slabs can also be placed over the lip of a sill to extend the ramp and extend the undercut zone which provides overhead cover for trout.

Drop-over structures necessitate a considerable degree of upstream impoundment. They should be sited below steep reaches to minimise the length of the impoundment which should never be more than five channel widths. The banks also need to be high enough to contain the upstream ‘ponded’ section even under high flows, otherwise, flood waters will bypass the weir around the sides and may wash it out. Drop-overs should not be built below spawning riffles as they may be drowned out.

Logs are an appropriate material for constructing drop-over weirs. At its simplest, in a small stream, a single log may span a stream with the ends keyed well into the bank within a foundation of heavy rocks. A strong apron of geotextile fabric extending several metres upstream should be fastened to the upstream side. Strong slats leaning on the log should be fitted under the apron to take pressure off the apron. Alternatively it is possible to construct a ramp of close-fitting planks or place concrete slabs or flagstones against the log. Once complete, the ramp should be backfilled with cobbles and gravel. It is important that the weir is well sealed so that the woodwork remains waterlogged. This will prolong its life.

On the diagram a more complicated structure (a “K-dam”) is illustrated with bracing logs on the downstream side. This design is more suitable for larger channels where pressure on the log is greater. It also has the purpose of narrowing the channel (as in the V weir, Section 8.5.8) to further concentrate the flow. As the downstream brace logs are also undercut, further cover results from this design. It is fundamentally important with this design that the ends are securely anchored in the bank and protected with rock as the structure could be subject to considerable stress.

A more simple form of drop-over can be constructed in a small stream by bedding in a line of large boulders with a flat vertical face on the downstream side. Large flagstones, concrete slabs or even planking can be placed against the upstream side of the boulders and buried by cobbles, but leaving an overhang on the downstream side.

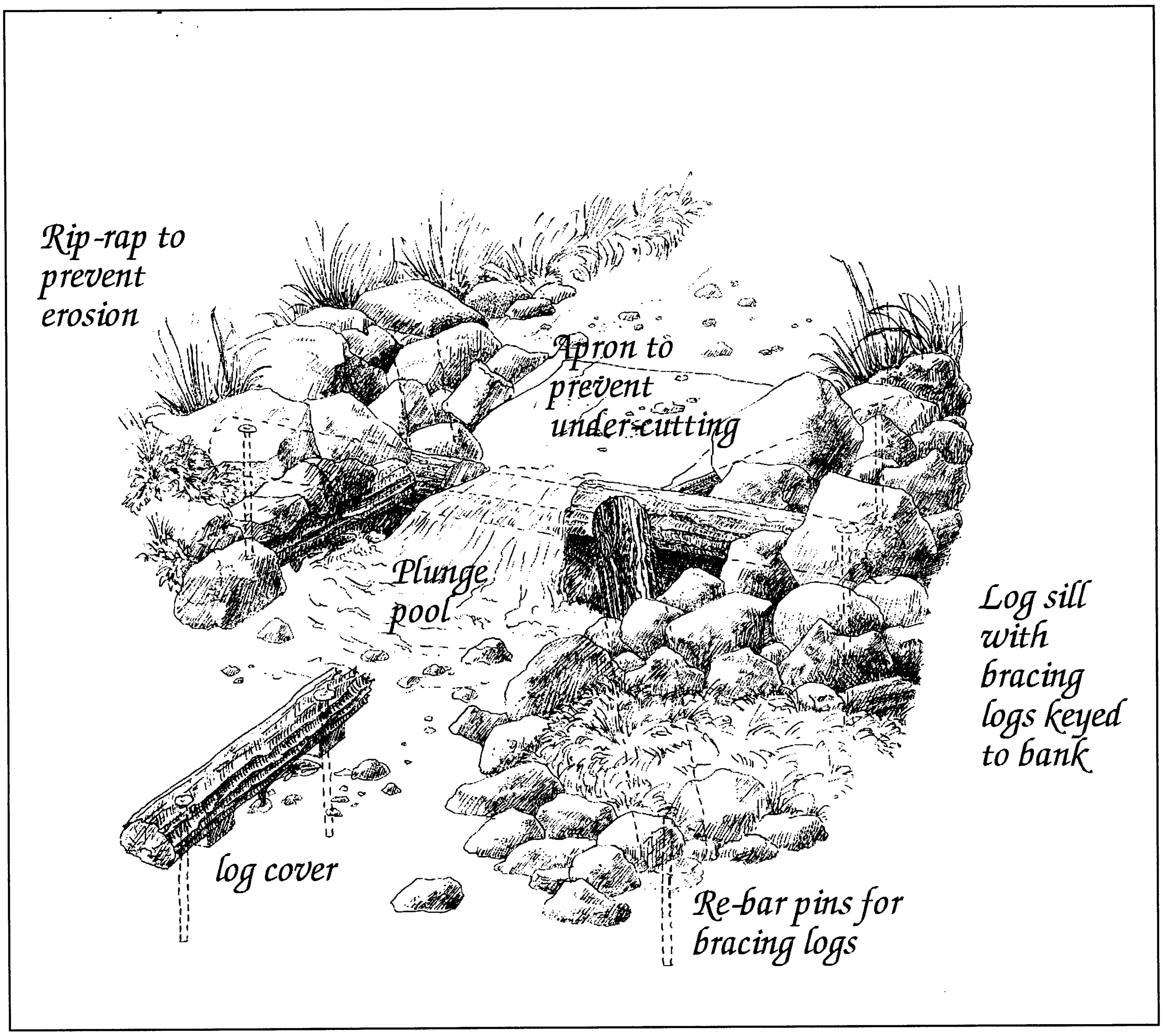


Figure 8.22 A drop-over weir ("K-dam") producing a plunge pool (Adapted from Hunt (1993))

Applicable stream types

Whilst drowned weirs are designed to re-create pools and riffles in alluvial streams, drop-over weirs are used in high gradient streams. In such streams classical pools and riffles do not occur (Chapter 2). In that environment, pools must be created by waterfalls which scour the bed immediately under them. Waterfalls can be created with weirs employing exactly the opposite principle to that of drowned weirs.

In high gradient streams, fallen trees naturally form an extremely important element in creating trout habitat. Drop-over weirs attempt to mimic the effect of a fallen log.

Drop-over weirs should not be created on low gradient streams as the degree impoundment which results may damage more habitat than is created.

Drawbacks
Waterfalls require migrating trout to jump over them rather than swim over them. In order to jump a fall, trout and salmon require an adequate take off depth of water. This has been found to be at least 1.25 times the height of the fall (Stuart 1962).

Drop-over structures must be very strong otherwise they are prone to wash out. High gradient streams can transport large stones and impose considerable stress on a structure. More simple and robust structures are probably the best. Streams which transport coarse sediments ought to be avoided.

Effectiveness
Many studies have appraised the effects of drop-over weirs. Since these are used in higher gradient streams they tend to be used on their own and consequently specific appraisals are generally performed.

Riley and Fausch (1995) in one of the best appraisals of any habitat restoration, showed that in six streams where they installed drop-over structures, pool volume increased by an order of magnitude within two years. Increases in numbers of fish were generally seen, with a 231% increase in adult brook trout numbers in one stream. Immigration accounted for about half the increase, demonstrating they had created a preferred habitat.

Gard (1961) found that after drop-overs were installed, previously barren water held brook trout. Of a series of fourteen rock and log dams constructed in the headwaters of Sagehen Creek, California, around half were in good to excellent condition twelve years later. The new habitat created supported brook trout stocks at a minimum density of 973 trout/ha weighing 18.6 kg.

Binns (1994) found that after eighteen years in a Wisconsin stream, ramp weirs yielded variable results with some being washed out. Better results were found with plunge pools created with flat rock sills which tended to be deeper and provided better cover than natural pools. All sixteen survived the eighteen years in a functional state.

Morrison and Collen (1992), in a Scottish stream, found as a result of creating log-drops, numbers of trout increased by almost ten times in three years. Numbers also rose in a control area, but only by about two times.

Maughan *et al.* (1978) found that angler harvest confounded an appraisal of the effectiveness of log-drop weirs on population numbers, but did find that trout distribution was associated with the structures. They found that some weirs had lasted for thirty seven years, with the wider weirs and those with a plank ramp being most durable as opposed to a wire apron.

However, upland streams may not always benefit from pool creation. Rockett (1979) considered that a limited food supply prevented trout from benefiting from nine drop-overs placed in a Wyoming stream.

Richard (1963) found that seven log dams built in a Californian stream caused erosion and provided no better habitat.

Rinne and Stefferud (1982) found that pools made by weirs had a 50% to 70% greater volume than natural pools. They were also 38% to 50% deeper, had seven times more cover and held 50% more Gila trout (*Oncorhynchus gilae*) in terms of number and 200% by mass.

Cost considerations

Seehorn (1982) estimated that a four to six man crew can construct one or two K-dams each day on a four metre wide stream. Gard (1961) found that it took three to six hours to construct a rock weir in a stream a few metres wide.

The more complex the structure, the greater the costs are. Richard (1963) found that it took 16 hours to construct a single span weir with a log one metre in diameter but it took 41 hours to construct a K-dam.

Further information

Details on the construction of drop-over structures can be found in White and Brynildson (1967), Finnigan *et al.* (1980), Wesche (1985), Buchanan *et al.* (1989), Adams and Whyte (1990), Hunter (1991), Hunt (1993) and Central Fisheries Board (1995b).

8.6 Channel Reconstruction

8.6.1 Introduction

In streams where modification or damage has been really severe it is sometimes necessary to completely reconstruct the channel. This necessitates either the cutting of a completely new sinuous channel (e.g. when changing a straight channelized stream back into its former sinuous form) or altering the capacity of an existing channel (e.g. the reconstruction of a lower capacity channel within an enlarged channel). Channel reconstruction is a developing but specialist area and their are frequently major financial and socio-political constraints on its use. Brookes and Shields (1996a) provide a recent authoritative text on the subject.

8.6.2 Channel narrowing

Introduction

Due to dredging, overshading or grazing by stock, streams can become so wide that habitat quality is impaired. In such an instance it is possible to reconstruct a narrower channel within the course of the wide channel.

Benefits

The narrowing of existing channels is intended to reduce capacity thereby increasing depths and velocities. A sinuous thalweg can be created which allows pools and riffles to be maintained. Habitats for all life-stages of trout can thus be improved.

Design considerations

In some instances, removal of the problem which causes widening (e.g. livestock or shade) can result in channel recovery through natural sedimentary processes. However, the success of this approach depends on sediment loads carried and the power of the stream. Revegetation and bank consolidation may happen relatively quickly in a small silty low gradient lowland stream. However, it may take a very long time if spates prevent deposits from consolidating.

The channel narrowing process involves the partial infilling of a channel with material. This may be non-erodible material, but commonly involves creating an erosion resistant face to protect a softer backfill. Commonly used revetment techniques - rocks, wood, geotextile fabrics etc. - are described in Section 8.3. Unless infill material is coarse, it is necessary that the infill material is protected, at least until vegetation is established. In some instances protection may not be necessary after revegetation. This is especially true on point bars and on low power streams with low banks. In this situation temporary revetment methods may also be used. These include building retaining bank faces with biodegradable fabrics or densely packed bundles of brush (faggots) pinned together with stakes.

Channel narrowing has to be performed in a precise manner. Like meander creation (Section 8.6.4), specialist advice should be sought. The stream must be narrowed enough to prevent silt deposition, but not so much as it constricts the flow excessively. This will result in increased scour, removing beneficial features, creating velocities which are too high for juvenile trout and possibly leading to instability of the bank fill material.

Narrowing will also affect channel capacity and thus land drainage. If land drainage must be maintained, it can be compensated through the creation of a multi-stage channel (Section 8.6.3), but the low flow channel should not be made smaller than it needs to be.

To determine an appropriate degree of narrowing, unwidened reaches of the same stream (if there are any in the vicinity) with a similar gradient should be used as a template. Specialist hydraulic modelling can also be employed to predict velocities in different narrowing scenarios. These may be used to achieve a design which will move silts but rarely gravel.

Channel narrowing should not merely amount to the creation of a uniform higher velocity channel - i.e. transforming a canal into a gutter. Pool and riffle creation should be incorporated into the design. This may be achieved by varying the degree of narrowing and adding a degree of sinuosity. Bends should be narrower and deeper and the inflections wider and shallower. Banks can be firmer and steep on the outsides of bends but should be low and gently sloping alongside riffles and on the inside margins of pools.

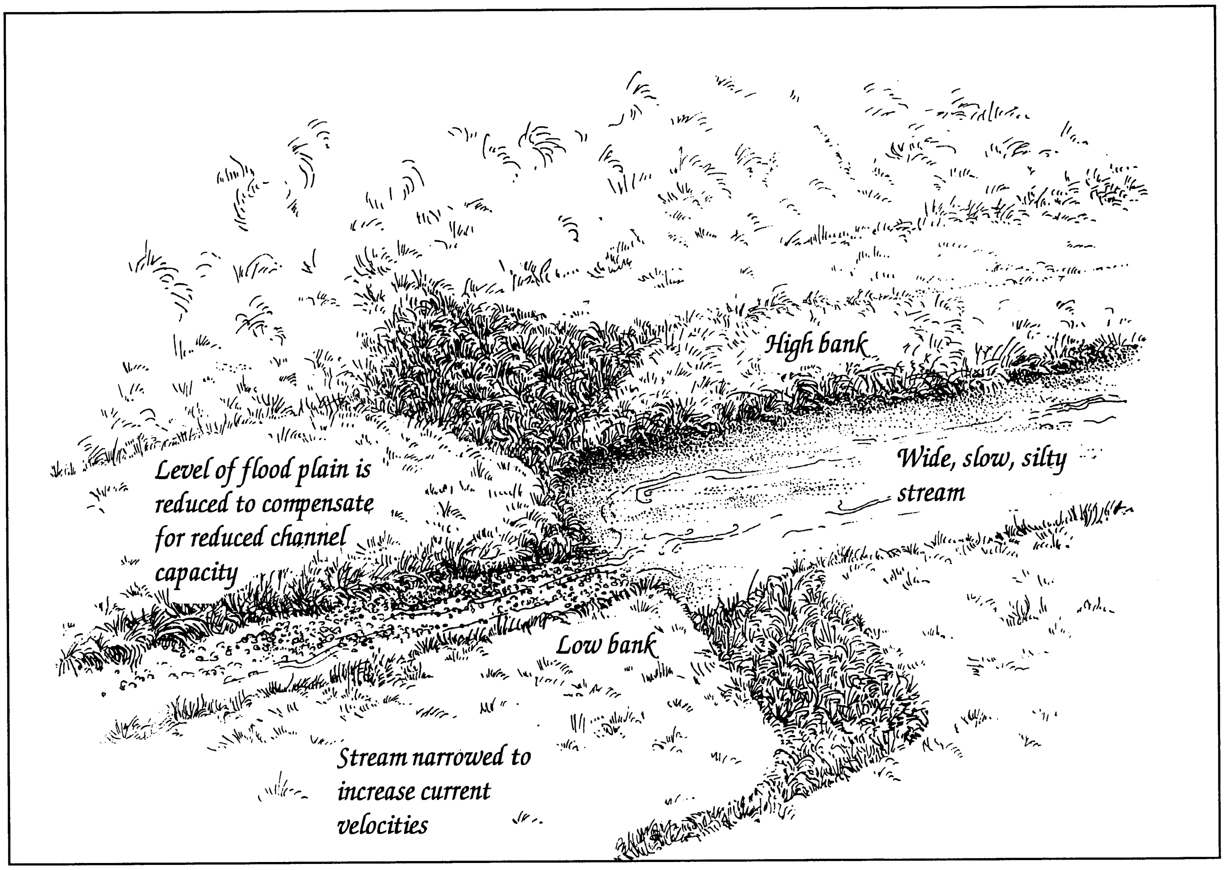


Figure 8.23 The principles of channel narrowing and multi-stage channels

Applicable stream types

Channel narrowing is applicable to many types of stream, assuming they have been widened. The important consideration is that increased velocities will result, promoting scouring. Consequently the bed needs to be stable enough to withstand these. It is recommended that specialist advice is obtained.

Drawbacks

Channel narrowing reduces channel capacity. This results in increased water levels and potentially flooding upstream. Upstream trout habitats can also be affected by impoundment and the deposition of fine sediment. Immediately downstream from a narrowing operation, stream velocities may be increased because the height of the upstream hydraulic head will have increased. This may result in some channel readjustment downstream.

The increased velocities in the narrowed section will cause bed scouring and in the immediate post work period, deposition of this sediment may occur downstream. The temporary storage capacity of the reach is also reduced, meaning that more sediment may be temporarily deposited on downstream during low flow periods

Effectiveness

No appraisals have been found of the effectiveness of this technique on trout habitat. However, the technique has been widely applied in streams in southern England and clearly can recreate valuable channel habitats (see Further Information).

Cost considerations

Costs involved are generated both in the design and construction phases. Major costs can be incurred in transporting materials to the site and then installing them.

Further information

A number of examples of channel narrowing, and modes of construction, are described in Ward *et al.* (1994). These include stone revetments and geotextile stabilization with much information on biodegradable materials. Details of major channel narrowing operations in chalk streams are described in National Rivers Authority (1992b).

Wesche (1985) also describes the construction of a low gabion barrier within a wide channel to concentrate drought flows. Other information is provided in a leaflet of the Irish Central Fisheries Board (Central Fisheries Board (1995b).

8.6.3 Multi-stage channels

Introduction

Many of the procedures outlined in this chapter, like the one described previously (8.6.2), have the effect of reducing channel capacity. Consequently, overbank flooding will occur more often and this may often be considered an unacceptable price to pay for improving trout habitat. However, reduction in the capacity of the main channel can be compensated by creating a wider, shallow high flow channel out with the main channel (see Fig. 8.23).

Benefits

The creation of multi-stage channels allows the creation or maintenance of a low flow channel with habitat features which reduce channel capacity to such an extent that the increased flood risk would otherwise be unacceptable. This can bring benefits to all life-stages of trout. Another benefit is to cut a lower mini-floodplain alongside an incised channel which will allow the creation of a meandering channel, where otherwise the banks would be too steep (Shields 1996).

Design considerations

The design of multi-stage channels is still relatively specialized. The dimensions of the overflow channel must be well designed otherwise serious problems can occur in the main channel. Whilst it is recommended that professional advice is sought, the procedures and principles involved are described.

The main design consideration is in balancing the loss in original channel capacity associated with trout habitat improvement works with the new overbank capacity. It is not a question of providing an equivalent channel volume because velocities will differ in the overbank channel. Hydraulic modelling techniques will be required to predict the amount of channel necessary. If too much extra capacity is provided, velocities will be reduced in the main channel resulting in aggradation of sediment and destroying the trout habitat. This will especially be a problem in low power streams. A wider channel can also allow floodwaters to flow on a straighter course resulting in an increased gradient. This, in turn, leads to increased current velocities leading to channel instability. This is likely to be more of a problem in higher power streams.

Applicable stream types

Multi-stage channels may be created in any type of channel which has a low gradient floodplain which has a tendency to flood. A main consideration is that there must be land within the meander belt that can be taken out of its current land use.

Drawbacks

If designed correctly, multi-stage channels could have few drawbacks. Indeed they are intended to counter many of the drawbacks of other techniques. However, if they are not designed correctly they can affect stream habitats through either aggradation of fine sediment or even erosion.

Effectiveness

No examples of this technique have been appraised in terms of their impact on trout. However, examples where the technique has worked can be found in Ward *et al.* (1994).

Sellin and Giles (1988) describe the effects of a multi-stage channel on a stream in Essex.

Cost considerations

The creation of multi-stage channels can involve considerable expense. Major costs are involved in scheme design and then in the excavation and removal of the spoil.

Further information

Much general information on the principles involved with multi-stage channels can be found in Ward *et al.* (1994) and Brookes and Shields (1996a).

8.6.4 Meander reinstatement

Introduction

Meander reinstatement is the process by which channelized streams are reconstructed to their former meandering state by cutting a new channel as opposed to increasing the sinuosity of the thalweg within a channel (see Section 8.6.2). This type of work has scarcely been performed in Britain, one example being the River Cole (Brookes and Shields 1996a). However, this has been more widely practised in Denmark (Brookes 1992, Nielsen 1995, 1996). A major problem affecting its widespread adoption in Britain is that the necessity for the original channelization often still exists - i.e. to maintain efficient drainage of agricultural land - and also because of the value of floodplain land. However, opportunities do arise when channels can be reconstructed - e.g. as a result of a road development.

Benefits

By reinstating channel sinuosity it becomes easier for gravel riffles and pools to be maintained in a stream. This results in more sustainable habitat diversity than may be created using structures in a straight stream. Gravel riffles and pools can be reinstated providing habitat for all life stages of trout. Also, by increasing the length of the channel, further habitat is created.

Design considerations

This is a highly recommended technique to implement where conditions are appropriate. However, the design procedures involved are complex and specialist advice must be obtained (Brookes and Shields 1996a). A detailed description of this technique is beyond the scope of this manual but, the following sections outline the broad issues involved.

Initially it is necessary to establish the former stream pattern if possible. This may be found from the first 6 inch to 1 mile Ordnance Survey maps (around 1870), estate plans, aerial photos of crop marks etc. to use as a template. Then detailed hydrological surveys, levelling surveys and analyses of floodplain materials are required to design appropriate channel dimensions relative to the new gradient. Channel dimensions must be matched to gradient otherwise the channel may be too small and scour, or else be too large and aggrade. Computer modelling can be employed to perform this task.

When designing a new channel, features like pools, riffles and meanders need to be incorporated into the design according to established geomorphological principles. These include creating a meander wavelength of about ten to fourteen channel widths, with pools excavated at bends and diagonal riffles in between.

Applicable stream types

This technique is applicable to any stream which has been straightened in the past, except if they are deeply incised, in which case lowering of the floodplain is also necessary (Shields 1996). However, for trout habitat, it is most applicable in moderate gradient streams which are essentially composed of riffle habitat. The pre-altered stream can be faster than ideal trout habitat as the gradient will be reduced on lengthening the channel. However, a stream which is already deep and slow will only become more so. This technique should not be applied to streams which would naturally be straight.

Drawbacks

Channel reconstruction can have many detrimental side effects and it is for this reason that it should be performed by professionals. For example, loosened sediments in the new channel may be prone to erosion, resulting in the deposition of sediment further downriver and affecting habitat there. Furthermore, the loss of stream energy caused by lengthening the channel may reduce the competence of the stream to transport sediment in reaches immediately downstream, resulting in further sediment aggradation. To some degree, flows upstream of the restored area may also be impounded resulting in deposition of sediment also.

Effectiveness

No example of meander restoration which has been appraised in terms of its effects on trout has been found. However, effective meander restoration can clearly be performed as shown in the case of the River Brede, a previously straightened stream in Denmark, is described in Nielsen (1995).

Cost considerations

Meander reinstatement involves costly procedures. Significant costs may be incurred in the actual design of the scheme in addition to the costs of excavation and removal of the spoil. Further costs may be incurred in introducing substrate material and revegetating the banks.

Further information

Further information on this technique can be found in Brookes (1987, 1992), River Restoration Project (1993) and Brookes and Shields (1996a).

8.7 Bankside Cover Creation

8.7.1 Vegetative cover

Introduction

In Sections 8.3.2 and 8.3.3 the value of maintaining vigorous vegetation on stream banks was described in the context of bank protection. However, bankside vegetation has a dual role. It is also very important in providing cover.

Benefits

Vegetation which drapes out onto, or rather into, the water surface, is particularly valuable. This is especially so along the deeper outside banks of pools. The value of cover depends on its width relative to the depth of water. A narrow fringe may conceal trout in shallow water, but not in deep water. Therefore, the appropriate type of vegetation depends on the depth of water. It also depends on the height of the bank, because higher banks require longer stems to reach the water surface. However, cover is also necessary in shallower nursery areas and at spawning areas to provide shelter for spawning adults.

Design considerations

Grasses can provide adequate cover in small streams where depths are never greater than 50cm and the banks are low but vertical. Species like reed canary-grass (*Phalaris arundinacea)* will provide cover in streams up to one metre deep where banks are not more than 50 cm high.

Bushes or low growing trees, if their branches drape into the water, create excellent cover for trout in any depth of stream. Trees have an advantage over grasses in that they maintain their cover value throughout the whole year. Twigs and branches are stronger than grass stems and so afford fish more protection. In addition, they collect debris, further adding to the cover. In water greater than one metre deep adjacent to steep banks in excess of one metre high, trees are the only option.

Unlike grasses, trees have to be regularly managed to maintain their cover value. In Section 8.3.3, coppicing was described in the context of preventing “overshading”. Coppicing has a dual role in that young shoots have to be encouraged to drape into the water. Branches of trees may be partially cut through, bent and trained onto the water surface.

Common causes of the lack of vegetative cover include grazing or overshading by trees. Therefore fencing may be required to promote cover restoration (Section 8.3.4) or management of the trees (Section 8.3.3).

Appropriate stream types

Vegetation is very important in creating bankside cover in all stream types. The only exception is really in deep pools in large rivers where the depth of water alone constitutes cover.

Drawbacks

The promotion of low bankside cover has few negative effects on trout habitat. However, encroaching vegetation may reduce channel capacity and increase the flooding risk upstream.

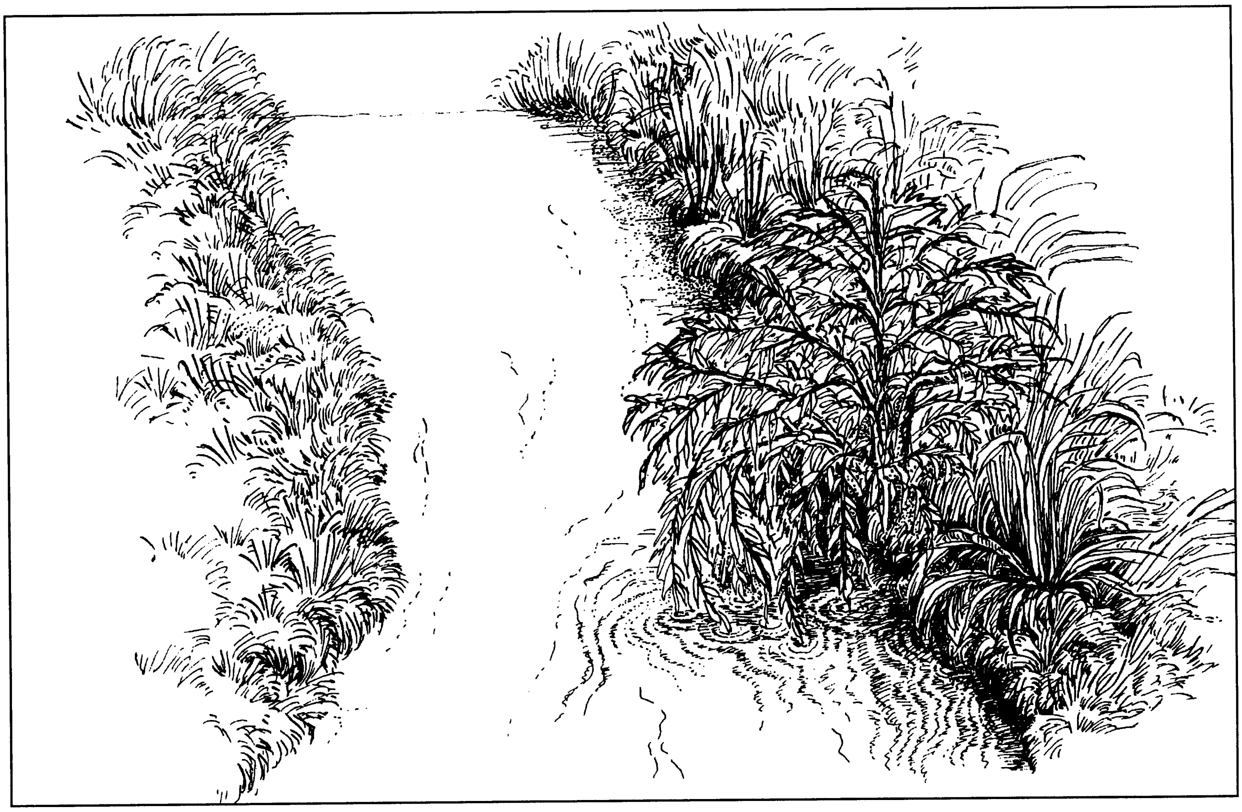


Figure 8.24 Draping bushes and grasses providing cover for trout

Effectiveness

The value of bankside vegetation on trout populations was clearly demonstrated by Boussu (1954) who found that trout numbers fell on removing cover and increased on replacing it. Lewis (1969) also demonstrated that trout tended only to occupy those pools which had well developed cover. Wesche, Goertler and Frye (1987) also demonstrated that bankside cover was the most important determinant of brown trout numbers in Wyoming streams. Keller and Burnham (1982) found that in a stretch of stream from which cover recovered following fencing, rainbow trout (*Oncorhynchus mykiss*) were 1.5 times more abundant and brook trout between 2.4 and 4.5 times more abundant than in grazed areas. Giles and Summers (1996) found that in a small Dorset chalk stream numbers of brown trout occupying two short sections increased six-fold within a year following pool creation and fencing which allowed the recovery of previously grazed riparian vegetation.

Cost considerations

The main costs involved in creating bankside cover are those of fencing if that is required (see Section 8.3.4), or manual labour in clearing shaded streams. Costs will also be incurred in planting trees and annual maintenance.

Further information

Information on the promotion and maintenance of good cover for trout is provided by White and Brynildson (1967) and Adams and Whyte (1990). Further information regarding suitable species for river banks can be found in Ward *et al.* (1994).

8.7.2 Bank cover structures

Introduction
Bank cover structures consist of solid artificial platforms up to a metre or more in width, constructed under water alongside a bank. In the North American literature, there are many different designs on this basic theme. These are referred to as Bank Covers, Cover Logs, Skyhooks, Lunkers etc. This manual does not describe each of these structures. Instead, the basic principles are described in this section.

Benefits
Bank cover structures simulate an undercut bank and provide cover for both juvenile and adult trout depending on the water depth. Unlike some types of vegetation, bank covers provide year-round cover.

Cover structures are often constructed to stabilize a steep bank, for example opposite a diagonal weir (see Fig. 8.20) or a wing deflector. Cover structures have an advantage over rock revetments in bank stabilization because rock revetments cannot be undercut. Tree root revetments also have the disadvantage of the time it takes them to develop, and trees are not always desirable if access to the bank for angling is required.

Design considerations
The simplest design consists of a floating board tethered against the bank. However, these have deeper water under them than completely submerged covers and may not be so attractive to trout. The simplest type of submerged cover structure consists of a platform solely supported by long stakes driven horizontally into the bank. Alternatively, a cantilevered overhang can be created by cutting a step into the bank, laying the platform partially on the step and then replacing rocks and coarse aggregate on the bank. By incorporating vertical supports under a platform - either stakes driven into the bed or large boulders - a heavier and stronger structure may be created which will bear the weight of rock, soil and turf placed on top. In streams where the bed is very hard and stakes cannot be driven in, prefabricated structures can be used, where the supporting legs are attached to a flat base and do not need to be driven into the bed. Such a structure can be anchored merely by the weight of material placed on top or with steel rods driven into the bed.

The height of any cover structure will depend on the width of overhang, water depth and stream power. Where wood is used as a construction material, the cover should be permanently submerged to prolong its life. In faster water the cover should be low as the structure will be subject to less stress. Velocities underneath will also be lower, providing better shelter. The height of cover should be tailored, of course, to lowest base flow. It is also important that cover structures be placed alongside a scouring current. Covers placed in slack water areas may merely accumulate fine sediment underneath and covers right in the fastest current may not provide adequate shelter in energetic terms.

Cover structures will be further improved if dead branches and brush are fastened underneath to simulate roots under an undercut bank.

Wood is normally used to construct cover structures. Hardwoods are best since they last longer. However, many other types of materials have been used, including concrete slabs and glass-fibre boards. Geoweb or a similar plastic/textile mesh grid can be used to anchor the rock/streambank material and turf on top of a structure until it stabilizes. Any gaps in the boarding can be sealed with a layer of fine weave textile or heavy gauge plastic sheeting to prevent erosion and wash-out from underneath. It is important that aesthetic considerations should always be borne in mind when using artificial materials.

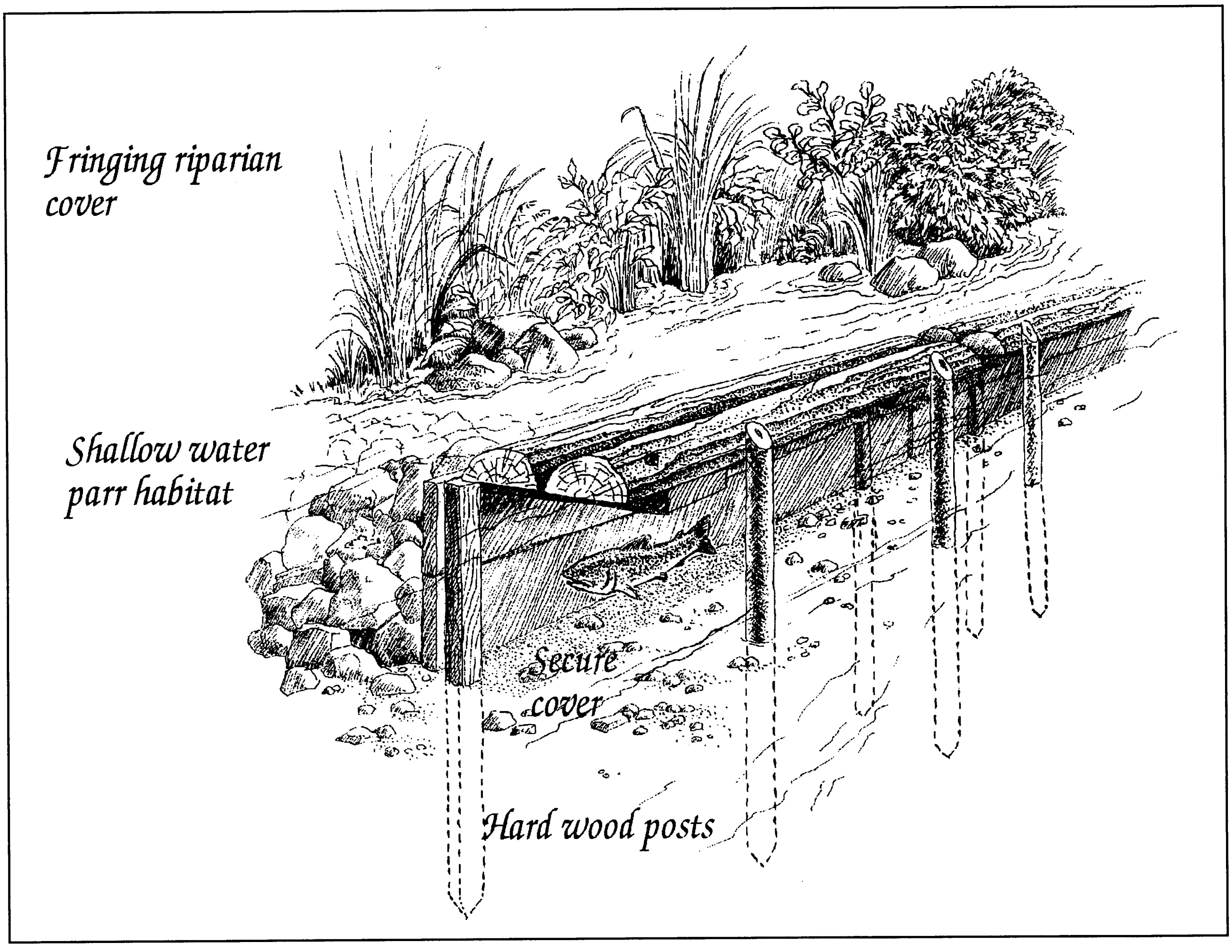


Figure 8.25 A submerged wooden cover platform alongside a bank (Adapted from Hunt (1993))

Applicable stream types

Artificial cover structures can be used on practically any type of stream. As has been described, some specific designs are more appropriate for particular type of stream. For example, low structures are more appropriate in high energy systems.

Drawbacks

Relative to vegetative cover creation, cover structures can be relatively expensive to create. Another major drawback over vegetation is that their value depends on the channel maintaining stability. Erosion or deposition under a structure can mean it has to be completely rebuilt. Unless cover structures are well designed and constructed they can look artificial.

Effectiveness

Bank cover structures have been widely used in streams in Wisconsin and increases in trout numbers have been documented in many instances. Their benefits have been described by Hunt (Hunt 1969, 1971, 1988, 1992). In Britain, Swales and O' Hara (1983) reported that in the River Perry, Shropshire, dace, chub and roach preferentially took up residence under floating covers.

In terms of physical performance, Kelso and Hartig (1995) provide examples where bank erosion was successfully reduced with a series of prefabricated wooden cover structures in 2.4m by 1.2 m to 1.8 m sections. Moreau (1984) described the performance of covers in Beaver Creek, Wisconsin, where after eighteen years, only 29% remained in good condition. All showed sagging and 86% had exposed planking, but nevertheless, 71% remained functional.

Cost considerations

Most of the cost involved in cover creation is the manpower involved in installing the covers. In a larger stream an excavator may be necessary. Materials generally have to be purchased as some use of milled timber will be necessary in most instances. As an example, Kelso and Hartig (1995) report that the cost of constructing a 2.4 m length prefabricated structure was $115 and two could be built and installed per man-day.

Further information

The most detailed descriptions of cover creation are provided in White and Brynildson (1967) and Hunt (1993). Wesche (1985), Buchanan *et al.* (1989), Adams and Whyte (1990) and Hunter (1991) also provide considerable detail.

8.8 In-stream Cover Creation

8.8.1 Boulder placement

Introduction
A simple but effective means of creating cover and refuge areas under water is to place boulders on the streambed.

Benefits
Boulders and cobbles form important cover for brown trout, especially fry and juveniles (Chapter 3). By reducing visual contact, they increase the number of potential territories. Also, they create frictional resistance to the current at the stream bed surface, creating large numbers of quiet resting places essential if trout are to hold station in strong currents.

Boulders also trap organic debris and offer protection for invertebrates, and so can increase invertebrate productivity. Therefore, where there is little in-stream plant growth, boulders are important ecological features.

Design considerations
There are no hard and fast guidelines with regard to the size and density of boulders placed in a stream. However, bigger boulders should be placed in deeper water and the spacing should also be greater. The height of boulders (unless planted to re-create a riffle by raising the bed) ought not to be greater than the depth during low flows. Boulders should be planted with their long axis parallel to the current to minimize frictional resistance. As boulder placements create a degree of upstream impoundment and reduce overall velocities they should not be placed on a spawning riffle. They should be placed on the downstream faces of riffles to provide habitat for fry and juveniles.

Whilst, in deeper pools, single large boulders may provide cover for adult trout, in juvenile holding areas, boulders create the best habitat when arranged in clusters adding habitat complexity to the stream. Maughan *et al.* (1978) found that fine sediment tended to accumulate behind single boulders, but if three boulders were placed in a triangle with the apex pointing upstream, the turbulence created swept away the sediment.

In environments where boulders are not available, or are costly to transport alternative forms of feature can be created. Wesche (1985) described an “artificial boulder”, an isolated rock filled gabion placed on the bed in mid stream. In gravel substrates where boulders bed in, lengths of log can be driven into the bed to leave a protrusion. The log should be driven in at an angle with the log sloping downstream. This ensures that debris will not be trapped.

Boulders can be hand-placed on a small-scale scheme, moved by mechanical diggers or tipped from lorries into larger rivers. Boulders should be placed during low-flow periods to ensure proper location and to allow easy access for heavy machinery. Vertical logs can be driven into river beds with the help of water-jets to break up the gravel, or, even more easily, by hydraulic digger arms.

Appropriate stream types
Boulders or cobbles can be placed in practically any type of stream so long as the boulders are

large enough to be stable. A main constraint on boulder placement is bed stability and sediment loads. Boulders placed on an erodible bed can bed in as a result of scouring which can take place around the boulder. Boulders and cobbles, by obstructing the flow can cause accumulations of fine sediment around them in low power streams. Boulder placement is not appropriate, therefore, in low velocity streams with high sediment loads.

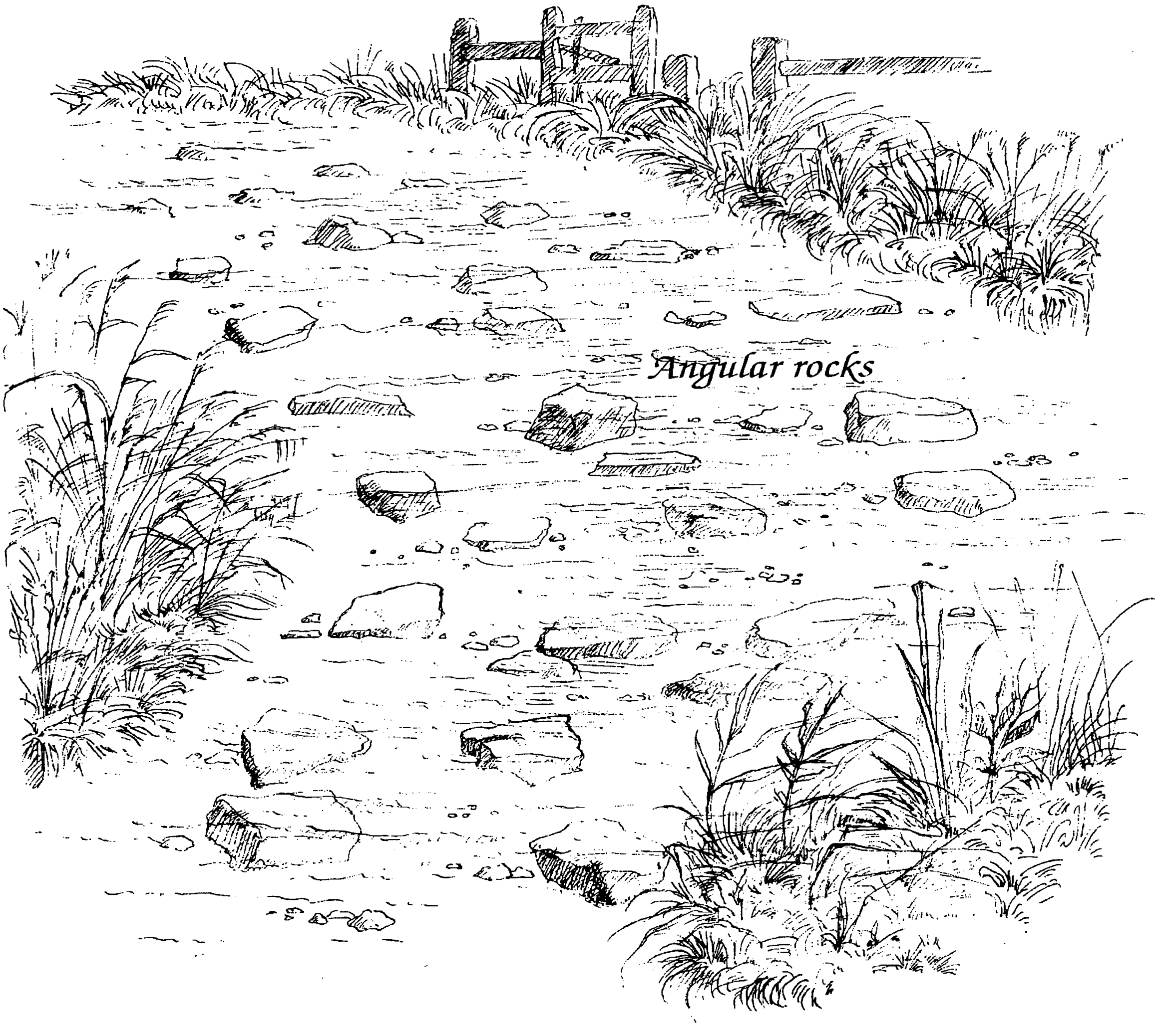


Figure 8.26 Boulders placed to create habitat complexity for juvenile trout

Drawbacks

The main drawback with placing boulders in a stream is that mean current velocities are reduced through increased frictional drag. This results in a reduction in channel capacity and an increased degree of impoundment upstream. As a consequence there is an upper limit to the number of boulders which may be placed in a stream. Increased sediment deposition can also result with a loss of habitat for other life stages.

Effectiveness

A number of studies have looked at the effectiveness of boulder placements on trout habitat. For example, O' Grady *et al.* (1991) re-instated bed "roughness" through boulder placements in the River Boyne, Ireland. They found clear increases in numbers of salmon parr in the treated areas and lesser, but significant, increases in trout parr numbers. Hunter (1991) describes a project on the John Day River, Oregon where habitat for chinook salmon and steelhead was improved by the addition of, amongst other features, boulders placed on the river bed. Hunt (1988) reports increases in both wild brown and brook trout due to habitat improvements including boulder placement in a stretch of the Hunting River, Wisconsin. Boulder clusters were associated with a twenty-fold increase in coho salmon on Keough River, Wyoming. Reeves *et al.* (1991) provide several examples of successful applications of boulder placements.

Moreau (1984) used boulder wing deflectors, weirs and boulder clusters in Hurdygurdy Creek, north-western California. Steelhead parr estimates rose by 100% two years after boulder placement whilst those in control areas fell by 56% to 61%. West (1984) reports on the placement of large rock clusters on 1200 m of South Fork Salmon River to improve salmonid rearing conditions. Eight triangular wing deflectors and 180 boulder groups were placed with a ten-fold response in steelhead parr abundance whilst control sections remained stable (West 1984).

However, Shuler *et al.* (1994) found that brown trout tended to avoid single boulders placed in mid-channel, showed no preference for clusters of boulders but selected boulders placed in a line out from the bank.

Maughan *et al.* (1978) found that although they observed trout lying near boulders, they found no overall improvement in trout numbers where boulders were introduced.

Cost considerations

The cost of boulder placement varies greatly with the availability of materials. In upland areas boulders may be available on surrounding land. However, where quarried rock is necessary costs can rise significantly (up to £15 per tonne or more delivered to relatively local site, 1995 price). A mechanical excavator should be able to place at least 20 to 40 large boulders, depending on local conditions, or reinstate a 100 m stretch of channelized river bed, given the close proximity of suitable stone infill, in a working day. A professional fisheries presence is normally required to ensure satisfactory placement of materials.

The results of the River Boyne study (O' Grady *et al.* 1991) show that, for one kilometre of restored juvenile salmonid habitat, the capital outlay of £14 571 would be recovered in only four years through the saving on stocked hatchery salmon parr and brown trout of various sizes. This ignores any economic benefit from increased fishing income on the improving fishery.

Further information

Further information on boulder placement can be found in Shields (1983), Wesche (1985), Hunter (1991), Reeves *et al.* (1991) and Hunt (1993).

8.8.2 Brush placement

Introduction

In natural forested streams, brush and woody debris can be a major feature of within-channel habitat. The introduction of brush and branches to streams is a very simple but effective enhancement technique.

Benefits

Brush makes very good cover, especially for fry and juvenile trout. It also offers good protection from larger predators. It has been found to be more effective than boulders in producing low velocity niches under spate conditions. As brush provides year-round cover, it can offer valuable cover to newly emerged fry in spring before the vegetation has started to grow and when high current velocities prevail.

Design considerations

Brush may consist of anything from bundles of branches lashed together to whole dead trees or root wads. To prevent it washing off and becoming a flood hazard and to ensure it remains where it is intended, it should be firmly anchored to the bank or to the bed with a cable.

Irrespective of the target life-stage, brush should be placed in a current as opposed to slack water areas. Otherwise fine sediment may accumulate and reduce the value of the habitat.

For fry and juvenile trout, the brush needs to be anchored in shallow margin areas on and near the riffles on which trout spawn. For adult trout, large woody material should be placed into deep water where there is a scouring current. Benefits will be greatest again if it is placed adjacent to a bank.

Brush, of course, can occur naturally in many stream and rivers and such material is frequently removed from streams by the EA for flood defence purposes. Where, its removal cannot really be justified in terms of flood defence such material should be left *in situ.*

Applicable stream types

Brush placement is a widely applicable technique. Its hydraulic impact is minimal and it does not depend on the stream bed for a foundation so it can be placed in any type of stream.

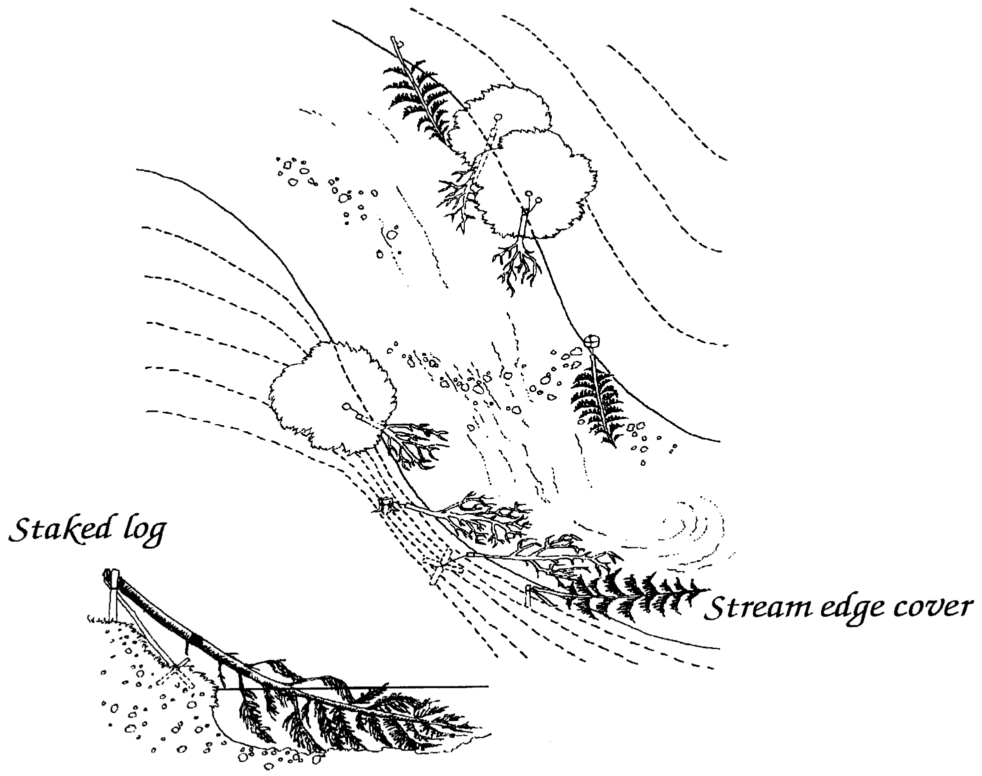
Drawbacks

It is most important that brush is fastened securely. Woody debris carried off in floods can become a flood hazard further downstream by accumulating in bridges or on weirs. It can also cause physical damage to structures.

Where brush is encouraged to accumulate naturally it should be noted that excessive debris on small tributaries can create impassable dams which impede upstream migration of mature salmonids. This subject is reviewed extensively by Reeves *et al.* (1991).

Effectiveness

A number of North American studies have demonstrated improvements in salmonid numbers consequent to introducing brush habitat. For example, Shirvell (1990) investigated natural and artificial rootwads placed in a stream and found that coho fry (whose habitat requirements are similar to brown trout) occupied positions which they never occupied previously. In fact 99% of the fry chose positions associated with rootwads. Other similar studies are reviewed by Reeves *et al.* (1991).



Tree trunks and logs can be tethered to stream banks to provide cover for trout

Figure 8.27 Brush fastened to banks creating submerged cover (Adapted from Whyte and Brynildson (1967))

Cost considerations

Brush placement is an inexpensive form of habitat creation. Materials costs are low, the only major costs being labour. The exact labour costs will depend on the size of stream and material to be placed. Placing branch bundles in a smaller nursery stream can be done manually, though introducing whole trees into a larger river would require machinery. In one North American study (Boehne and Wolfe 1986) trees were felled into a river using explosives.

Further information

Placement of brush is described in White and Brynildson (1967), Finnigan *et al.* (1980), Hunter (1991) and Hunt (1993). Reeves *et al.* (1991) provide a good review of the subject.

8.8.3 Management of in-stream plants

Introduction

In many streams in Britain, submerged in-stream plants form an important feature of the habitat. For example, in the classical chalk stream trout fisheries, management of plants is one of the most important aspects of fishery management.

Benefits

Plants have a number of effects on habitat quality. They create valuable cover for trout, especially during the territorial juvenile phase. By obstructing the flow they can also slow and deepen the flow in summer, maintaining depths for trout in otherwise shallow fast streams. Where plant growth is not uniform across a stream hydraulic diversity can be created by the channelling of the current between clumps of plants. This is especially important in low power and channelized rivers which lack features like pools and riffles and boulders which provide hydraulic complexity and cover. Plants also form a complex substrate for invertebrate colonization and a surface for epiphytic algae which many invertebrates eat.

Management considerations

Where a stream has undergone physical restoration, plants will recolonize it. However, to speed up this process, many plant species are readily transplanted. Plants should be obtained from other parts of the same stream to ensure the native community is maintained. Transplanting is best done in the spring after the winter spates have past and conditions are good for growth. Remove plants by their roots or rhizomes and then bury these in a similar substrate from which they were taken. A flat stone can be placed over the base of a transplanted plant to hold it in place until it becomes established. It is important to ensure that plants are transplanted to where they will have sufficient light to grow.

Most plant management for trout fisheries entails the cutting of established plant communities. This is necessary because, if left to grow unchecked, plants can fill a channel to such an extent that reduced velocities and increased depths can make the habitat unsuitable for trout. However, before specific practices are described, some of the effects of cutting on the plants themselves are now described (after Dawson (1989)).

In-stream plants, if unmanaged, follow an annual cycle with rapid growth in the spring and maximum biomass occurring around the time of flowering. Time of flowering is very variable, and tends to occur in spring in smaller streams and summer in larger rivers. After flowering, the biomass tends to decline and may be considerably reduced by winter. However, cutting, especially before flowering, promotes plant growth, and indeed causes plants to grow vigorously later in the year where they might not otherwise do so. It also encourages particular plant species which have a capacity for rapid regrowth. Increased autumnal growth can give rise to an increased overwinter biomass, which can then be translated into a much higher biomass in spring. In fact, it has been found that the maximum biomass can be twice as great where plants are managed than where they are not managed. Therefore, management of plants is not as simple as may first appear, with the need for management being somewhat self-reinforcing.

The effects of management from a fishery point of view is essentially to thin out the growth when it would be at its maximum, whilst leaving a sufficient degree of cover for trout, and to encourage growth in the autumn when it would otherwise be in decline, and its value as trout cover reduced. Cutting may also be performed in autumn on specific areas to expose spawning gravel (Section 8.4.6). Plant management needs therefore to be performed actively throughout the year, using different cutting regimes at different times. For example, at times of most rapid growth, cutting ought to be done selectively, with channels being cut to concentrate the current. Such cutting leaves existing plants at a disadvantage as the water level falls and retards their growth (Dawson 1989). However, a fine balance must be struck later in the year between plant abundance and discharge so that plants can still maintain the water level as discharge falls.

River-keepers employ a number of different techniques when cutting weed. Whilst this traditional plant management has not been objectively assessed to formulate guidelines, the techniques include leaving clumps with fast flowing channels in-between, cutting transverse bars across the stream to produce a form of pool-riffle effect or cutting longitudinal channels to concentrate the current.

To produce such precise habitat features requires selective cutting. In smaller streams this is normally performed with a hand scythe, but in streams which are too deep to wade, chain scythes with operators on either bank may be needed.

Figure 8.28 Cutting plants to increase the diversity of current velocities

Cut plants must not be left within a stream as they cause a nuisance to river-users downstream and can cause low dissolved oxygen levels on decomposition. Therefore, the floating stems and leaves must be netted out by hand or trapped by a boom placed downstream from the cutting operation. Plant cutting is a labour intensive operation.

In-stream plants are greatly affected by shade. Plants can be encouraged in shaded streams by thinning out trees and reduced in streams with prolific plant growths by planting trees. Such management needs to be sustained in the long-term with a planned tree maintenance programme.

Applicable stream types
Plant management is most associated with southern chalk streams which have clear water and high levels of nutrients. However, prolific plant growth can occur in streams which can hold trout over much of lowland Britain. Plant management is not applicable in nutrient poor upland streams.

Drawbacks
Prolific plant growth in summer can choke a channel so much that currents become minimal and depths increase, making it especially unfavourable for juvenile trout. Predatory fish, like pike, have more of an advantage under such conditions. The effects of plants on spawning habitat have already been described (Section 8.4.6).

Effectiveness
No information has been found to demonstrate benefits of plant management on trout numbers. It is likely to be the case that very dense growth can be a problem (Seymour 1970), but equally, Mortensen (1977a) found that wholesale plant clearing operations for flood prevention in Danish streams greatly reduced numbers of juvenile trout. Somewhere between the two extremes there is a balance but this has not been defined.

Cost considerations
The cost of plant management for trout habitat largely entails manpower. Capital costs are low, but manpower is required to cut plants and removing them from the stream.

Further details
Details on the principles involved in classical chalk stream plant management including cutting times for different weed species and patterns can be found in Seymour (1970). General details on plant control issues can be found in Seagrave (1988), Dawson (1989), Wade (1994) and Ward *et al.* (1994).

8.8.4 Submerged shelters

Introduction
Boulders, brush and plants can provide in-stream cover for trout but may not provide overhead cover which is also important. Submerged shelters can be used to provide this habitat requirement.

Benefits
Submerged shelters are underwater platforms which produce overhead cover in mid-stream. Overhead cover is normally only present along the banks, but, by providing cover in mid-stream, more habitat may become available. The habitat so created is intended to create refuges primarily for adult trout.

Design considerations
Submerged shelters basically consist of a board, a log cut in half longways or even a whole log, fastened to the bed by supports which maintain a gap of about 10 cm above the bed. For adult trout, shelters should be around 3 m long and at least 30 cm wide, the wider the better. Shelters are pinned into the bed with rebar (bent over at the tip to hold the shelter in place) and held off of the river bed with solid wood spacer blocks.

Suitable sites are the edge of strong flows where there is a stable bed. If shelters are located in areas of deposition rather than scour, fine sediment will collect underneath rendering the structures ineffective.

Shelters should be placed parallel to the flow where the depth is adequate to cover them fully at all flows and be designed so as to collect minimal amounts of drifting debris. If the front spacer block is made of a round section log and placed at the tip of the structure, then it will tend to deflect floating weed and other debris. If rough logs are used, any forks in the trunk should face downstream. The trout holding capacity can be increased by creating visually isolated cells under the shelter by using several wide support blocks.

Applicable stream types
Submerged shelters may be used in any type of stream where there is not much cover for adult and juvenile trout, so long as the bed is stable. Areas or streams which have a high degree of sediment deposition should be avoided as should streams which transport large woody debris which could accumulate on, and dislodge the structures.

Drawbacks
These structures have little negative impact on trout habitat or on streams in general, because except where debris accumulates, these structures have little hydraulic effect on the stream.

Effectiveness
A number of North American studies have appraised the effectiveness of these structures. Hunt (1982) found that by placing 142 structures over 750 m in one stream, numbers of trout over 30 cm long increased by 533%. That stream had little adult cover otherwise but good juvenile recruitment. However, in another stream, 60 shelters were introduced, and although all but one functioned as intended, no increase in numbers was found. Likewise, Hartzler (1983) found no increase in trout numbers after installing shelters. However, he considered

that the stream studied had abundant bankside cover anyway.

Wesche (1985) reported that electrofishing surveys in Wisconsin have shown, especially at sites lacking natural cover, that trout utilize a high percentage of shelters. Cunjak and Power (1987) also showed that, on a small stream in southern Ontario, wild brown and brook trout prefer to lie below submerged plywood shelters in winter, both in pools and riffles. DeVore and White (1978) demonstrated that brown trout preferred 10 cm high shelters to ones 15 cm high.

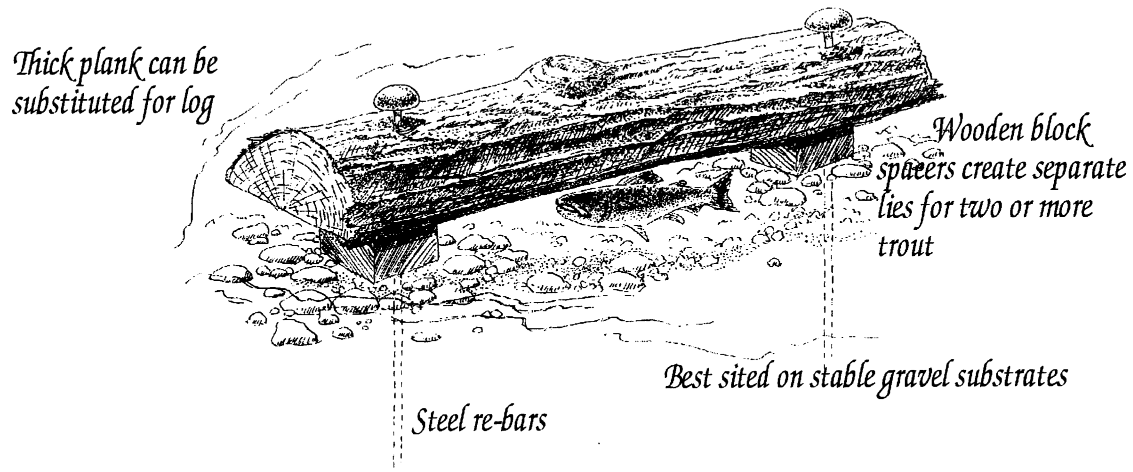


Figure 8.29 A submerged shelter constructed from a split log (Adapted from Hunt (1993))

Cost considerations

Costs involved in shelter creation largely consist of the labour to install the structures. If logs are available near the site materials costs may be low although they will be significant if sawn logs are obtained from a sawmill at some distance. A four-man crew can install around ten log shelters in a working day.

Further information

Descriptions of shelter construction and installation can be found in White and Brynildson (1967), Wesche (1985), Hunter (1991), Hunt (1993) and Central Fisheries Board (1995a).

8.9 Hypothetical Examples of Habitat Restoration

8.9.1 Introduction

Whilst the techniques in this chapter have all been described individually, in any restoration scheme, different techniques are not used in isolation. Different techniques are frequently applied together to create some desired habitat type. Whilst, an infinite combination of techniques exists, this section describes how some commonly used techniques fit together in three hypothetical examples of stream restoration in different environments. The examples also provide some indication of the considerations which are involved in designing a scheme.

8.9.2 Example 1: A dredged stream

Pre-restoration scenario
In this simple example, a stream has been dredged such that the entire bed is of uniform level, but the meandering channel form is still intact. The water is a uniform 50 cm deep with a gravel bed, abundant plant growth but with a considerable degree of fine sediment deposition. The outer banks on corners are stable but are bare because of having been dredged.

Limiting-factor assessment
The limiting-factor assessment finds the stream too deep and slow to provide spawning habitat and lacks deeper pools with cover for adult trout. However, habitat is generally good for parr.

Scheme design
Since the stream essentially lacks a pool riffle sequence, the main element in its restoration is to re-instate this. Therefore, pools are excavated on the corners of bends and gravel and cobbles are introduced in between the bends to raise the bed level and increase the current speed. Trees are planted alongside the crests of riffles to provide shade to suppress plant growth in order to maintain spawning habitat. However, in between pools and the introduced gravel, weed is encouraged to provide cover for juvenile trout. Cover, in the form artificial bankside covers or brush is installed along the banks, especially in the deepened pools.

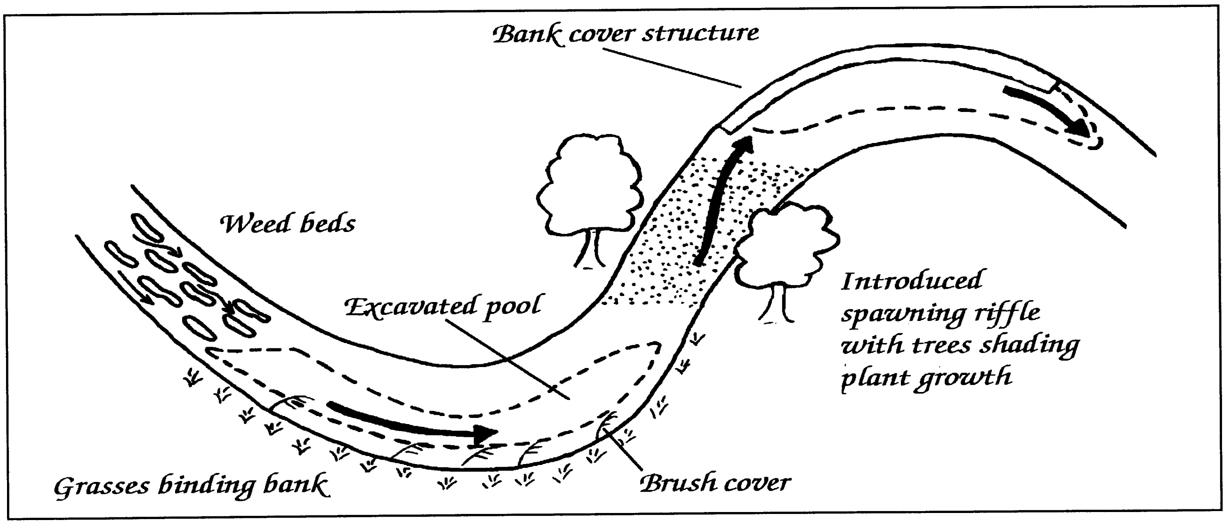


Figure 8.30 A hypothetical example of restoring a dredged stream

8.9.3 Example 2: Overgrazed lowland stream

Pre-restoration scenario

A low gradient stream has been open to cattle which have caused a gradual widening and shallowing of the channel because of the treading of the soft banks by their hooves. The stream tends to be uniformly shallow (say less than 50 cm) with deposits of fine sediment covering the bed.

Limiting-factor assessment

As there are no gravel riffles this stream completely lacks spawning habitat. Also, because there are no fringes of cover or late summer growth of plants (due to grazing) there is little habitat for juvenile trout or adult trout.

Scheme design

A major element of the restoration work is in narrowing the effective channel width. This is achieved by infilling the insides of bends with aggregate protected by a facing of logs, brush or geotextile fabric. In order to create more diversity in the narrowed channel, diagonal low-profile weirs, wing deflectors or introduced riffle deposits (as in 8.9.2) are used to concentrate the current against the outer banks of bends and pools excavated. Where the banks are liable to be eroded, willows and alders are planted, with a view to future coppicing. Brush is placed in the stream to provide bankside cover and submerged shelters are installed to provide cover in midstream in the initially bare pools. A fence is also erected along the edge of the floodplain, both the protect the stream from grazing and allow regeneration of the bankside vegetation, but also to allow the entire floodplain to become a buffer strip, assimilating nutrients and sediments washed off the surrounding arable land.

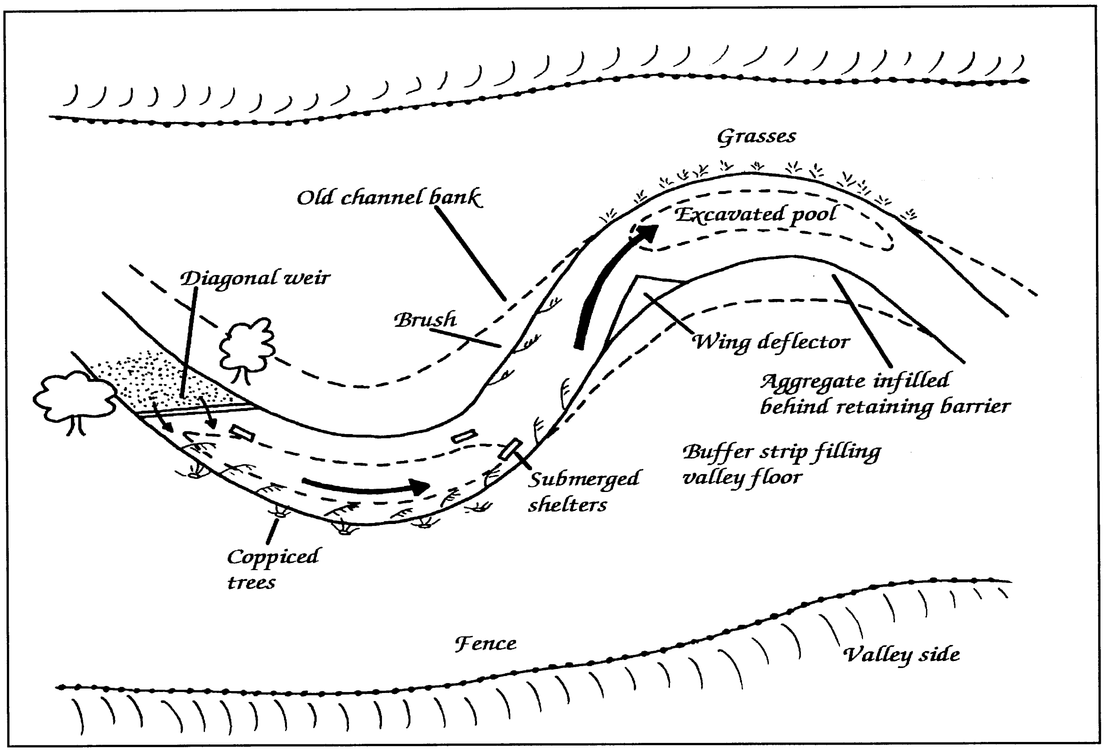


Figure 8.31 A hypothetical example of restoring an overgrazed lowland stream

8.9.4 Example 3: An overgrazed upland stream

Pre-restoration scenario

The banks of an upland stream have been subject to high grazing pressure from sheep. Consequently, the banks on either side have caved in resulting in loose cobble deposits forming the banksides, with the channel being bare and uniform.

Limiting-factor assessment

The gravel on the bed is too loose and unstable to provide a good habitat for spawning. There, is also little habitat for juvenile or older trout as there is little bankside cover or depth.

Scheme design

To stabilize spawning gravels in uniform gravelly reaches, pairs of gabion gravel traps are installed. To create deeper pools in straight sections drop-over weirs (e.g. the K-dam) are built and cover in the form of brush and submerged shelters are provided below these to make the scoured pools more attractive. In steep reaches where the bed is armoured and loose cobbles do not accumulate, large boulders are placed to create habitat for juveniles especially. On corners the banks are protected by large boulders and a pool is excavated alongside these. Brush is also placed to provide cover for the larger brown trout and returning adult sea trout which will use this habitat. Finally, and most importantly, a fence must be erected along the bank crest.

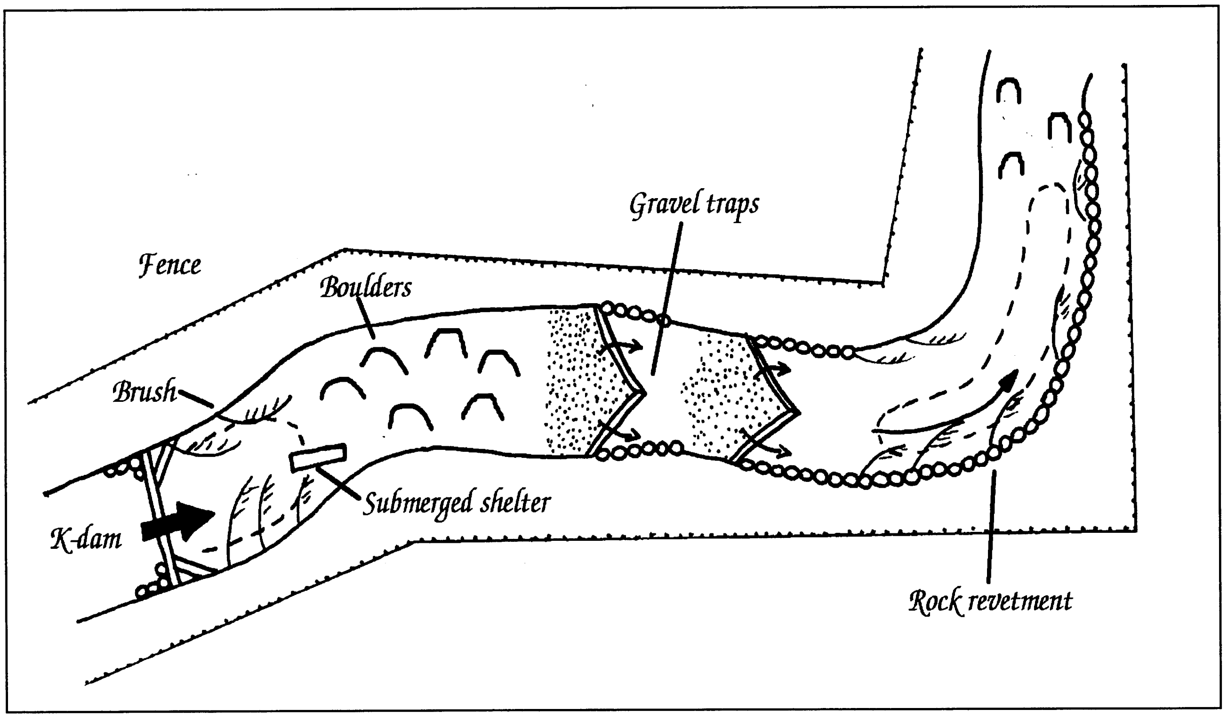


Figure 8.32 A hypothetical example of restoring an overgrazed upland stream

9. CURRENT LIMITATIONS TO TROUT HABITAT RESTORATION

9.1 Introduction

This chapter summarizes a number of issues which have been identified in the course of producing this manual as having a major constraining influence on the effectiveness of the restoration of trout habitat. Furthermore, overcoming these issues forms the basis of recommendations for the advancement of the subject which are detailed in Chapter 11.

9.2 Habitat Requirements

Although a lot is known about trout habitat requirements relative to most other fish species, knowledge is still far from complete. Some aspects of habitat are better understood than others. Much attention has focused on the habitat requirements of adult trout but knowledge is limited with regard to spawning and fry habitat. There is, for example, a dearth of robust quantitative information to assess the suitability of gravels, both in terms of the ease of redd construction and the potential for sedimentation.

Overall, the most important individual habitat features are known. However, the habitat of a trout is composed of a range of features and the interaction between these is important. For example, trout will occupy water of different depths depending on the availability of overhead cover, or they will occupy water with different velocities if substrate type differs. Unfortunately, prediction of how different habitat features interact is at an early stage.

A further complicating influence on the overall suitability of a stream to hold trout is that habitats for different life-stages are not independent. For example, spawning habitat quality is irrelevant if the habitat nearby is unsuitable for post-emergent fry. Relatively little is known about how much habitat there needs to be for different life-stages and how these habitats need to be geographically distributed to maximize numbers of adult trout.

As a consequence of these knowledge limitations, the quality of the physical trout habitat in a stream cannot always be easily determined. It is probably fair to say that good habitat can be differentiated from bad habitat and an absence of key features will be evident to the experienced worker, but it may be difficult to differentiate between moderate and good habitat.

Whilst these comments apply to the physical habitat, it is also the case that trout are dependent on other factors like water quality, biological productivity and temperature regimes which involve a great deal of work in identification.

9.3 Identification of Limiting Factors

The identification of the specific habitat deficiencies which limit trout numbers in a given stream is not always easy. Most studies agree that this is a fundamentally important exercise but most provide little or no detail on how to go about it. Many studies have relied on the intuition of the workers themselves.

This is a major limitation on the effectiveness of habitat restoration. Habitat restorations may often fail because the really important habitat deficiencies are not treated. However, by actually performing restoration schemes and thoroughly appraising them, more information will be obtained on this subject. It is accepted that restorations have to proceed on the basis of limited knowledge and that some limiting factors may only become apparent when other elements of the habitat have been improved. However, as more well appraised restorations are performed more information will become available on limiting factors. Therefore, in order to learn more effectively, it is critical that such work is undertaken.

9.4 The Approach to Habitat Restoration

A great range of effective techniques for improving trout habitat has been reported in the literature. The prevalent approach to restoration has been to treat these various techniques as options in a recipe book which are selected by comparing the target stream with standard examples of bad habitat. The techniques considered most appropriate are then implemented according to step-by-step instructions. However, given the infinite combinations of stream type, technique and potential limiting factors, such an approach is greatly limiting. Furthermore, this type of habitat restoration essentially concentrates on treating the symptoms of habitat degradation and does not tackle the root cause.

A better approach to habitat restoration is to work primarily with formative processes at the catchment scale. Restoration schemes would often be more successful if the sources of problems are treated at the catchment scale and effectively encouraged streams to self-heal. In-stream works can often work in opposition to catchment scale processes and are not sustainable in the long-term. Not enough emphasis is placed on catchment management and techniques which are geomorphologically sustainable.

Where work has to take place within the stream, as opposed to at the catchment level, it is still important to work with the natural stream processes. Instead of the recipe book approach, habitat restoration should be based on the understanding and identification of limiting habitats. Based on a working understanding of riverine processes, the stream restorer must then visualise how the limiting habitats would be created and maintained by natural stream processes. Then appropriate techniques are selected to re-instate these processes as far as may be possible. The important point is that the habitat to be created should be considered first, and then a restoration scheme should be designed to create this habitat according to conditions in the particular stream. The focus should always be on the habitat forming processes.

However, the advance of this approach is currently limited due to a lack of information. For example, information on the hydraulic effects (both positive and negative) of many techniques, especially structures, is limited. Therefore, it is not always possible to accurately predict all the ways in which processes will change as a consequence of employing a particular technique. As a result, some restoration schemes may fail even with the best available knowledge.

9.5 Good Project Management

9.5.1 Introduction

The lack of good project management is often seen as a limitation on the effectiveness of habitat restoration to date. Schemes frequently do not adopt a planned approach with the formulation of clear objectives and appraisal of the effects. They are often performed as isolated schemes in a piecemeal manner which do not form part of any overarching strategy within the overall catchment. As a consequence, little information accrues from such restorations and the overall subject does not develop.

9.5.2 Scope of restoration schemes

To date, restoration schemes in England and Wales have tended to take place at a very local level, although trout populations exist within, and are affected by influences, on the entire catchment. This general lack of a strategic planned approach mean that restoration schemes can be ineffectual. This can result from a lack of appreciation of trout ecology and to a lack of an effective supra-catchment management structure for brown trout populations. However, this situation is improving with the formulation of Catchment Management Plans (CMPs), where strategic habitat management can be put in its proper context.

9.5.3 Interdisciplinary co-operation

Whilst restoration schemes are often performed piecemeal, the practitioners of trout habitat restoration often operate in an equally isolated manner. Trout habitat restoration is being limited by a lack of interdisciplinary co-operation for it has tended to be performed by fisheries specialists who lack detailed geomorphological and engineering knowledge. However, much potential information and expertise exists which could greatly improve restoration schemes, but is frequently untapped. Individuals working in relative isolation have produced successful schemes as a result of trial and error, but much faster progress would be made if habitat improvement start from a basis of well founded theory and design.

9.5.4 Appraisal

Another limitation on the development of habitat restoration is that thorough appraisals can be difficult in practical terms and so are often avoided. There is no alternative to a thorough disciplined approach.

9.5.5 Benefits of restoration schemes

A major limitation of habitat restoration is the prediction of benefits which will accrue. Relatively little of this type of work has been done and consequently costly schemes may be instigated in completely unsuitable environments.

9.6 Integration of Habitat Restoration

Fisheries habitat restoration is currently a science in its infancy in Britain. A major reason for this may be because it has attracted little serious attention in its own right. Rather, it has tended to exist tangentially to other disciplines. There is currently no established forum for the exchange of information between schemes and between the relevant specialisms. There is also little integration between different bodies (Government departments, agencies and private interests) involved in the subject. This fragmentation has not been conducive to learning.

Even within the EA there has been relatively little integration with other departments whose activities can affect trout habitat. However, this is changing as a result of the adoption of CMPs, where the needs of different interests have been taken account of.

9.7 Learning from Experience

Trout habitat restoration has not progressed very rapidly over a long period. Many techniques and practices outlined in this manual were known about and correctly described many decades ago (e.g. Carter-Platts 1930). Yet, it is still common to see ineffectual techniques being applied. A good example of this is the principle of current deflection. Carter-Platts (1930) described how a downstream pointing groyne caused flow dissipation but that an upstream pointing V weir concentrated the current at all flows. Yet, today, downstream pointing groynes are still one of the commonest types of habitat modification device being used.

This situation stems in a large part from a lack of readily available information. It has already been stressed that trout habitat restoration is an undeveloped discipline, with a lack of documentation of different practices and their effects. This manual was written, in a large part, to provide information. However, this foundation needs to be built upon by the instigation of effective and thoroughly appraised schemes from which it will be possible to learn.

10. CONCLUSIONS

10.1 Literature Review

This manual was largely based on a literature review on salmonid habitat relationships and stream restoration. A huge literature base exists on these subjects, with over 2000 references being identified, though mainly North American. Of these, over 400 references were actually selected. It was found that a lot of the literature on habitat restoration represented variation on common themes and that relatively few could be regarded as key references which represent milestones along the progress of the discipline. Consequently, it is apparent that, though there is a lot of information, habitat restoration is not a mature discipline and this is further outlined below.

10.2 Habitat Requirements of Trout

A lot of research has been performed into the habitat requirements of trout. At the broad scale, the basic features are well known. For example, spawning generally takes place on gravel riffles in small streams and adult brown trout have been found to prefer deep pools which have a diversity of current velocities and draping bankside cover. However, it has proven more difficult to arrive at robust quantitative descriptions of habitat incorporating the wide range of factors which are thought to be important. Nevertheless, physical aspects of the stream environment have been demonstrated to be very important. These, in turn, are the products of complicated geomorphological processes which are ultimately governed by climate and wider catchment variables such as relief and sediment supply. However, many other factors like water quality, temperature, biological productivity and predation may be equally important, so habitat restoration always needs to be considered within a wide context.

One very important aspect which has not been well studied is how habitat quality actually constrains numbers of trout. The identification of “limiting habitats” (i.e. the habitat for whichever life-stage is most limited) has been identified as a major element in deciding which habitats need to be restored in any restoration scheme. Unfortunately, research has tended to concentrate on habitat requirements for specific life-stages rather than considering the juxtaposition of habitats for different life-stages. Some information is known about the necessary geographic distribution of different habitats but little is known about the relative quantities required. Therefore, the identification of limiting habitats remains an imprecise exercise.

10.3 Review of Restoration Techniques

A considerable amount of literature exists on trout stream restoration, though mostly North American. Most examples have concentrated on re-creating those habitat features broadly known to be important; for example the local increase of velocities to scour pools combined with the addition of cover. A number of basic techniques, described in the manual, have been used to achieve these aims. Most of these techniques essentially treat the symptoms of habitat degradation within the stream and do not actually address the causes which may be operating at the catchment scale. This situation may have arisen because treatment on a catchment scale is more difficult to implement, although it is likely to produce more sustainable results.

Numerous studies have demonstrated that restored habitats can be preferred by trout over the pre-existing habitats. On the other hand, many studies have demonstrated no impact. However, failure need not indicate that a particular technique is inherently flawed. A particular technique may be applied in an inappropriate environment or it may not be correctly designed for local conditions. Commonly, a particular technique may be applied to a stream where that form of habitat is not lacking, just because the same technique has been found to work elsewhere.

Thus, a common approach to stream restoration has been along the lines of a recipe book. A stream is viewed as suffering from a particular problem and standard restoration techniques are taken off the shelf and applied. There is frequently little regard for the natural dynamism of stream forming processes and there has been little emphasis on these techniques being a means to an end rather than as being an end in themselves.

According to Orth and White (1993), the important advance which needs to be made in trout stream restoration is for practitioners to understand why a particular technique or structure creates habitat, not that it does create habitat. By understanding why a technique works and what it is intended to create, will result in it being used in the correct context with the correct design.

10.4 Project Management

A major failure of many habitat restoration schemes has been the lack of a systematic project type approach to their implementation. For example, a lot of unpublicised stream restoration work has been undertaken in England and Wales, much of it by the EA. Most of this work has tended to be small scale projects implemented in an opportunistic manner to overcome some perceived habitat deficiency which required no detailed appraisal (Mann and Winfield 1992). As these schemes are rarely appraised, little information exists on whether these schemes really do work. Also, the limited exchange of information prevents the development and improvement of techniques and thus habitat improvement in general. As yet, trout stream restoration has not developed as a serious discipline in this country and lacks the interdisciplinary co-operation required.

It is considered to be a fundamental requirement that a logical project approach be applied to all habitat restoration schemes. This approach is spelled out in the manual and basically consists of a series of self-evident steps. By following the recommended approach, restoration schemes will not only be more successful but will also provide opportunities for learning and the future development of the discipline.

10.5 The Need to Develop a Process-Based Approach

To perform successful habitat restorations, it is imperative not only to have a knowledge of the habitats in which trout prefer to live, but also an understanding of the processes by which these habitats are created and maintained in nature. In any given stream, the habitats which are most limited have to be identified and schemes must be designed to re-create the processes which create these habitats. The intended effects of various techniques should be fully understood and schemes should be designed within the context of the processes operating within specific streams.

The achievement of these aims requires the skills of ecologists, engineers and geomorphologists. At the present time, there is a lot of relevant, but disparate, knowledge within these disciplines which needs to be drawn together to produce sustainable techniques. Many of the reported failures of the past, which have tarnished the image of habitat restoration, may have been avoided with an interdisciplinary approach. For example, Sear (1994) argues the case for geomorphological input into such schemes. He points out that in-stream works usually suffer from "over-design", probably resulting from a lack of understanding of the processes involved, and although geomorphological principles may be employed on a local level to design the course of a stream reach, wider catchment effects are often ignored.

10.6 Potential for Trout Habitat Restoration in England and Wales

Many factors have been identified as impacting on streams and rivers in England and Wales. This is true in all environments from the lowlands to the uplands. It is considered that much interest and potential exists for habitat restoration. This is seen as a major way of improving the sustainability of wild populations and the fisheries dependent on them. There is also considerable interest in stream restoration for other elements of the biota and much of this interest is compatible with trout habitat restoration. Furthermore, the recent development of catchment management plans now provides a suitable vehicle for planning and prioritizing habitat restoration, so ideal opportunities now exist for the formulation of fishery management plans based on habitat restoration.

Finally, it is very important that habitat restoration be held in perspective. Habitat restoration can be costly and the focus should not fall on restoration to the detriment of habitat protection. The protection of existing good habitats is paramount as it is much harder to replace something once it has been lost.

11. RECOMMENDATIONS FOR FUTURE DEVELOPMENT

11.1 Management of riverine fisheries habitat restoration must be improved via implementation of the project model presented in this manual. This will have significant advantages in terms of developing this activity to improve effectiveness and efficiency. SMART objectives and robust appraisal are two key areas requiring improvement. Managers responsible for promoting fisheries habitat restoration should place more emphasis on the quality rather than the quantity of work undertaken and focus on learning from implemented schemes.

11.2 The *ad hoc* and localised approach to scheme identification and prioritisation must be improved. Future habitat restoration initiatives should be progressed within the framework of strategic catchment management planning. Habitat restoration should be considered as an integral fisheries management tool to be considered and used appropriately within a catchment fisheries strategy.

11.3 Future promotion of habitat restoration projects should be progressed via a multi-disciplinary approach involving appropriate input from a range of professionals (fisheries biologists, geomorphologists, river engineers, conservation officers etc.). Such an approach will promote multi-functional river restoration activities and develop sustainable and multi-objective initiatives.

11.4 Riverine fisheries habitat restoration should be developed as a specialist field within the EA . Selected regional staff should be chosen to develop their knowledge and skills base in this field. A key role would be to oversee regional activities and to promote intra and inter regional communication and knowledge transfer.

11.5 The EA needs to promote co-ordination, integration and collaboration of fish habitat restoration initiatives undertaken within the EA and by other government and external agencies. The benefits of knowledge transfer and the production of a structured approach to future R&D initiatives are clear. Current plans to promote an inter agency workshop represent important progress in this area. Within the EA, promotion of recommendation 11.4 and the concept of 'Unit Programmes' to integrate appropriate R&D initiatives would provide significant benefits.

11.6 A future co-ordinated R&D plan should be an objective of the above inter agency co-operation and be identified following review and prioritisation of existing plans and perceived requirements. However, the need to continue to improve our strategic knowledge of brown trout ecology, habitat requirements and limiting factors will remain a core requirement to underpin this activity area.

11.7 Given the pressure on existing high quality populations of trout and the current level of ability to efficiently restore damaged habitat, priority should be placed on habitat protection. Such stocks should be identified and recognized within the catchment management process.

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13. APPENDIX

Legal consents required

The main legislation associated with habitat restoration is provided below:

1. Salmon and Freshwater Fisheries Act (1975)

2. The Water Act (1989).

3. The Land Drainage Act (1991).

4. Regional Land Drainage Byelaws.

5. The Water Resources Act (1991).

6. The Environment Act (1995).

7. Local Authority Planning Legislation.

Consents concerning 1 to 6 above are the responsibility of the EA.

A review of some general areas of habitat restoration which require consent is provided below:

1. **Work which will cause modification to the watercourse or flow.**

   This includes the vast majority of techniques used for trout habitat restoration (e.g. bank erosion control, gravel introduction, pool creation, in-stream structures, weed cutting etc.).

2. **Work which will cause modification to river banks**

   The erection of any structures including, fences, erosion control techniques, planting of trees or other vegetation within a set distance from the top of the bank. The specific distance for watercourses designated as “main river” is set under Land Drainage Byelaw and varies between EA Regions. In general, the distance is in the region of eight metres.

3. **Work which could potentially cause water quality problems**

   This may include gravel washing techniques, general silt removal, use of herbicides etc. Advice should be sought from the EA Area Environmental Quality Manager.

4. Work which will impound or abstract water

This may include weir construction or diversion of flow to newly constructed channels etc.

5. Fish pass construction

The EA is responsible for consenting fish pass construction. Local authority planning consent may also be required.

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