

8 Works in the river channel

8.1 Introduction

8.1.1 Striking the right balance

Successful – and indeed sustainable – engineering works are those that are planned, designed, operated and maintained with due regard for the environment in which they function. In this context, the term ‘environment’ is used in its broadest interpretation, including the physical forces that have to be resisted as well as the ecological, social and visual contexts. Works in a river or stream are no different in this regard; indeed it can be argued that the fluvial environment is one of the most challenging for engineers.

A common mistake in the past was to ‘over-engineer’ river works. Although such an approach may have achieved the hydraulic objectives (increased flood capacity, for example), this was often at the expense of other matters such as ecology and visual amenity. The quest to improve the hydraulic conveyance of river channels also created a huge maintenance obligation. This is because, left alone, a river tries to return to its ‘regime’ condition, in which flows significantly greater than the mean annual flood are not contained by the dominant channel. Today’s river managers must strive to achieve the right balance (Environment Agency, 2003).

This is not to say that under-engineering is the right approach. If the works cannot withstand the hydraulic forces imposed upon them, they will fail to achieve the desired objective and may damage the environment in the process. Nor is the complete abandonment of historic maintenance practices an appropriate response to environmental pressures, as this can also result in environmental degradation of a different kind (see [Figure 8.1](#)).



Figure 8.1 Inadequate maintenance?

In the past this urban stream has been concreted to improve its hydraulic capacity. But it has not been maintained regularly and the sediment in the bed now supports a lush growth, which acts to obstruct flow.

The appropriate level of maintenance should be determined by the desired hydraulic capacity of the channel as well as by the ecological value of the stream. Complete clearance of the vegetation may not be appropriate. However, the removal of most of the vegetation, perhaps leaving a strip on the inside of the bend, could improve flood capacity without unduly damaging the ecological status.

Getting the right balance ensures that both hydraulic and environmental objectives are achieved.

The stability of a natural channel (that is, its resistance to short-term change) is inextricably linked to its geomorphology and ecology. Aggressive channel ‘improvement’ works or vegetation clearance not only inflict severe damage on the ecology and visual amenity, but may also lead to erosion on the channel bed or banks, with consequential damage to adjacent infrastructure. It is therefore important that engineers and river managers:

- seek expert advice on geomorphology and ecology when contemplating significant works in rivers (see [Chapters 3 and 4](#));

- consider the impact of any works on other users of the river or stream, from those who simply appreciate the fluvial environment to those who actively use it for sports and recreation (see Chapters 5 and 6).

Works in a river channel not only have the potential to alter the river environment permanently, but they can also have a significant impact during construction and when maintenance works are required. Consultation with all affected parties (stakeholders) in the early planning stages will therefore pay dividends later on. In particular, it may be possible to programme works both to minimise the environmental impact and to avoid conflict with river users (such as anglers, boaters, canoeists and ramblers).

When works in river channels are planned, opportunities for the enhancement of the fluvial environment should also be considered. Examples include:

- improvements to riverside access;
- the provision of fish ledges;
- installation of nesting pipes in the riverbank for sand martins;
- the removal of invasive plant species (see Chapter 4).

The overall aim should be to achieve the objectives in a manner that is sustainable, while adding to the environmental value whenever possible. There is useful guidance in an RSPB handbook (1994).

Since the starting point for channel improvement works, including vegetation removal and desilting, is usually the desire to increase (or maintain) flood conveyance, it is clearly important to define the channel capacity required. In its simplest form this means defining a flow (in m³/s – cubic metres per second) for given water levels along a reach of the channel. The recently developed ‘conveyance estimation system’ (CES) allows the user to estimate the flow capacity of any channel for a range of assumptions regarding channel maintenance; for details of the CES and its development, see the project website (<http://www.river-conveyance.net>).

8.1.2 Legal issues

The legal framework for works in rivers is outlined in Chapter 1. The fundamental legal issues are set out in Acts of Parliament which define the rights and responsibilities of all parties with respect to rivers and streams. More recently, the European Union has enacted the Water Framework Directive with the aim of securing and, where possible, improving the ecological status of watercourses throughout all Member States.

Anyone contemplating works in any watercourse must therefore consider carefully the impact that such works may have, either directly or indirectly. In particular, the works should not cause damage or loss to other users of the river – in the reaches upstream and downstream as well as in the reach in question (see Box 8.1) – and there should be no long-term reduction in the ecological status of the watercourse. It is recognised that a temporary, short-term reduction may be inevitable during and immediately following the works. An environmental impact assessment (EIA) considers both short-term and long-term impacts of proposed works.

As a general rule, the first point of contact when considering river works should be the Environment Agency, which will be able to provide advice on current use of the river and any restrictions or legal requirements. This should then lead the way to establishing contact with all persons with rights or responsibilities for the reach of river in question, not least of all the riparian owners (the owners of land that abuts a watercourse, with ownership usually extending to its centreline).

Box 8.1 Consider and consult before starting work

In a recent legal case, one landowner (the plaintiff) sought compensation from another (the defendant) when works carried out on behalf of the defendant fundamentally changed the flow regime through the plaintiff's land. The watercourse in question comprised two roughly parallel channels, one being the original course of the stream and the other a man-made channel constructed generations ago to feed water meadows. The crude structure that regulated the division of flow was on the defendant's land and he owned the land through which the man-made channel flowed. The plaintiff's land was on the original channel downstream of the division structure.

The defendant asked the Environment Agency to carry out maintenance works on his channel because it was overgrown. The work was carried out with the result that the majority of the stream flow was thereafter channelled through the defendant's land, leaving the plaintiff with a mere trickle. One would have thought, perhaps, that this would be an easy problem to resolve, but the reality was different. The case lasted for several years and the Environment Agency (as executor of the maintenance works) was inevitably drawn in to the legal battle.

Two very important lessons come out of this example:

- Always consider fully the range of impacts that any proposed works might have before undertaking them.
- Always consult all stakeholders in advance of doing the work.

Anyone who intends to construct works in a watercourse must seek land drainage consent from the Environment Agency. This applies to weirs, culverts, sluices and any works that could have an impact on the flow or water level in the watercourse.

Anyone wishing to take water from a watercourse (for irrigation, for example) must first obtain an abstraction licence from the Environment Agency or from the Internal Drainage Board (IDB) as appropriate for the specific area. The Environment Agency has particular responsibility for rivers designated as a 'main river'. Other watercourses are generally the responsibility of the local council (or the IDB in an IDB area).

In the specific case of culverting a watercourse, Environment Agency policy is that watercourses should not be culverted except where there is no other viable option because of the environmental degradation that would result. This policy is strongly reinforced by the Water Framework Directive. Similarly, the construction of weirs is generally discouraged because of the potential impact on fish migration.

Riparian owners have certain rights and responsibilities regarding use of the watercourse (Environment Agency, 2007). There may also be byelaws that define rights and responsibilities. There is no duty in common law for a landowner to improve the drainage capacity of a watercourse, but there is a responsibility to maintain the bed and banks and any trees and shrubs growing on the banks. The riparian landowners must also keep the channel clear of debris, including the removal of material that does not originate from their land. **Figure 8.2** shows an example of neglect.



Figure 8.2 Fluvial neglect by riparian owners

Allowing a watercourse to deteriorate to this degree is courting disaster. There are potential hazards relating to pollution, obstruction of the flow, and health and safety.

The tree on the right has been allowed to grow too large. The sheetpile wall is collapsing into the channel. The demolition debris invites vandalism. Although this is clearly a temporary state, the risks of flood damage, pollution or injury will persist until the channel has been restored to a more natural state with adequate capacity and stable banks.

A riparian landowner has the right to receive water in its natural quantity and quality, although it is often difficult to define what is meant by ‘natural’ in this context. By the same token, a riparian landowner has the responsibility to pass on flow without obstruction, pollution or diversion affecting the rights of others.

Although many of the fundamentals of the law affecting watercourses are straightforward and sensible, their interpretation can be legally complex. If there is any doubt about the legality of any proposed works – whether new works or the maintenance of existing works – the promoters of such works should seek legal advice at an early stage of their proposal.

8.1.3 Rivers as dynamic systems

Natural channels are subject to continuous change in response to a wide range of influences. Not least of these is the ever-changing flow pattern which reflects day-to-day weather conditions, seasonal changes, and longer term changes to the catchment and in the global climate. **Figure 8.3** illustrates this hydrological variability with flow data from the River Trent. Fluvial designers ignore this dynamic nature of rivers at their peril.

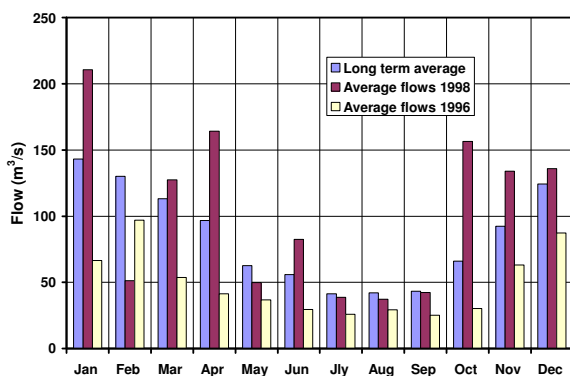


Figure 8.3 Hydrological variability

This graph shows the changing flow conditions in the River Trent. The three bars for each month represent (from left to right) the long-term average flows, flows in 1998 (a wet year) and flows in 1996 (a dry year).

The variability is pronounced, even more so when it is appreciated that these are monthly averages. Although the monthly average varies from a low of 25 m³/s to over 200 m³/s, mean daily flows (not shown here) fell as low as 15 m³/s in August 1976 and reached a peak of 1019 m³/s in November 2000.

This natural variability has implications for construction, operation and maintenance activities in the river.

Not only does a natural watercourse exhibit variability in its flow regime, but the boundaries of the channel are also subject to change. The rate of change depends on a wide range of factors including:

- the nature of the soils through which the channel flows;
- climatic conditions;

- human activity.

In any given reach of channel, there tends to be a natural regime which defines the channel cross section (that is, the width, the depth and the slopes of the banks). Artificial changes to the channel cross section are generally temporary as the channel naturally reverts to its regime condition. Gravel-bed rivers can be particularly problematic, because large quantities of gravel can be deposited in a single flood event. This can result in any benefits achieved by dredging works being wiped out in a matter of hours.

Considerable research has been carried out into the regime state of natural channels (Nixon, 1959) and it is generally accepted that the regime cross section is one that is capable of conveying the mean annual flood. This makes it clear that engineering a channel to carry much bigger flows (for example, the flood with a 1% annual exceedance probability – see [Section 2.4.1](#)) represents a major change from the natural state.

An artificially deepened channel tends to silt up so that the bed level returns to its pre-dredged level (hence the cyclical nature of maintenance dredging in navigable rivers). Similarly, widening a river to achieve greater flow capacity often achieves only a temporary outcome, as shoaling tends to restore the natural width. Steepening a reach of channel (for example, by cutting off a meander loop) can introduce instability, leading to erosion of the bed or banks as the stream attempts to revert to its former regime state.

An obstruction in a river channel also changes the natural regime, though over time a new regime may establish itself. Thus the construction of a weir in a river causes a backwater effect, and the resulting slower flow velocities encourage sedimentation upstream of the weir. A new balance will be achieved after some time (possibly many years). Weirs and similar structures also create an obstruction for wildlife – especially fish – unless special measures are incorporated (such as a fishpass). [Figure 8.4](#) shows an example of fluvial adaptation.



Figure 8.4 Fluvial adaptation

This large capacity culvert has been engineered to ensure that it does not cause a restriction to flood flows. But for most of the time flows in the stream are relatively small, with low velocities that encourage sedimentation. The islands of sediment become colonised with vegetation, making them erosion-resistant and prone to attracting more sedimentation.

Regular maintenance is needed to clear out the sediment and vegetation to avoid loss of flood capacity. Provision of an access ramp may be required to facilitate sediment removal. A two-stage culvert (with the outer boxes at a higher level), with similar approach channel geometry, could help to reduce maintenance obligations.

With construction works in river channels, there is a wide range of potential adverse impacts that must be addressed in advance in order to avoid or mitigate the impacts. Of course, there are often opportunities for positive impacts associated with works in river channels. It is up to the promoters of the works to liaise with river users and local interest groups (anglers, conservationists, fisheries, navigation interests, etc) to explore the possibilities for mutual benefit. [Table 8.1](#) indicates potential negative impacts but also includes references to potential benefits.

Table 8.1 Works in river channels – potential negative impacts

Nature of work	Potential negative impacts	Notes
Construction of a structure in the watercourse (a weir, for example)	<ul style="list-style-type: none"> ▪ Rise in flood level upstream. ▪ Obstruction to the passage of fish. ▪ Sedimentation upstream. ▪ Restriction to navigation. 	<ul style="list-style-type: none"> ▪ These are all potentially permanent negative impacts which may require mitigating action (such as raising flood defences or creating a fishpass). ▪ Potential benefits include improved amenity, aeration of the water, navigation and micro-power generation.
Diversion of the watercourse (resulting in shorter stream length)	<ul style="list-style-type: none"> ▪ Increase in stream slope, leading to erosion of bed and banks. ▪ Possible interference with agricultural drainage systems. 	<ul style="list-style-type: none"> ▪ Can be addressed by erosion protection measures. ▪ Potential benefits include reduced maintenance requirement and freeing up land for other uses.
Widening of the watercourse	<ul style="list-style-type: none"> ▪ Temporary loss of marginal and bankside vegetation. ▪ Damage to habitats (for example, water voles). ▪ Reduction in flow depth. 	<ul style="list-style-type: none"> ▪ Natural streams tend to revert to regime width over time. ▪ Benefits include the potential for a wider range of habitats.
Deepening of the watercourse (dredging)	<ul style="list-style-type: none"> ▪ Promotion of sedimentation (also depriving downstream reaches of sediment). ▪ Temporary damage to the ecology of the stream bed and hence the natural fauna. ▪ There are also negative impacts while the work is being carried out (increased sediment entrainment in the flow). 	<ul style="list-style-type: none"> ▪ In any sediment-transporting stream, a deepened reach of channel tends to silt up. In gravel-transporting streams, reversion to the former bed level may be rapid (perhaps in the course of one flood). ▪ Dredged material has to be safely disposed of, and this may be expensive, particularly as the material may be contaminated. ▪ Benefits are improved flood capacity and increased depth for navigation.
Construction of erosion protection works on the bed or banks	<ul style="list-style-type: none"> ▪ Damage to natural vegetation and habitats. ▪ Water pollution (avoid by using appropriate materials). 	<ul style="list-style-type: none"> ▪ Mature trees and shrubs should be maintained where practicable. ▪ Benefits may include a reduction in regular maintenance liability and the security of adjacent land, property and infrastructure.

8.2 Maintaining or increasing flood capacity

The most common reason for carrying out works to rivers is to increase their capacity to carry flood flows. There are a number of ways that flood capacity can be increased, but the two commonest are channel maintenance and enlarging the channel cross section (typically by widening or deepening – see [Case study 8.1](#)). These two methods are discussed below.

Flood capacity can also be increased by straightening a river, which has the effect of increasing the slope and removing bends, both of which increase the flow capacity for a given cross section. But because the channel suffers environmental degradation as a result, this approach to hydraulic engineering is no longer acceptable except in situations where no alternatives exist.

Increased flood capacity can also be achieved by creating a flood bypass channel around the properties and infrastructure at risk from flooding. A ‘normally dry’ floodway is set at a higher level than the main channel and therefore only carries flows during flood conditions. This option needs space for the new channel and there may be safety issues to consider as a result of the potentially sudden change from dry channel to flood conditions. An alternative is to provide a ‘normally wet’ bypass channel, typically carrying a small ‘sweetening’ flow. This avoids complete stagnation during the majority of the time, when the bypass channel is not carrying flood flows.

8.2.1 Channel maintenance

The term ‘maintenance’ in this context means:

- keeping the channel clear of excessive vegetation;
- removing debris and any obstructions (natural and dumped);
- desilting where appropriate.

The main objective is usually the maintenance of channel capacity to ensure it is adequate for flood conveyance. In the past, rivers were often dredged to provide a deeper channel for navigation purposes. This led to the need for a regular programme of dredging to maintain the depth of the channel, and this is still an important activity on some rivers, especially in the vicinity of lock structures.

The following example illustrates the potential impact of excessive vegetation on flood capacity. Assuming the channel is well maintained, a small stream can carry about $5 \text{ m}^3/\text{s}$ with a depth of flow of 1.0m. Allowing the channel to get heavily overgrown could require a depth of flow of 1.2m in order to convey $5 \text{ m}^3/\text{s}$. This increase in depth results in an equivalent rise of water level in the stream; this rise of 0.2m could make the difference between the flow being contained within the channel and the banks being overtopped and causing local flooding. If the channel was also obstructed by debris and fallen trees, the rise in flood level could be 0.4m or more. **Box 8.2** illustrates how Manning’s equation (see **Section 7.4.2**) can be used to assess the impact of maintenance operations.

Box 8.2 Use of Manning's equation

Manning's equation can be used to estimate the discharge capacity of an open channel (that is, the maximum flow that the channel can carry). This is a useful way of obtaining a rough idea of flow capacity and of checking the impact of maintenance works; for design purposes, the approaches described in [Chapter 7](#) are advised.

$$Q = \frac{AR^{2/3} \sqrt{i}}{n}$$

where: Q = discharge in m^3/s

A = area of cross section of flow (m^2)

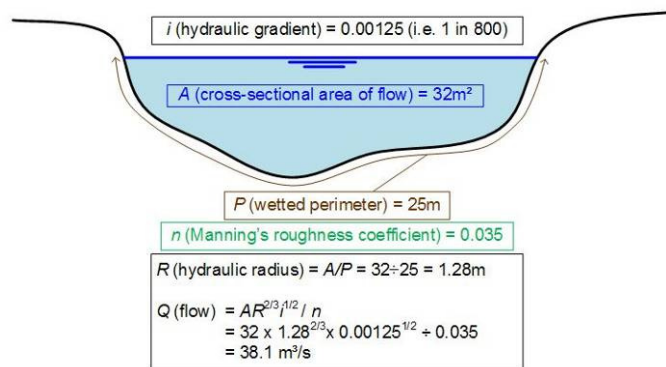
$R = A/P$ (the hydraulic radius, m)

P = wetted perimeter of the channel cross section (m)

i = hydraulic gradient (usually approximates to the longitudinal slope of the channel)

n = Manning's roughness coefficient.

Note that the value of Manning's n is a measure of the hydraulic roughness of the channel (that is, its resistance to flow). A value of $n = 0.035$ would be typical of a natural channel with some vegetation. The value of n for a very clean straight channel might be 0.025, whereas for a heavily overgrown channel it might be 0.050. Selecting the right value of Manning's n is crucial. The CES (conveyance estimation system) website (<http://www.river-conveyance.net>) provides comprehensive guidance on this subject.



In the past, the impact on the local environment was considered to be secondary to the achievement of the fundamental objectives (flood conveyance or navigation depth), but nowadays it is essential to strike an appropriate balance. The Water Framework Directive promotes the maintenance and improvement of the ecological status of rivers and streams, and places onerous restrictions on the carrying out of any works that might have the opposite effect.

It is therefore vital that channel maintenance works are carried out with due regard to watercourse ecology as well as the environmental setting. This means that the need to clear the channel of unwanted obstructions should be set against the potential ecological effects, so that a balanced and proportionate solution is found.

In general, maintenance work on a watercourse should be carried out when it is least likely to impact on other uses of the river. This means avoiding the summer season on recreational waterways.

Wholesale clearance of a long reach of channel in one go should be avoided. Clearing out short reaches of channel with gaps in between, or only clearing one bank and half the channel width, are options which reduce the environmental impact.

As far as practicable, cut vegetation should be removed from the channel so that it does not float downstream and cause a nuisance to other river users or block a culvert or trash screen.

[Figure 8.5](#) shows an example of what is now deemed appropriate maintenance and [Figure 8.6](#) an example of overdue maintenance. A well illustrated guide to channel maintenance, with the emphasis on achieving the desired hydraulic effects without damaging the environment, has been issued by the Environment Agency (2003).



Figure 8.5 Appropriate maintenance?

The banks of this small stream have recently been cut back hard to leave a short grass cover. Although this is fairly aggressive maintenance, the stream retains a natural appearance while achieving maximum flood conveyance for the channel cross section available.

Access to this stream is restricted, so the clearance has to be carried out manually using equipment such as a strimmer.



Figure 8.6 Overdue maintenance?

Here willows have fallen into the river and continued to grow. Not only do they cause an obstruction to flow themselves, but they also trap floating debris, such as the fishing platform shown here, which can significantly exacerbate the blockage effect of the trees themselves.

The need for maintenance works depends on the hydraulic requirements for the channel and the impact of high water levels on flood risk. If there is an urban area downstream, it may be beneficial to allow the channel to become constricted, so that water flows onto the floodplain and is stored temporarily, thereby reducing flooding in the urban area. However, achieving the right degree of constriction would be difficult, and a more engineered approach to flow control is likely to be preferable.

In planning maintenance works for river channels, especially for newly engineered channels, it is essential to consider access requirements for plant and equipment. This may include the construction of riverside access tracks and ramps down to the bed (for example, to gain access to the inside of a large culvert). Maintenance works can be carried out from the river using specialist boat-mounted plant. But it is still necessary to consider the access requirements for the floating plant and suitable disposal sites for the material removed (dredged material, debris and vegetation).

8.2.2 Channel enlargement

Making the channel bigger seems the obvious way to increase its capacity and thereby overcome a flooding problem, and many flood alleviation schemes have gone ahead on this basis. Though, as promoters of such schemes have found to their cost, there are drawbacks too. These include:

- environmental degradation as of the result of the loss of natural channel features and vegetation during the enlargement process (recovery may take a long time);
- channel instability due to the removal of vegetation that helps to prevent erosion and maintains the integrity of the riverbanks;
- sedimentation in the engineered channel leading to the formation of shoals and bars, and eventually to the reversion to a smaller, more natural channel (frequent intervention may be required in the form of desilting to keep the desired channel size, again with adverse environmental impacts);

- a stark and unnatural appearance, particularly in the usual low-flow conditions (which are much more common than flood flows).

Some of these problems can be overcome by creating a two-stage channel, in which the usual flows are contained within a smaller channel and flood flows occupy a much larger second stage channel. This design emulates the operation of a natural floodplain, but in a more contained and controlled manner.

As a variant of the two-stage channel, a low-flow section can be engineered by the provision of low groynes that confine these flows and result in enhanced flow velocities, but do not interfere significantly with flood flows. Low weirs can also be used to maintain the depth of water in the channel in low-flow conditions without impacting on the flood capacity.

All these options require careful consideration and the involvement of an experienced geomorphologist (Chapter 3) to ensure they are stable in the long term and do not result in adverse impacts.

8.2.3 Dredging and desilting

Desilting is the term used when accumulated sediment deposits are removed from a channel. Dredging is the general term used for the excavation of material below water level either as a maintenance activity (when the term desilting could also be used) or as part of channel enlargement works. The main purpose of dredging and desilting is either to maintain the navigation depth or the flood capacity, or sometimes both.

Dredging is an expensive operation and can have severe environmental drawbacks. The expense is not only in the dredging operation itself but also the disposal of the dredged material, which may be contaminated and require disposal to a licensed landfill, with associated transportation costs. Dredging should therefore be avoided wherever possible, especially since it is almost never a ‘one off’ operation.

Environmental damage can be reduced by carrying out the dredging in the appropriate season, for example to avoid polluting fish spawning grounds with fine sediment disturbed by the dredging process. Avoidance of the summer season when boating and other river-based activities are at their peak is also advisable, but this may leave a narrow window for the dredging operations when other restrictions are taken into account.

The environmental impacts can also be minimised by choosing the right plant and equipment for the dredging. Mechanical removal of material from the bed (for example, using a dragline or a grab) is likely to create the most disturbance and hence sediment pollution, although measures can be taken to reduce this impact (see Section 8.7).

8.3 Channel stabilisation

8.3.1 The need for stabilisation

Any river, left to its own devices, eventually forms a channel profile, planform and gradient appropriate to the flows being carried. These are all interlinked, as an over-steep river may cut back its bed to form a flatter gradient, or form meanders which, by increasing the flow path length, also achieve a flatter gradient. The cross section also adjusts to suit the flows, so that the bankfull capacity of a natural river is normally about equal to the mean annual flood. During a large flood, the cross sections and longitudinal profile may change, with the possibility of a new course being formed on occasions. Following the flood, further erosion and deposition gradually take place to restore the regime conditions, albeit probably not creating an identical watercourse to that which existed previously.

Ideally a river would be left to ‘do its own thing’, as this would require no maintenance work such as bank repairs or dredging. This is also likely to be most beneficial for the ecology of the river. But in many cases, allowing a river free rein would be unacceptable because of potential damage to riparian property and infrastructure such as bridges, utilities and footpaths.

River engineering works such as bank protection and weirs may have to be introduced to prevent the river from moving from its course and causing damage to property (see [Case study 8.2](#)). In a few cases, it may be possible to provide a ‘last stand’ form of protection whereby a line of steel sheetpiling, for example, is installed at the closest point that the river would be allowed to approach towards a structure, but the river would be unconstrained until it moved sufficiently to expose the piling. Bank protection may also be required as part of – or in response to – other engineering works. For example, protection may be needed downstream of a culvert or opposite an outfall structure – in both cases to protect vulnerable banks from erosion by fast-flowing or highly turbulent water.

The Environment Agency publication, *Waterway bank protection: a guide to erosion assessment and management* (Cranfield University, 1999) should be used to identify the causes of erosion. It provides a logical method of choosing an appropriate method to control such erosion, if indeed control measures are needed. [Figure 8.7](#) shows an example of active erosion where no action was required and [Figure 8.8](#) an example of a lack of timely repairs.



Figure 8.7 Active erosion

This riverbank in Wales is actively eroding, with the bank being undercut and clods of turfed soil falling into the water. These clods may provide some temporary erosion protection, but will soon be broken up and washed away, allowing the cycle to continue.

In this case no action was required, as there was no asset with economic value at risk.



Figure 8.8 Lack of timely repairs

This bank is on a navigable river, with the banks subject to boat-wash as well as flood flow velocities. Concrete bagwork protected the bank at normal water level, but when this started to fail, erosion occurred on the earth banks.

As no action was taken (because of a dispute as to who was responsible) the erosion continued, eventually undermining the footpath.

In situations where river stabilisation works are required, the aim is generally to constrain the river in a defined location with little or no change in planform, grade or profile being acceptable. This may require low weirs (drop structures) to change a steep gradient into a series of shallower ones, and will almost certainly require a form of erosion protection on the banks to maintain both the planform and profile.

For flood risk management, the desired hydraulic capacity of a river or stream is usually considerably greater than the mean annual flood, which means maintaining a larger channel cross section than would occur naturally. Sometimes this can be achieved using two-stage channels, but otherwise dredging is likely to be required.

All works to stabilise rivers require careful investigation to ensure that the benefits achieved in one reach are not at the expense of adverse impacts elsewhere.

Once an acceptable scheme has been devised, it must be costed and compared with the benefits of stabilising the reach. Where property or infrastructure is at risk, such benefits are likely to outweigh the costs but, in farmland, the balance is unlikely to be so clear-cut. When weighing up the costs and benefits, the analysis should go further than just the economics. The impact on the ecology of the river and riparian zone must be considered, as must the risk to any heritage sites adjacent to the river.

8.3.2 Options for stabilisation

A watercourse that is cutting back, with a drop in the bed that is eroding its way back upstream, has a gradient that is too steep and it is trying to achieve a stable grade. A drop – or a series of smaller drops – can be introduced, with hard engineering material, to arrest the drop (that is, to stabilise it in the selected location). Such drop structures need an appropriate stilling basin with bed protection in order to dissipate the hydraulic energy of the flow before it continues downstream. An alternative would be to accept high, erosion-inducing velocities but to line the riverbed throughout the reach; this may indeed be the chosen solution in some areas.

Many rivers can be left to erode in hilly rural areas, but in doing so they bring eroded material downstream. There is often a marked change in gradient where a river moves from a hilly rural area to a developed area, as most development has taken place in the flatter lowland areas. This is where the suspended sediment load of the river tends to drop out of suspension, and the bedload ceases to be moved forward as velocities reduce.

This creates a problem, as the sediment restricts the flow capacity just where the river is – in all probability – constrained and where flooding could cause damage. One solution is to trap the sediment before it reaches an area where it can cause a problem, or where it would be difficult to remove. Accordingly, some hilly rivers have silt or gravel traps constructed just upstream of the town. These do not function if they are full and therefore require clearing at the appropriate time. This may not be at regular intervals, but would depend on the distribution of flood flows. Although this is often not a ‘sustainable’ solution, it may be the only practical means to maintain flood risk at an acceptable level.

To prevent a change to the planform or profile, the riverbanks must be prevented from eroding. Where the banks are formed by stable retaining walls (such as vertical concrete, gabion or sheetpiled walls), no additional protection is required and the stability of the soil behind the wall is immaterial. However, erosion of the channel bed in front of a retaining wall can destabilise the wall.

Where an earth bank is to be protected from surface erosion, the fundamental requirement is that the bank must be inherently stable, as surface protection will only prevent the surface from being eroded, and not prevent any slips or other forms of mass failure.

In some cases, all that is needed to stabilise the bank is to allow natural vegetation to occur without damage from humans or animals. Typically this involves fencing the top of the bank and letting nature take its course. In other cases, more robust action may be needed to prevent rogue anglers clearing vegetation and cutting steps and platforms in the bank. [Figure 8.9](#) illustrates best practice for access of stock to a watering hole.



Figure 8.9 Watering hole access

Ideally stock should be fenced off from rivers for a number of reasons, not least being their own safety, and provided with a safe water supply in troughs. Where access to a river is permitted, damage to the banks and bed can occur and water quality can suffer.

In such cases it is preferable to limit access to defined locations (as illustrated). A hard ramp down to the water is essential, and the bagwork at the water's edge ensures a deep enough area to drink from. The fencing should not extend beyond the toe of the bank (because it may obstruct flow), but it must be located to ensure there is water on the land side of the fence for all states of flow.

A bank that is inherently stable can become destabilised if the toe is undermined. It is this part of the bank that is at most risk of erosion, as it is always underwater. It is therefore subject to constant and varying local flow velocities, often with little vegetation to reinforce the soil and reduce velocities at the soil surface. Toe erosion can lead to failure from slippage (slumping) or slab failure; the fallen material is then washed away in the flow, allowing the next part of the bank to be eroded. Toe protection is therefore a vital component of a riverbank revetment. This is often formed from a flexible mattress or dumped stone, so that the protection adapts to erosion of the bed and stabilises it.

All retaining walls and forms of bank protection inhibit erosion. This affects the river geomorphology because the bank material that was previously eroded and passed downstream is no longer available. This could have either beneficial or adverse impacts in the reaches further downstream.

Aesthetics and amenity should also be taken into account in the design of bank protection works. River users can be classed as those who enjoy the river from the bank, and those who venture into or onto the water. Whereas riverside walkers simply like to walk alongside the river with a view of a 'natural' river, anglers require easy access down to the water. Fishing stands are needed to avoid the bank damage caused by anglers accessing the water at inappropriate points.

For those in the water, such as swimmers or boaters, any bank protection should avoid sharp underwater projections or submerged vertical drops to avoid injury or damage to craft.

8.3.3 Weirs, riffles and cascades

With the principal exception of **weirs** provided to facilitate navigation (see [Figure 8.10](#)), the original purpose of many ancient weirs no longer exists and many are in a very poor state of repair. Weirs impede the passage of fish and cause the reach upstream to act as a silt trap, covering the natural bed over the length influenced by the backwater effect. But as they reduce the velocity of flow, weirs lessen the need for bank protection in vulnerable areas and stop any regression or headcutting of the bed. Instead of the energy of the river being dissipated more-or-less evenly along the river, it is dissipated in peaks at discrete points known as weir pools. These are invariably much wider than the natural river and have deep pools; both these features are caused by the turbulence of the energy dissipation and the resulting eddies and reverse-currents. These features attract fish and therefore anglers.



Figure 8.10 A large weir on the Thames

The primary purpose of this weir is to maintain river depth for navigation. Like many weirs on the Thames, this weir is equipped with movable gates and a length of 'self-regulating' free flow crest. This combination allows the upstream river level to be maintained over a wide range of flows.

For channel stabilisation or environmental enhancement, a **cascade** offers an alternative to a traditional weir. With a cascade, the water changes level over a much longer distance than at a single vertical weir. A cascade may be formed of a series of small vertical drops or from rock laid on a slope (for example, 1 in 20). In the latter case, the rock is usually laid on a geotextile underlayer to prevent the substrate from being washed away. Any cascade should enable fish to pass more easily upriver than a vertical drop, but in this respect a rock cascade can cause environmental problems. This is because, during low flows, water may pass through the rock matrix rather than over it. This can be overcome to a large extent by spreading pea gravel over the finished rock cascade. The surplus is washed off downstream (to the benefit of the substrate) while all the large interstices should remain filled. As silt is brought downstream, this further seals the matrix and ensures that water flows over the surface.

Pools and riffles are the natural geomorphological features of a gravel-mix substrate in rivers with moderate bed gradients (steeper than 0.5% or 1 in 200) where there is sufficient gravel to armour the bed. A pool–riffle sequence will occur naturally, but the individual features may move during a flood, and re-form subsequently. In meandering rivers, the pools are found on the outer point of the bends, with the riffles along the straights between the bends. If pools and riffles form on a straight reach of a river, these are normally the precursor of an attempt to meander, although the meandering planform may take centuries to develop (see [Chapter 3](#) for a more detailed discussion of river geomorphology).

8.3.4 Bank protection

Bank protection is needed where there is the risk of erosion of the bank and where this erosion would cause economic or environmental loss. If there is sufficient space available, it may be possible to reduce the need for bank protection by re-profiling the bank to a flatter slope to reduce velocities and encourage good vegetation growth. Even if bank protection is still required, it may be less severe if a flatter slope can be achieved, or may only be required below normal water level. [Case study 8.3](#) illustrates a traditional form of bank protection using steel sheetpiling, but with additional features to improve the visual appearance and ecology of the finished works.

Where it is needed, erosion protection for a bank can range from a good grass cover to heavy concrete slabs, but is broadly categorised as 'hard' or 'soft'. Soft bank protection is generally considered to be vegetation of various types, whereas hard bank protection consists of concrete blockwork, riprap or similar. This is not a universally accepted definition as, in some parts of the country, riprap is termed 'soft' (because it is locally sourced and more natural than concrete), with 'hard' being reserved for the likes of piling and solid concrete walls. [Figure 8.11](#) shows the use of an erosion protection mat.



Figure 8.11 Erosion protection mat

The top photograph shows a newly installed erosion protection mat on a small stream. The mat is securely anchored to the bank, which has been prepared to give an even surface on which to lay the mat.



The same mat eight months later is shown in the lower photograph. Note the degree to which vegetation has established on the bank and how the mat is no longer visible.

It is often wise to seed the mat with the sort of plant material that is desired. Otherwise, the choice of vegetation establishment will be left to nature and unwanted species may dominate.

Bank protection also has an impact on the ecology of a reach, and in this respect the softer the bank protection the more ecologically friendly it is likely to be. Vegetated banks offer little or no restriction on habitat, although animals that dig holes may need to be discouraged. This can be achieved by laying an open geotextile on the bank before adding a layer of topsoil (30–40mm thick) mixed with grass seed over the top. The geotextile assists in binding the grass roots together, at the same time making burrowing more difficult (though not impossible for determined creatures with sharp teeth).

Coir rolls, willow spiling and faggots can all be used to provide erosion protection, and each can also provide habitats for a range of species. However, the softer forms of erosion protection are not appropriate for situations where flow velocities or turbulence are high. Whereas the achievement of an environmentally acceptable protection system is very important, this has to be in the context of achieving the primary aim of bank stabilisation. A revetment that is destroyed in the first major flood because it was not up to the job would fail to achieve both structural and environmental objectives.

Some hard engineering solutions such as riprap can also provide habitats for a different range of species, both above and below the water, as the interstices provide shelter for fish fry and invertebrates below water, and for a range of insects, birds, animals and plants above water. Concrete slabs and solid concrete lining, on the other hand, provide a somewhat barren environment for flora and fauna.

Correct design and implementation are essential for long-term success as illustrated in [Figure 8.12](#). Further guidance on bank protection can be found in Hemphill and Bramley (1989).



Figure 8.12 Bank protection not long enough

This bank protection using gabion mattress downstream of a weir did its job, but it was not continued far enough downstream. Erosion in such areas may be initiated by a small step in the bank profile, which causes localised eddies. These start to erode bank material, thus enlarging the step, and so the cycle continues until the end result is similar to that shown here.

It is often advisable to change from a heavy bank protection such as gabion mattresses to a light, more flexible protection such as a geotextile, rather than just stopping the heavy protection suddenly.

The common approach to protecting the toe of a riverbank from erosion is to provide some form of flexible protection such as a gabion mattress or riprap. Alternatively, the toe can be protected by sheetpiling, with the top level of the piles below normal water level. Protection of the bank toe may be achieved in some cases by the use of in-channel structures such as vanes or groynes to deflect high velocities from the bank, and ideally cause a deposit of material in their lee to help protect the bank toe. These may be especially useful where the bank is well vegetated above the normal water level, and not, in itself, at risk of erosion. In floods these vanes or groynes are fully submerged, so offer minimal reduction in flow capacity.

8.3.5 Revetments

A revetment is a heavy cladding constructed on the face of a sloping earth bank to protect it from erosion by water (see [Figure 8.13](#)). It may comprise loose rocks (riprap), contained rocks (gabion mattresses), or concrete slabs or blocks which may or may not be tied together. *River and channel revetments – a design manual* (Escarameia, 1998) provides a comprehensive guide to the design and identification of appropriate revetment systems. For a comprehensive guide to the use of rock in hydraulic engineering, see *The rock manual* (CIRIA *et al*, 2007).

A revetment does not retain the bank if it is built at an inherently unstable slope, nor is it a waterproof layer. Indeed, it is essential that it permits water to drain easily.

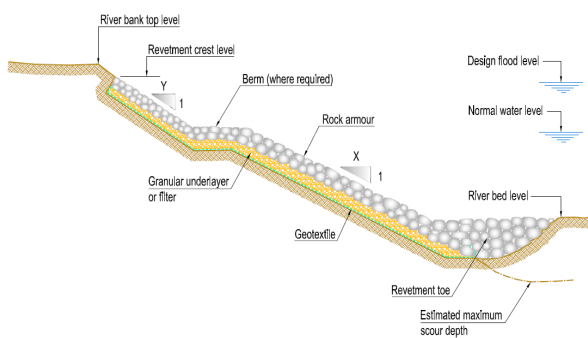


Figure 8.13 Cross section of a typical rock revetment

This section shows the composition of a typical rock revetment, with the rock armour layer and the underlayer (in this case gravel plus a geotextile).

The berm is not essential, but may be provided for stability, access, or at natural ground level if the upper part is a flood embankment. Note the excess of rock at the bottom to provide protection to the toe.

To function satisfactorily, any revetment system must consist of two layers:

- cover (or armour) layer;
- underlayer.

The cover layer is exposed to the flowing water and provides protection against the shear forces produced by currents, eddies and wave action. The two most important properties which the cover layer must have are permeability and flexibility – the latter to accommodate any settlement or migration of the underlying layer without creating a void.

The cover layer will not function effectively, though, if it does not have a well-engineered underlayer. This underlayer must act as:

- a drain parallel to the slope to prevent a build-up of water pressure under the cover layer;
- a filter to prevent the underlying soil from washing out.

The underlayer normally consists of a granular material laid on a geotextile filter cloth that separates it from the bare earth bank. To reduce the risk of voids, the underlayer must be finished to provide an even formation for the cover layer.

For proprietary revetment materials, manufacturers normally provide the specification needed to be included in any contract to ensure their material is installed properly.

A well-designed revetment will last for tens of years, often with little maintenance. Severe hydraulic loading and vandalism can result in local damage, so it is essential that revetment systems are inspected regularly and repairs carried out as soon as any damage occurs. Failure to act quickly could lead to a rapid deterioration of the whole system once the integrity of any part has been compromised.

When carrying out repairs, it is important that identical components are used for their repair; details of these should be available in the ‘health and safety file’ if the work was relatively recent. Otherwise, some careful investigation may be needed to match materials as closely as possible.

Appropriate characteristics of riprap are given in [Table 8.2](#).

Table 8.2 Appropriate characteristics of riprap (Escarameia, 1998)

Parameter	Characteristic
Nominal size	Given in terms D_x or W_x , which are the size or weight of a stone for which $x\%$ of the sample of stones (by weight) is smaller.
Grading	$W_{85}/W_{15} = 3.4$ to 16 , with a smooth, well-graded curve
Shape	Ideally blocky
Angle of repose	Typically between 35° and 42°
Angle of internal friction	Typically between 40° and 45°
Specific gravity	Typically between 2.5 and 2.7
Revetment thickness	Not less than $2 \times D_{50}$ or 1 to $1.5 \times$ maximum dimension of individual stones
Porosity	Ranges between 25% (well-graded riprap) and 40%

Many formulae have been developed to determine the size of rocks in a revetment, but that of Escarameia (1998) is one of the easiest to use. It can be used for bank slopes not steeper than 1V:2H to determine the 50% passing size of the revetment:

$$D_{50} = k \frac{U_d^2}{(s - 1)}$$

where: $k = 0.050$ for continuous revetments, 0.064 at the edges of revetments

D_{50} = characteristic stone size (the equivalent sphere size)

s = relative stone density (usually taken as 2.5 – 2.7)

U_d = depth-averaged velocity of flow at the toe of the bank (m/s)
(if U_d is not available use U , the mean velocity at the section)

With a well-constructed gabion mattresses much smaller stone can be used and the formula given above can be used to determine the stone size, but with $k = 0.007$. The minimum thickness of the mattress is then 1.5 times the nominal stone size.

Loose or interlocking concrete block revetment may also be designed using the formula above, in which case $k = 0.037$ for continuous protection and 0.048 at the edges of the revetment. For concrete blocks, D_{50} is taken as the block thickness. For linked concrete blocks more complex formulae apply (Escarameia, 1998).

Ideally a revetment should be placed on a newly formed sloping bank in the dry, but this is only likely to be possible for new channels – more often it is a case of repairing an already eroded bank. In either case, care taken in the preparation of the foundations pays dividends in reduced maintenance and repairs in future years.

Where material has to be placed underwater (underlayer or cover layer), the ability of the contractor to control the quality of the finished product is reduced – particularly for riprap – and so the specification should be upgraded to compensate.

8.3.6 River training

River training is the term used to describe engineering works aimed at keeping a river on a chosen course. It has been the driver for some very bold engineering works in the past, often associated with bridge construction, most notably in areas of the world where rivers are very dynamic (for example, the Indian subcontinent). Massive river training works have also been used on the major European rivers as part of the development of navigation (for example, the Rhine). In the UK, such works are much less common, but river training techniques still have a role to play.

The stabilisation works described in the preceding sections can all be used as river training techniques. Other measures include groynes and guide banks.

Groynes are linear engineering structures that project from the riverbank into the channel, the idea being to keep fast-flowing and highly turbulent water away from the bank and thereby protect it against erosion. The design of these structures follows empirical rules regarding the length, spacing and angle to the bank. They are more suited to rivers that have relatively shallow waters near the bank, because otherwise the cost of the groynes becomes too high. Often the groynes are designed to overtop in floods, so as not to unduly restrict flood capacity and also to keep the costs down. Perhaps the most important design feature is the stability of the groyne itself because, by its nature, it promotes more turbulent, high-velocity flow at its head. Heavy erosion protection is therefore required at the head (river end) of the groyne. Groynes can be constructed from dumped rock, gabions, timber and even brushwood (the latter for low-velocity applications).

Guide banks are linear structures located on the floodplain parallel to the river course. They are often heavily armoured to resist erosion, their function being to keep the river on a defined course in flood conditions. They are commonly used in the USA to maintain a river course at a major road or rail crossing. They are much less common in the UK.

8.4 River restoration and improvement

People always have modified rivers for their own purposes. Many rivers and streams that appear, at first glance, to be natural, may in fact have been changed hundreds of years ago to feed mills or to permit navigation.

In the last century, many more rivers were modified to reduce flood risk, often by straightening and canalising them – frequently with concrete beds and sides, and sometimes with a concrete lid as well, forming a culvert.

More recently, the considerable disadvantages of such techniques have become apparent. Not only is there a realisation that loss of habitat represents a significant environmental disbenefit, but it has become clear that, in many cases, the flood risk has actually been increased by such interventions. For example, development constructed over a culverted watercourse lies in the floodpath when the flood exceeds the capacity of the culvert and the floodwater finds an overland route down the valley. Compare that to an open channel, where – even if the water is above the channel banks – the bulk of the flow is still in (or directly above) the actual channel. De-culverting ('daylighting') a watercourse is therefore beneficial from both an environmental and a flood risk management perspective (see Case study 8.4), even if the planform cannot be restored to a less artificial one.

Rivers that have in the past been straightened and constrained can be restored to their original length, complete with meanders and floodplains where space permits (see [Figure 8.14](#)). The drainage system is then able to store more water during a flood, and the attenuation provided by this storage reduces peak flows downstream compared with a straight, lined channel (where the aim is to move the water downstream as quickly as possible).



Figure 8.14 Restored River Cole

This reach of the River Cole has been restored to a meandering and more natural course. Active bank erosion is evident, but this is part of the natural process of channel adjustment and can be left to continue.

The natural features created by erosion and deposition create habitats for a wide range of aquatic flora and fauna. Many of these may be damaged or lost when a stream is over-engineered.

It is unfortunate that in many places where rivers have been straightened, lined or culverted, it is not possible to regain a natural (or naturalised) channel due to man-made development and infrastructure – probably the reason the river was altered in the first place. Where such a possibility does exist, the aim should be to restore the river to its natural course, as this reduces the need for bed or bank protection.

If old maps showing the natural course are not available, look for any natural reaches upstream and downstream, and aim to mimic these. Nearby rivers of similar size and slope may also give clues as to what a 'natural' river in that area should look like.

If the strata in which the restored channel is to run are erodible, it is advisable to create a new channel that is only approximately as the finished one should be. The flows will then fine tune it to a natural regime with, for example, pools and riffles forming naturally. But if the strata are likely to erode only slowly, then some extra work at the construction stage enables a more natural river to be achieved earlier. Features such as pools, riffles, varying bank slopes and berms can all be included with the expert advice of fluvial geomorphologists, ecologists and fisheries advisors.

A restored river invariably provides a wider range of habitats than its predecessor, not only within the river but also on the banks and in the floodplain (if included in the restoration). This will go some way to meeting local biodiversity action plan targets. A natural river enhances the amenity of an area and provides riverside walks, as well as providing an opportunity for formal and informal education.

8.4.1 Restoration techniques

The River Restoration Centre (RRC) collates information on river restoration schemes, and disseminates this information in a number of ways, one of which is the *Manual of river restoration techniques* (RRC, 2002). This should be among the first references to be consulted when considering a river restoration project.

Careful consideration is needed when proposing the removal of permanent artificial obstructions from a watercourse (such as a redundant weir) in order to restore a river to a previous state. Although there may be an immediate gain in flood conveyance and the removal of an obstruction to fish migration, there are also potential negative impacts. These include the release into the flow of accumulated sediments, which may be contaminated if the site has an industrial history. Removal of a weir may also be seen as a loss of amenity. It can also temporarily destabilise the river by causing bed erosion upstream, and this could undermine infrastructure such as bridges and riverside walls. But in many circumstances, a weir can be removed with no adverse – and many beneficial – impacts (see Case study 8.5).

If a weir is to be removed, consideration must be given to the changes in the pattern of energy dissipation that may be caused. A weir pool may have formed over many years, with a shape and size that allow it to act as an effective energy dissipator. If removal of a weir takes away that function, that energy must be dissipated elsewhere – which is along the bed and banks of the river upstream. Careful assessment is required to determine the mean and maximum velocities likely to be encountered and the shear forces generated at the bed and banks. If these are likely to cause unacceptable erosion, then either the areas at risk should be protected or perhaps the weir should be only partially removed.

An alternative is to replace one large weir with a series of lower weirs or possibly a cascade, which would permit fish passage and improve flood capacity while restricting velocities and potential bed erosion. In less steep rivers, a pool and riffles sequence can be established, often by the introduction of imported gravel to form the riffles. Guidance on the establishment of pools and riffles can be found in the Environment Agency's *Guidebook of applied fluvial geomorphology* (Sear *et al.*, 2003).

In some situations, a meandering channel with pools and riffles can replace a shorter straight channel containing a weir, to the benefit of fish passage, an increase in habitat potential and additional flood attenuation. Where restoration involves reintroducing meanders to a long straight channel, it is likely that the new channel will cut across the existing channel in a number of places. If possible, parts of the straight channel that are intersected should be left open rather than being backfilled to provide backwaters (see [Figure 8.15](#)). These will provide a still water habitat, as well as offer refuges for fish during periods of high flow. If land constraints permit, purpose-made backwaters or perhaps shallow bays can be excavated.



Figure 8.15 Backwater

When a floodbank along the River Roding was reconstructed further from the edge of the river, it gave the opportunity to construct a small backwater in the floodplain between the river and the floodbank.

The photographs show the backwater just after excavation and a year later. Some marginal planting had been carried out, but all terrestrial growth is from natural re-vegetation.

The entrance to the backwater can be seen at the far end of both photographs. In major floods the entire area is submerged by flowing water.



Not all river works are carried out in natural earth channels. In Boscastle, for example, the existing channel has been deepened through bedrock. Rather than just slicing a vertical wall through the rock, it was carefully broken out along its bedding planes, leaving the bank with the same appearance as the more natural banks elsewhere on the river. Such attention to detail and consideration of how to work with nature are the keys to successful river restoration.

8.4.2 River diversions

Sometimes it is necessary to divert a river or stream course to make way for major infrastructure such as a motorway. This should be seen as the opportunity to re-create the river corridor, incorporating existing and new environmental features to ensure the new reach of channel adds value to the environmental and ecological status of the stream in question. The Water Framework Directive requires this type of approach. The river restoration techniques described above can be adopted for river diversion schemes (Fisher and Ramsbottom, 2001).

In other cases it may be that the existing course of the river is too constrained to allow enlargement to carry flood flows but is adequate for low flows. In such cases an alternative route for excess flows must be found. This may be a new channel, although this can involve significant land acquisition for something that is rarely used, or it can be a floodway where land is used for its original purpose (except when a major flood occurs) provided that such use is compatible with occasional flooding (see [Figure 8.16](#)).



Figure 8.16 Floodway

This floodway is normally used for cattle and horse grazing but, when a major flood occurs in the adjacent river, floodwater is diverted across the fields by the operation of an automatic gate. The scheme has been designed so that floodwater rises slowly, from the middle of the floodway, leaving no islands, and thus any stock in the fields are able to make their way to safety on the banks along each edge. There are large areas of field on each side which do not flood.



8.5 Outfalls, abstraction works and service crossings

8.5.1 Outfalls

Outfalls range in size from individual land drains to large stormwater sewers. In all cases it is important that the location of the outfall is obvious to those with responsibility for maintaining the structures and the channels in which they sit. For large outfalls this is not a problem, as their size makes it impossible for them to be disguised. For smaller structures it may be appropriate to place a marker post of some sort above the normal water level, especially if the outfall tends to be underwater for most of the time. [Figures 8.17 and 8.18](#) show examples of a small and a large outfall respectively.

It is sometimes necessary to take samples from the flow emerging from an outfall to check for signs of pollution. This would normally be done when flow conditions in the receiving stream are relatively low. If pollution monitoring is a major consideration, the provision of safe access to the outfall pipe may be a significant design consideration, but in many cases this is not so.

Outfall structures into a large watercourse need to be protected against erosion of the bank. Often this involves the provision of a local revetment of dumped stone or other appropriate material. Large outfalls may require the provision of a security screen to prevent adventurous children from gaining access to the pipe, but under no circumstances should there be a screen at the outfall unless there is a screen at the inlet to the pipe or culvert.



Figure 8.17 Small outfall

This small outfall structure has been over-engineered. It serves a very small drainage area and discharges into a slow-flowing watercourse

The creation of an outfall structure was unnecessary in this case. A simpler and less expensive solution would have been to surround the drain outfall with stone revetment, avoiding the need for a reinforced concrete structure.

The flapgate (not visible in the photograph) is also unnecessary here as there are no raised defences along the bank top; in an extreme event the area will flood by overtopping rather than backing up the drains.

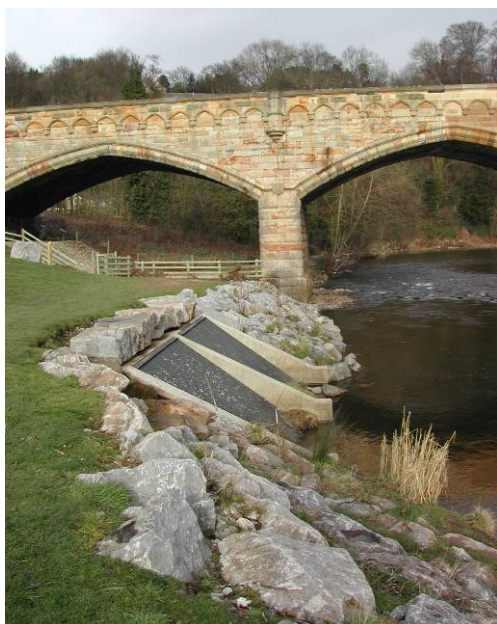


Figure 8.18 Large outfall

This is a twin-pipe outfall from a large stormwater sewer into a major river. The setting is environmentally sensitive, so the designers buried the structure in the riverbank and used locally available rock both to provide erosion protection and to help the outfall to blend in. Just upstream of the structure (not visible in this photograph) a mature tree on the riverbank has been preserved, with the erosion protection extending round it.

The outfall has been provided with a security screen as the location is at the foot of a public recreation area near to a school.

The outfall itself is of the US Bureau of Reclamation (USBR) impact type, with an inverted L-shaped concrete baffle positioned in front of each pipe outlet. This destroys much of the energy of the incoming flow (the pipes are very steep and fast flowing when the sewer is operating as a storm drain) and minimises the risk of erosion of the riverbed.

Where the velocity of flow exiting the outfall is likely to be high, some means of energy dissipation is necessary to reduce the risk of erosion in the vicinity of the outfall. This may take the form of baffle blocks on the apron, or an impact type stilling outfall can be adopted (USBR, 1973).

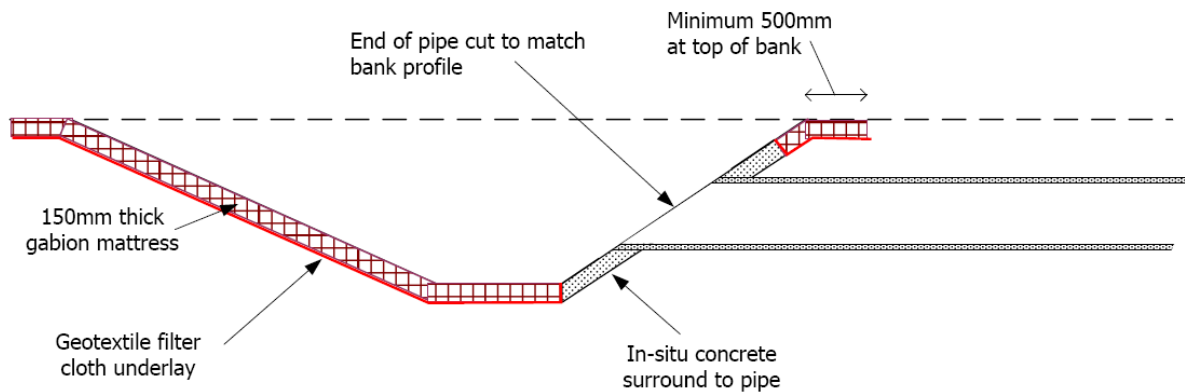
Outfalls do not have to be large and visually intrusive provided careful thought is given to the purpose of the outfall and the hydraulics (velocity, direction) of the flow (see [Figure 8.19](#)).



Figure 8.19 Outfall with low visual envelope

A diversion channel was excavated to replace a culverted reach of river, but this intercepted a 1050mm diameter surface water sewer at right angles.

The chosen solution for the outfall was to cut back the pipe to the bank profile and reinforce the cut end with a concrete collar. Gabion mattress bank protection was then installed on the bed and both banks for 2m upstream and 6m downstream. This has proved very successful in bankfull flows, with the flow being discharged from the culvert at least equal to that in the upstream reach of river.



Sometimes an outfall carries water of very different quality to that of the receiving water. In the case of a storm sewer this may be in terms of sewage pollution, although normally the impact of this is not severe because of the dilution in the sewer itself and in the receiving watercourse. Cooling water from a power station presents the particular problem of a large temperature difference between the incoming flow and the receiving water. As this can impact adversely on the ecology of the receiving watercourse, it is essential to evaluate this further, seeking specialist guidance as appropriate. The problem is likely to be most severe when the flow in the receiving watercourse is at its lowest.

In situations where the outfall could allow high water levels in the receiving watercourse to back up and cause local flooding, it may be necessary to provide a flapgate on the outfall (see [Figure 8.20](#)).

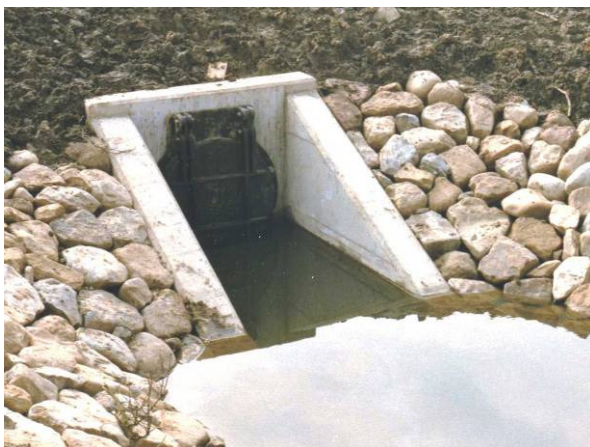


Figure 8.20 Flapped outfall

This simple outfall structure allows for the provision of a flapgate in order to prevent backing up of high water levels.

The concrete box structure is perhaps a little too narrow, as the flapgate could be wedged open or closed by small pieces of debris trapped between the edge of the flap and the face of the concrete. Note the use of hand-placed stone as a revetment. Although the erosion risk here is small, the revetment ensures that the excavated bank remains stable.

8.5.2 Intakes (water abstraction)

Anyone planning to take water from a watercourse must first seek approval from the Environment Agency from whom an abstraction licence is required. If the abstraction requires the construction of any form of structure in the river, land drainage consent is also required.

The construction of an intake structure allows abstraction of water at the required rate while at the same time excluding (as far as is practicable) sediment, debris and floating material. The best location for an intake to exclude sediment is the outside of a bend in the river. This is because the bend induces a rotational current in the river that results in surface flow moving towards the outside of the bend and near-bed flow (which is where sediment concentrations are highest) towards the inside of the bend. This fact is graphically represented by the formation of sand bars on the inside of a river bend. Unfortunately the rotational current also tends to draw floating material towards the outside of the bend, but generally this is easier to deal with than a heavy sediment load.

A screen can be used to keep coarse floating material out of the intake (with finer screens also excluding leaves and small trash), but there is a risk that this material will frequently block the screen, necessitating onerous cleaning arrangements. Floating trash is less of a problem where the rate of water abstraction is small in comparison with the flow rate in the river because the onward current tends to carry much of the trash downstream. Strong winds can also influence the movement of floating debris, especially when the current in the river is sluggish, such as upstream of a weir.

Most intakes supply water to a pumping station, which is why the exclusion of sediment and debris is important (to avoid damaging the pumps). For small installations – such as a pumped abstraction to deliver water to a farm reservoir – the intake works may be modest – the simplest being a fixed pipe attached to the riverbank. For industrial-scale intakes, such as for water supply purposes or for cooling water, a substantial structure is required. The intake structure commonly includes a control gate, so that the supply of water can be shut off; there is normally also a further gate or stoplogs to allow inspection and maintenance of the control gate. **Figure 8.21** shows a longitudinal section through an intake.

A major consideration in the design of any intake is the variation in water level in the river. Generally speaking, there will be a requirement to abstract water throughout the year and in dry years as well as in wet years – except when, for environmental reasons, the licence prohibits abstraction when river flows are very low.

Although unacceptable variations in river level can be corrected by the construction of a weir downstream of the intake, this brings its own problems – especially in rivers with a high sediment load. The most common solution in such cases is the provision of scour sluices in the weir to allow periodic flushing of sediment from in front of the intake. In this case, the design of the intake works and the weir becomes complex, requiring consideration of the movement of sediment and its entrainment in the flow, often with the help of physical and mathematical models.

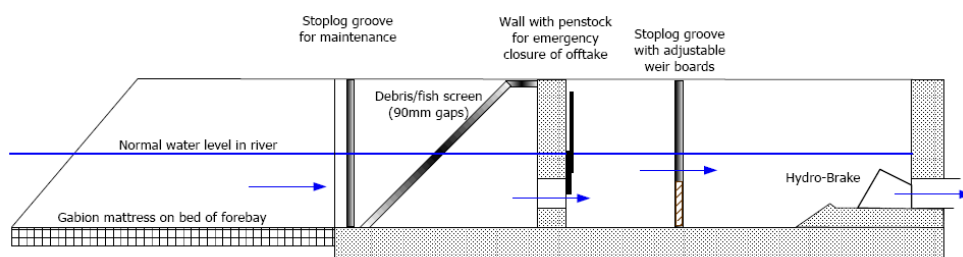


Figure 8.21
Longitudinal
section
through an
intake

The function of the penstock is to close off flow in an emergency or if not required. The adjustable weir boards prevent abstraction if the river level drops below a specified level. The Hydro-Brake® is an example of one method of limiting flows to the maximum permitted by the abstraction licence.

8.5.3 Service crossings

Services such as gas and water mains, sewers and telecommunication cables commonly have to cross rivers and streams. There are a number of issues to address with this type of work including:

- the need to avoid obstructing the flow (low or flood conditions), both during and after construction;
- the difficulty of construction work in the bed of a river;
- the need to protect the services from damage after construction or from erosion of the stream bed;
- the need to minimise the risk of pollution of the watercourse.

To avoid obstructing the flow, the best approach is to bury the service in the bed of the channel, below the maximum depth of erosion. This can be complicated and expensive, particularly for a large river or one that is used heavily for navigation. The service can be laid in a shallow trench, so it is just below the bed, but then it is essential to provide protection in the form of a revetment to avoid damage due to scour or impact. The route also needs to be marked clearly to avoid dredging activities in the vicinity.

An alternative is to attach the service to a nearby bridge, where it remains accessible and visible; although this may be considered to be a disadvantage in aesthetic terms and it may obstruct high flows in the river, as illustrated in [Figure 8.22](#).



Figure 8.22 Service crossing obstructions

This brick arch bridge has been widened by the addition of concrete piers with a concrete deck. The hydraulic performance of the bridge has already been compromised to some extent by the increased length (in the direction of flow) and the change in cross section (which introduces additional headlosses).

Services have been installed in the waterway area under the bridge. While the gravity sewer on the far side of this photo may be excusable (line and level difficult to change), there is surely no justification for setting the multiple ducts at a level that could severely interfere with flood flows, especially when they catch floating debris.

The most difficult service to deal with is probably the gravity sewer (see [Figure 8.23](#)), which has to follow a prescribed line and gradient. Using an inverted siphon to pass the sewer under the riverbed is an option, but one that is not liked by sewerage engineers because of the risk of blockage. But if the sewer is simply taken across the river at the required level, it is likely to interfere with the river flow at some stage, causing an obstruction and potentially gathering trash and debris.



Figure 8.23 Gravity sewer

This gravity sewer has an impact on all flood flows, even those that are well within bank (as illustrated in the lower photograph).

There is only about 600mm clearance between bed level and the underside of the pipe. This traps debris and a scour hole has formed.

Additionally, higher floods reach the bridge soffit level, and large debris can hit the edge beam and then rotate to go under the bridge. Unfortunately on several occasions such large debris has then been caught on the pipe, causing a severe blockage which has flooded nearby houses.

The normal dangers of removing such debris with a grab lorry are exacerbated when there is a live sewer of unknown condition involved.

8.6 Culverting of watercourses

8.6.1 General policy regarding culverts

Environment Agency policy is that no watercourse should be culverted unless there is an overriding need to do so. This is because:

- the ecology of the watercourse is likely to be degraded by culverting;
- culverting introduces an increased risk of blockage (with consequent increase in flood risk);
- it can complicate maintenance because access into the culvert is restricted (in some cases being classified as a confined space and requiring trained operatives and specialist equipment).

A blockage in a culvert can be very difficult to remove and likely to result in a severe flood risk. For these reasons the provision of a screen at the entrance to the culvert is often considered. Such a screen eliminates the risk of a blockage inside a culvert, but introduces a significant maintenance obligation (to ensure that the screen is kept clean) which far exceeds the typical maintenance requirements of an open watercourse.

Alternatives to culverting include:

- construction of a bridge – much lower impact on the watercourse hydraulics and ecology;
- constructing the infrastructure elsewhere – often not a practical option;
- diverting the watercourse – this has its own disadvantages but also some opportunities for environmental and hydraulic improvement;
- for small streams, constructing a ford.

8.6.2 Impacts of culverting

The culverting of a watercourse can have a many different impacts on the water environment including ecology, channel form, flow regime and chemistry. Table 8.3 summarises the impacts that need to be considered in the design of any new culvert in addition to the risk of blockage and impact on flood regime described above.

Table 8.3 Impacts to be considered in the culvert design

Aspect affected	Description of impact
Ecology	Culverts can be impassable to riverine fauna and can create barriers to the movement of fish. Culverting results in the loss of natural in-stream and bankside habitats through direct removal and loss of daylight.
Pollution	In urban areas, culverted watercourses are often highly polluted due to misconnected foul sewers, overflows from blocked sewers or discharges of contaminated surface water.
Morphology	Culverted sections may create or exacerbate downstream or upstream bank and bed erosion or promote sediment deposition, as a result of altered water velocities and disruption to the natural transport of sediment.
Restoration	Culverts can hinder future restoration options. This is particularly significant where urban development results in the burial of once open watercourses beneath housing or commercial centres, or where new development is placed on top of existing culverted watercourses which otherwise might be available for restoration.
Landscape and amenity	Culverting of urban waters leads to the loss and degradation of distinctive components of the local landscape. Culverting leads to the loss of green amenity space along river banks and reduced access for recreational opportunities such as angling, walking or canoeing.

8.6.3 Culvert design

In cases where culverting is unavoidable it is necessary to seek land drainage consent from the Environment Agency to allow culverting to go ahead. The Environment Agency scrutinises design submissions carefully to ensure all steps have been taken to reduce environmental degradation (or mitigate it) and to reduce the risk of blockage. Box 8.3 sets out the ‘golden rules’ of culvert design.

Detailed guidance on the design of culverts can be found in *Culvert design guide* (CIRIA, 1997). An updated version of this guide is expected to be published in 2009 as *Culvert design and operation guide*.

Figure 8.24 shows an example of good practice in culvert design.

Box 8.3 ‘Golden rules’ of culvert design

Size

Design the culvert to flow freely (part-full rather than surcharged) unless there are overriding reasons to do otherwise.

Choose a size that readily accommodates the design flow (for example, the 1% annual flood) with no appreciable increase in water level upstream. Allow for future development of the catchment upstream and for climate change effects (it is suggested that 20% is added to the estimated 1% flood to allow for this).

Adopt a single barrel in preference to multiple barrels, so as to present the largest possible waterway through the culvert and hence reduce the risk of large debris getting trapped inside it. Multiple barrels are acceptable for large watercourses and they have environmental benefits if one or more of the barrels is above normal water level (reduced sedimentation risk and provision of passage for mammals).

Length

Adopt the shortest length possible. Fish will migrate through a short culvert, but will be discouraged by a long culvert. The shorter the culvert the less likely are problems associated with blockage, and the lower the hazard associated with unauthorised or accidental entry into the culvert.

Invert level

The invert level of the culvert should generally be set lower than the existing bed level of the channel. This allows for any future regrading of the watercourse and also promotes the formation of a more natural bed through the culvert (which helps to maintain ecological continuity).

Trash and security screens

Avoid – only install in situations where the benefits significantly outweigh the risks (see [Section 8.6.3](#)).

Bends, steps, changes of cross section

Avoid – because they reduce the hydraulic efficiency and increase the risk of debris getting trapped.

If a bend is unavoidable, adopt a long gradual bend.

If the bend has to be sharp, provide an access shaft at the bend to afford easy access in the event of a blockage.

Hydraulic performance

Should be investigated for very high flows and low flows, as well as for the design flow.

If very high flows have the potential to overwhelm the culvert and cause flood damage, then options such as a flood bypass route should be considered.

Low flows should be examined from the perspective of watercourse ecology.



Figure 8.24 Urban culvert

This culvert has a simple inlet structure formed from a stone revetment. The approach channel is well-maintained and free from debris.

Although the culvert is close to houses, the potential hazard associated with children entering or being swept into the culvert is not considered to be serious enough to require the provision of a security screen.

The culvert is short, straight and of reasonable size, and therefore presents a low hazard rating. These features also mean that the culvert is unlikely to trap debris internally, so there is no need for a trash screen.

8.6.3 Trash and security screens

Screens serve two main purposes:

- reducing the amount of debris entering a culvert or inverted siphon (where it could cause a blockage);
- preventing unauthorised access into the culvert or inverted siphon (for safety or security reasons).

Regardless of the primary purpose, all screens accumulate trash and debris over time (see [Figure 8.25](#)), reducing the hydraulic capacity and causing the water level upstream to rise. The build-up of trash can be rapid, and the consequences can be severe in terms of flood damage to local properties and infrastructure. Many more problems have been caused by blocked screens than have resulted from blocked culverts. The Environment Agency therefore strongly discourages the use of screens and designers are urged to investigate alternative measures such as addressing the trash problem at source.



Figure 8.25 Even coarse screens can become blocked

This screen has been designed to exclude large debris, though it is clear that it has the potential to be obstructed by accumulations of mat-forming vegetation, which could otherwise readily pass through the culvert without causing any problems. No proposal to install a screen is acceptable unless and until the inspection and maintenance obligations (principally routine and emergency cleaning the screen) have been assessed and accepted by the responsible party.

Screens can also be used to trap coarse bed material (cobble and boulders) that might otherwise cause a problem further downstream. Such screens must be capable of being safely overtopped when blocked by debris. In Boscastle, for example, a coarse screen upstream of the critical areas traps large bed material before it can cause an obstruction at pinch points in the channel through the town. It is located at a point where any trapped material can easily be removed after the flood has passed.

Fully detailed guidance on screens can be found in *Trash and security screen guide for flood risk management* (Environment Agency, 2009). [Figure 8.26](#) shows an example of a well-designed screen.



Figure 8.26 Well-designed screen

This screen prevents unauthorised access into a long urban culvert. It also has to cope with trash and debris in the flow, so it has been designed in accordance with accepted practice for trash screens.

Note the two-stage screen arrangement, with cleaning platforms for each stage. Note also the additional flow capacity provided by the horizontal section of screen to the rear of the lower platform. Safe access has been provided and the whole site is fenced off to reduce the risk of vandalism. The site is provided with lighting to facilitate cleaning at night.

8.7 Temporary works

Many permanent works constructed in, over, beside or below rivers may require some form of temporary works – sometimes to support what is going on overhead, but more often to permit new works to be constructed in (relatively) dry conditions (Morris and Simm, 2000).

Temporary works may consist of:

- scaffolding – perhaps to work on or inspect the underside of a bridge or a river wall;
- a cofferdam along or across part of the river;
- a diversion of the flow along a temporary course while permanent works are being undertaken.

While achieving their primary objective of permitting new construction or repairs, temporary works must be designed not to restrict the flow of the river. Such a restriction may raise floodwater levels upstream and can also increase the flow velocities through the site – which can lead to scour of the bed, and potential destabilisation of both the temporary works and permanent works. Inadequately designed temporary works which fail can easily damage permanent works, especially if these are in a vulnerable part-completed condition.

Just because temporary works are only intended to be in the river for a short period does not mean they are not at risk from floods. The probability of a flood event equalling or exceeding the flow of a specified return period during the construction period is given as:

$$P = 100 - 100 \left(1 - \frac{1}{T} \right)^d$$

where: P = probability that the 1 in T year flood flow will be exceeded (%)

T = return period of flow in years – the inverse of the annual probability

d = duration of construction (years).

For example, if a contractor decides to construct temporary works at the 1 in 10 year flood level and the construction period is three months, the probability of overtopping during that period is:

$$P = 100 - 100 \left(1 - \frac{1}{10} \right)^{0.25} = 2.6\%.$$

This assumes an even distribution of flood flows throughout the year, which is not necessarily the case. Contractors and designers should note that, during a one-year construction period, there is a 1 in 10 (10%) chance of the 10-year flood occurring. In addition, the estimate of the peak flow in the 10-year flood could easily be under-estimated by 20%, such is the uncertainty surrounding hydrological statistics. [Figure 8.27](#) shows a cofferdam in flood conditions.



Figure 8.27 Cofferdam in flood conditions

This cofferdam on the River Tyne formed part of the temporary works for the A69 Haydon Bridge bypass. It was designed with the intention that it would be overtopped in flood conditions (illustrated).

It is important to check the impact on flood hydraulics of such works to ensure they do not cause excessive interference or scour. It is also essential to have flood warning systems in place so that labour, plant and materials can be removed from the cofferdam before it is flooded.

The type of temporary works adopted may also be influenced by the anticipated warning time of a flood. Small urban watercourses may have very little warning time in the event of a thunderstorm, so any temporary works must be able to withstand the flood at any time (day or night) and not worsen the flood risk. On the other hand, a large river such as the Severn is likely to have several days warning of a major flood, and so temporary sluices built into a cofferdam can be opened at the appropriate time, after all vulnerable plant has been removed from within.

Any works that take place in the riverbed risk disturbing silt. This is a form of pollution for which the contractor can be prosecuted. Method statements should be prepared (and followed) that minimise the risk of disturbing silt. Siltation is the main risk to fisheries, but any obstruction that increases velocities may impair fish passage upstream, and if fish are denied access to spawning areas at the crucial time of year the stocks may decrease in future years.

In small channels, appropriate silt traps may need to be installed just downstream. These must be maintained throughout the course of the works, as a silt trap that is full is no longer effective. Another option is to construct a temporary silt barrier across the stream. This can be formed from two layers of geotextile suspended from a floating boom (which can be made from 300mm plastic pipes with closed ends). The geotextile is weighted at the bottom to make sure it remains vertical. The whole apparatus is suspended between the stream banks in two or more overlapping rows, with gaps to allow fish passage. A more sophisticated device involves creating a bubble curtain from compressed air leaving a perforated pipe laid on the stream bed. The bubble curtain dissuades fish from entering a works area and can help to contain silt.

On navigable rivers, major works should aim to avoid the peak holiday season. If this is unavoidable, temporary works should be designed to accommodate navigation – with the attendant risks of boats striking the works. Additional temporary works that may be required in such situations include signage and fendering.

All the safety issues referred to in **Section 8.8** must be taken into account in temporary works. The aim should be to:

- minimise the need to work in, on or over water;
- prevent accidental entry into the water of those working on the temporary works.

The Health and Safety Executive (HSE) strives to discourage the need for operatives to be exposed to these risks by encouraging designers and constructors to adopt alternative systems or working methods (for example, making more use of precast concrete elements).

8.8 Health and safety

In a typical year, between 200 and 300 people are likely to drown in inland waterways and other water bodies in the UK. About half of these deaths are of people who did not intend to be in the water – they fell in from the land. Most of the fatalities were not work-related, but it is imperative that all concerned recognise the additional hazards posed by water, over and above the normal hazards posed by any construction site.

Should an emergency arise, the provision of permanent and durable signage at each river structure (Figure 8.28) will help those responding locate the site.



Figure 8.28 Where are we?

So that a site can be easily identified in an emergency, asset managers should provide each river structure with a sign with the name of the structure and its grid reference. This sign should be readily visible to the public and not just to operatives working on or near the water. It will then act as a hazard warning as well as providing vital information to the emergency services.

However, signing alone does not ensure the safety of river users. Wherever river engineering or improvement works are carried out, the safety of members of the public must be considered from the outset. Designs should take into account potential uses of the river and make sure that hazards are not introduced or worsened by the works, both during construction and thereafter. Particular activities such as boating and canoeing need special consideration (see Chapter 6).

Many river construction sites are at weirs where white water can be 60% air and 40% water. This mixture is not dense enough to support a swimmer, or someone floating, but the proportion of water is more than enough to drown someone.

Even away from white water and wearing a buoyancy aid, water poses a considerable risk. Still water conducts body heat 25 times faster than air, while moving water removes heat from a body even more rapidly.

Fast-moving water can sweep a person's legs from under them in even modest depths of water, especially if the ground is slippery or uneven. All works in the river should avoid personnel having to wade in fast-moving water either through the provision of appropriate temporary works or the adoption of a different method of working.

It is essential that:

- safe working methods are devised for all operations;
- all operatives should have undertaken safety training for working in or near water.

Water-based operations are particularly hazardous and a safety boat crewed by qualified boatmen with first aid training is likely to be essential. In addition:

- throw-lines and life-rings should be available at strategic points on the bank or the structure;
- grab-lines should be provided spanning the river downstream and anchored securely to the banks (as a secondary line of defence where a safety boat cannot operate).

The maintenance of steep banks can present a serious risk to the operators of grass cutting and other machinery. There have been deaths and serious injuries resulting from plant overturning and trapping the operator under the water. To some extent, this risk can be designed out by adopting wide crest widths and shallow bank slopes for flood embankments. Where this is not possible, maintenance procedures should be adapted to avoid unsafe practices.

It may be necessary to construct an access ramp (see [Figure 8.29](#)).



Figure 8.29 Access ramp

If plant cannot operate from the bank then it may be necessary to work within the river bed. It is then essential to provide safe access to and egress from the bed.

This concrete ramp allows plant to enter the shallow, concrete-lined river bed for maintenance work. It is needed because of limited access to both banks in the downstream reach.

No river work should be carried out by someone working alone. Inspections from the bank may be permitted, but lone working procedures should apply with a short call-in period to the monitoring base. A frequent check that a good telephone signal is available should be made, and the monitoring base should be informed of the location (including which bank) and the direction of travel of any lone worker.

A buoyancy aid should be worn and a purpose-made waterproof bag with a lanyard used for keeping telephone and car keys dry.

All river operations should have close links with both the Environment Agency flood warning service and the Met Office. In determining the risk at each site, it is important to:

- assess how quickly water levels can rise;
- prepare an evacuation procedure that will ensure that all personnel – if not equipment – are out of the river before conditions become hazardous.

Other risks from working in rivers relate to health, with leptospirosis being important. This disease may be present anywhere, and most commonly occurs from bacterial transfer via rat urine. It may also be carried by livestock (cattle, sheep, and deer). Although the risk is low, anyone working near water should carry a leptospirosis card and ensure that any medical practitioner treating them for flu-like symptoms is aware of their particular risk.

Silt that may have lain undisturbed on a riverbed for decades may contain contaminants that are harmful to human health. It is therefore recommended that silt samples are analysed and methods adopted to avoid any unnecessary bodily contact with the silt. This may mean closing the windows of excavator cabs and dumper drivers standing well clear when their plant is being loaded to avoid splashing.

Key references

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Provides a logical framework to assess the causes of bank erosion and then the options available to manage that erosion. The solutions range from 'do nothing' through fencing to 'soft' revetment and ultimately hard engineering but, by following the framework, an 'over-engineered' solution can be avoided.

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This comprehensive guide covers the hydraulic design of new culverts and the hydraulic analysis of existing culverts. It also has comprehensive coverage of the practical aspects of designing and constructing culverts. It is due to be replaced in 2009 by the *Culvert design and operation guide*, an extended and updated guide which will cover the management of existing culverts, including repairs and rehabilitation.

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