Restoration of Freshwater Pearl Mussel Streams
The Freshwater Pearl Mussel and its Habitats in Sweden – a LIFE Project

The freshwater pearl mussel is a fascinating species that is under threat. It is therefore important to put measures in place to ensure the long term survival of the species. This work also has greater dimensions; creating favourable conditions for freshwater pearl mussels also benefits almost all other species in the watercourse. The freshwater pearl mussel is a flagship species for aquatic nature conservation!

Sweden and other Scandinavian countries are home to a large part of the world’s freshwater pearl mussel population and we therefore have a responsibility for the species’ survival. The project lead by WWF Sweden entitled “The freshwater pearl mussel and its habitats in Sweden”, has run from 2004 to 2009, financed by EU’s LIFE fund, Swedish Environmental Protection Agency, WWF Sweden and the project’s partners. The partners were the County Administrative Boards in the counties of Kalmar, Västra Götaland, Örebro and Västmanland, Swedish Forest Agency, the City of Göteborg and Karlstad University.

The main aim of the project was to test different types of restoration measures aimed at improving the conditions for freshwater pearl mussels and its host fish. Measures were implemented in 21 watercourses. The practical experiences from the project (and other projects) are summarised in this handbook.

The main author is Erik Degerman from the Swedish Board of Fisheries, Institute of Freshwater Research; input and feedback has been provided by the co-authors.

Lennart Henrikson and Sofi Alexanderson
Project managers, WWF Sweden
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1. Introduction

Freshwater mussels – a threatened animal group

The population of freshwater mussels is falling worldwide and 126 species were on the IUCN (International Union for Conservation of Nature) red list in 2007. Almost all of the threatened species belong to the Unionoida order, i.e. large freshwater mussels. The freshwater pearl mussel family is generally threatened in the whole of its distribution area; in Central Europe, the population has fallen by 95 percent. The freshwater pearl mussel (Margaritifera margaritifera) is therefore classified by IUCN as “endangered”. The species is also included in the EU Habitat Directive (Appendices 2 and 5) and is therefore protected in the Natura 2000 system (the EU network of protected areas). The parasitic larval stage is dependent on brown trout Salmo trutta or Atlantic salmon Salmo salar as host fish.

Freshwater fish are also a group of animals that are generally threatened, particularly the salmonids, for which over half of the species are red-listed. The threats to freshwater affect large freshwater mussels in two ways, both directly and through their host fish. The environmental effects are thus intensified and accentuated.

The freshwater pearl mussel family is believed to be 200 million years old which makes it the most primitive of large freshwater mussels. The 12 species within the family are spread across the northern hemisphere, in colder water than other large freshwater mussels; they are holarctic species. Margaritifera margaritifera is found in Northern Europe and at a few sites in Spain, Portugal and France (Figure 1).

Scandinavia hosts many of the world’s remaining populations of freshwater pearl mussels. There are now 350–400 watercourses in Norway (Direktoratet for Naturforvaltning 2006) and 551 watercourses in Sweden with freshwater pearl mussel populations (Söderberg et al. 2008a). Scandinavia, and in particular Norway and Sweden, are host to at least two thirds of all known populations. These countries therefore have an international responsibility for the species’ long-term survival. Many of the Swedish populations are small and the current trend is of degenerating status (Eriksson et al. 1998, Schreiber & Tranvik 2005). In a comparison of the status of freshwater pearl mussels in Sweden between 1998 and 2008, the number of populations with recruitment was found to have fallen significantly (Söderberg et al. 2008a).

Freshwater pearl mussels have a complex life cycle with a parasitic larval stage, a long juvenile period (around 10 years) and poor mobility. This is compensated by a long lifetime, thanks to a low metabolism and a high reproductive potential. The mussels are dependent on flowing water, which ensures that food is transported to them on the current. However, this current also means that the mussels must have mechanisms to ensure that they always retain their position in the riverbed without being washed downstream. If the host fish disappear and the rearing habitats for the mussels deteriorate then the mussel population remains, with only older individuals. They are a silent witness to the water landscape’s deteriorating status, an indicator that things were “better in the past”. Only half of the Swedish watercourses that host freshwater pearl mussels have viable populations; this calls for action before it is too late.

In most of the freshwater pearl mussel streams small/juvenile mussels are lacking. If there is no recruitment the population will die. Photo: Lennart Henriksson.
By saving the freshwater pearl mussel, we are also saving other species

Systematic and painstaking work is needed in order to save the fascinating, but threatened, freshwater pearl mussel. It can take as long as 10 years after the implementation of a measure/s before it can be seen if reproduction has been established or not. It is only then that the juvenile mussels can be seen on the riverbed with the help of an aquascopoe.

It is very important to keep all stakeholders in the river basin informed – if they do not know that the freshwater pearl mussels are there, then they cannot be expected to show appropriate consideration. Information can be summarised in an action plan which includes both the parts of the river basin that are affected and the actual location of the mussel waters. Such an action plan is very suitable material for informing all stakeholders.

A methodical and strategic way of working

A landscape perspective is necessary to work with aquatic nature conservation; what happens in one place can have impacts on other parts of the water landscape. It is important to see the wider perspective!

The first step in developing an action plan is to assess the status of the freshwater pearl mussel population (viability). The next step is to identify the threats (Figure 2). Viable populations should be legally protected, in a nature reserve. When the population is not believed to be viable, that is, recruitment is not satisfactory, or the population is too small, then measures must be taken.

The measures can be directed at the mussels themselves or the host fish. If the threats can be removed then re-introduction of mussels may be possible. Artificial infection of host fish or rearing and releasing of mussels can be needed where stocks are weak. Follow up studies show whether a measure has had the desired effects.

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About this manual

This manual provides a background to the fascinating biology of freshwater mussels, their habitat needs, threats and, above all, practical advice for restoration of freshwater pearl mussel waters through measures directed at the mussels themselves and at host fish.

The manual is mainly based on Scandinavian experiences, in particular from WWF Sweden’s EU LIFE project “The freshwater pearl mussel and its habitats in Sweden”. The aim of the project was to develop methods for the restoration of watercourses with freshwater pearl mussels. Experience from other European projects (Henriksson 2009) has also been included.

Throughout the manual, we try to provide scientific references to support our advice. Some restoration measures do not have such documentation, but are nonetheless grounded in our own and others’ experiences.

Estimated costs for measures are also based on Scandinavian experience and may be very different in other parts of Europe.

Other handbooks about restoration work

The report “Restaurering av vattendrag i ett landskapsperspektiv” (Malm et al. 2007) provides an overview of the restoration of watercourses. The report identifies a number of myths about restoration methods that are important to note and also discusses conflicts of interest that can arise.

A comprehensive Swedish handbook on stream restoration has recently been presented called “Ekologisk restaurering av vattendrag” (Degerman 2008) which gives advice of different types of measures. This manual is a good complement to aforementioned manual. The Finnish handbook “Bäckar – levande landsbygd” (Jord- och skogsbruksministeriet 2008) is a beautiful and illustrative publication. The German handbook “Leitfaden Flussperlmuschelschutz” (Sachteleben et al. 2004) concentrates solely on mussels and is very comprehensive and detailed.

Three recently published reports on stream restoration in Scandinavia.

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**Figure 2.** Work plan to save freshwater pearl mussels including reference to the appropriate chapter in the manual.
2. The water landscape

Water in the landscape

Most people are aware of the large-scale water cycle, from precipitation to runoff, which occurs both on the surface and below the ground (ground water), flowing out into the sea. Approximately half of all precipitation evaporates directly, some is stored in the ground-water stores and the rest is runoff. The dynamics are driven by solar energy and gravity.

Only 2.5 percent of the world’s water volume is freshwater and only 0.01 percent of this freshwater is flowing water. Fresh water is unevenly distributed across the continents.

20 percent of Sweden’s land area consists of wetlands (lakes, watercourses, fens and bogs). Watercourses are estimated to cover a length of around 600 000 kilometres, which is 1.3 kilometres of watercourse per square kilometre of land area.

Catchment

The catchment is a central concept in the water landscape. The source lies high up in the river basin, with the stream growing in size as it flows downwards. From source to river mouth, the watercourse gradually changes form, increasing in width and decreasing in gradient. A watercourse is a product of the catchment, which is governed by ecological, hydrological and geomorphological processes.

Terraces

The upper parts of a watercourse are often steeply sloping and because of the water’s erosive power the riverbed is composed of coarser material: gravel, stones and boulders. On its path downstream the watercourse is terraced with short calm stretches broken by currents and rapids. The terraces take care of the large amount of potential energy in the water. The watercourse, together with low-lying floodplains and side channels, is an energy levelling system which stores water and moderates variations in water flow. A natural watercourse is very probably the most effective way to moderate the geomorphological energy in the water, but it also demands a lot of space. Watercourses must be allowed to take up space in the landscape.

Meandering

Meandering takes place in two planes – laterally (from side to side) and vertically (up and down). In steeper stretches of moraine soil (with a bottom substrate coarser than 2 millimetres in diameter) the lateral meandering is less pronounced, partly because gravity creates a straighter channel, and partly because coarser substrate has greater resistance to water erosion. Meandering in this landscape is therefore a sequence of shallow fast-flowing stretches and deeper pools, the terraced watercourse. Further downstream, the watercourse becomes wider, deeper and has a lower gradient. The bottom substrate is finer and the watercourse can carry the particles that dominate the bottom substrate (alluvial watercourses). The lateral meandering becomes more pronounced, for example, in the farmed landscape. The vertical meandering does, however, remain. In this region freshwater pearl mussels are often replaced by other species of large freshwater mussels.

The hyporheic zone

The riverbed has a shallow, superficial zone through which the water usually penetrates well, the so-called hyporheic zone. Structures in the water, such as stones and dead wood (large woody debris), and the water’s own meanders (vertical and lateral) enable water to percolate into the ground zone next to the watercourse and in the riverbed. A good flow of water through the hyporheic zone is required to support rich fauna. The zone is most clearly developed where the riverbed is made up of stone and gravel with little sedimentation.

THE HYPORHEIC ZONE

The hyporheic zone is an ecotone (a transition area between two ecosystems) in the water landscape; the hyporheic zone is where the surface water and groundwater meet. In this zone, salmonids lay their roe, the fauna is rich and the juvenile freshwater pearl mussels live, completely buried.
Littoral zone
The littoral zone (Figure 3) is the area between the low water mark and the high water mark. The zone is a bridge between land and water. It is another ecotone that is productive and rich in species. The littoral zone is characterised by the balance between dryness and flood, erosion and sedimentation. This zone is therefore distinguished as a system in change, with both rapid changes over time and great natural variation. Attempts by humans to control the flow in a watercourse result in a narrower and less varied the littoral zone. In general, it can be said that the littoral zone is smallest in the smallest watercourses. In small forest streams it can be very hard for the untrained eye to see the littoral zone, in particular in soils that are poor in nutrients. The forest often reaches right up to the watercourse and the littoral zone is marked by the presence of willow (Salix spp.) or hydrophilous tall herb fringe. The width of the littoral zone can be less than one metre. Along larger watercourses there is often a clearer littoral zone because of recurrent floods; the zone can be tens of metres wide.

Lakes
Most lakes in Scandinavia, Scotland, northern Russia and northern North America have been formed through glacial processes, mainly as a result of the most recent ice age. Lakes can also be formed through other processes, in modern times they have unfortunately been formed through the building of dams on flowing water. Several processes within lakes affect the water system. Many of them are related to the lake’s function as a water store. The most important process is probably the lake’s function as a sedimentation basin. Particles that are transported in the flowing water are deposited in the lake and the water that leaves the lake is clearer than the incoming water.

In addition to being a sedimentation basin, lakes can also remove nutrients from the water. Phosphor is deposited with particles and some nitrogen is released into the air. In the summer, lakes also store heat. Waters downstream of a lake are significantly warmer than those upstream. The heat is retained far into the autumn. Variations in water temperature are smaller downstream of a lake than upstream of a lake. Additionally, the variation in flow rates is smaller downstream of large lakes because they also store water. Finally, phytoplankton and invertebrates flow out of lakes. Downstream of a lake the water is cleaner, can contain a lot of food and fluctuations in water flow and temperature are smaller.

Figure 3. There several ecological interactions among the littoral zone an the stream. The width and the littoral zone may vary. Along unregulated rivers, like Vindelälven, it can be hundreds meters. Photo: Lennart Henriksson.
Hydrology and geomorphology

A certain quantity of water flows continuously from the groundwater stores and emerges as surface water on lower levels, in so-called outflow areas. The constant flow creates a base flow, a certain minimum water level that usually flows in a watercourse (Figure 4). During the growing season, the terrestrial plants absorb some of the precipitation and evaporation is greater. Less water percolates through and runs off. During periods with high percolation, extra groundwater flows into the watercourse. In addition, there is surface runoff in the upper ground layers. In Scandinavia, this is greatest when snow melts and in the autumn. One can roughly identify different periods as follows: high flow rates caused by snow melt in the spring (spring flood), high flow rates caused by heavy rain (storm flood) and low flow periods where the flow is dominated by groundwater (base flow). Low flows occur in late winter and high summer. These periods describe the dynamics of water transport through the year.

It can be said that the low water level limits the biological production in a watercourse. The annually recurring low water level is the limit for aquatic vegetation, invertebrates and fish. In the area between the low water mark and the normal high water mark, riverbank vegetation usually grows, whilst trees grow above the limit of the most extreme high water flow.

Whilst it is the low water level that usually determines the limits for aquatic life, it is the high flow that transports most nutrients and sediment. High water flow is important for biodiversity, e.g. by flooding the landscape which rejuvenates and maintains the banks. It also determines the form of the channel and transports the greater part of the sediment. Sediment is not only eroded from stretches of the river that normally has a gentle flow, it is also sifted out of gravelly and stony riverbeds. In other words, the high water flow can rinse the sediment from stretches of the riverbed, but it can also deposit sediment in calmer stretches.

The three main geomorphological processes controlled by water in the landscape are erosion, sediment transport and deposition. A watercourse can be seen as a system for transport of water, sediment, nutrients and organic material downstream. There is a close relationship between the quantity of water and the quantity of sediment that is transported. In a simplified form it can be expressed as (Gordon et al. 2004):

\[
\text{Quantity of sediment} \times \text{Particle size} = \text{Water flow rate} \times \text{Gradient.}
\]

From this equation it can be seen that the finer the particles and the greater the flow or gradient, the more sediment that can be transported. The watercourse can be said to be in equilibrium, or stable, when all four of these parameters are in balance. If more sediment of a given size enters the watercourse from the river basin at given water flow, then the gradient must increase, i.e. the watercourse’s erosive power must increase. If the gradient increases through straightening of the river, then the quantity of sediment and/or the particle size transported will increase.

Biodiversity consists of species, processes and structures

Biodiversity is a term that can be summarised as “the right species, in the right place and in normal numbers, with good genetic variation, in a good habitat”. But it is not just species that are included in the term biodiversity; structures and processes are also included. This manual for restoration of freshwater pearl mussel waters is to a great extent about recreating natural structures and processes. One example is the process of the supply of dead wood structures to a watercourse, a process that requires sufficient tree coverage in the riparian zone. This process drives other water processes (for example, the regeneration of suitable gravel and stone beds for freshwater pearl mussels). The hope is that when structures (habitats) and processes are recreated then the third component of biodiversity, species, can recolonise. Sometimes this proves to be the case, sometimes not. It is, however, well documented that the richness of species increases when environmental diversity increases.

The main focus of this manual for the restoration of freshwater pearl mussel waters is on recreating natural structures and processes.

The water landscape is a naturally dynamic and changing system. (Figure 5) Just as fires are an important natural disturbance in forests, high flows, ice, storm felling and subsidence are all examples of the revolutionary processes that are needed to maintain structures and species. River banks are formed both by floods and the passage of ice, which cause erosion and deposition; otherwise the banks would become overgrown and the diversity of habitats would be reduced. A natural watercourse is not static. The full scale of variation in the hydrological regime within and between years, with normal duration, time of occurrence, frequency and speed of change in flow, are critical to upholding the full natural biodiversity of the waters.

Changing flow levels through the year can result in erosion or sedimentation at one site. Many habitats therefore alter greatly with the seasons. The natural watercourse is a constant mosaic of shifting influences, an environment that is far from the channelized and regulated watercourse.

Variation and change are thus an integrated part of the water landscape. Even without any influence from mankind, the water landscape is not sta-
Connectivity
In addition to natural disturbances, connectivity is necessary to maintain biodiversity. Connectivity allows animals to access their natural habitat in its entirety. For aquatic plants and animals, connectivity is the ability to move freely in the water system. Loss of connectivity affects flora and fish fauna directly and thereby indirectly affects other aquatic fauna (e.g. large freshwater mussels, whose larvae are spread by fish).

Fish in streams and lakes travel over great distances in the space of a year. The very youngest stages may have a limited area within which they remain, but resident brown trout have been shown to roam 2–23 km within a watercourse over the course of a year, to spawn, in the search for food and to overwinter (e.g. Bridcut & Giller 1993, Meyers et al. 1993, Burrell et al. 2000, Ovidio et al. 1998). Fish need to migrate and seek out new habitats to grow, survive and to maintain genetic variation. Large freshwater mussels are therefore also dependant on a water landscape with free migratory corridors.
3. The biology and ecology of freshwater pearl mussels

The biology of freshwater pearl mussel

Freshwater pearl mussels are generally dioecious, that is, individuals are either male or female. In Scandinavia, females usually mature at 15–20 years but some mature individuals have been found that are only 10 years old (Larsen 2005). After maturity, the mussels continue to reproduce throughout the rest of their lifetime; there are very few old mussels that do not reproduce (Bauer 1987a). The largest mussels can be 15–17 centimetres in length (Figure 6).

Sperm and eggs mature during the spring and summer. The male releases sperm into the water in an aggregate (spermatozeugmata) in July or August or even earlier in warm summers (Hastie et al. 2003). The sperm cannot swim; they can only reach females that lie downstream. The sperm enters the female through the incumbent siphon and travels to the gills where the eggs are fertilised. The fertilised egg embryos develop over a period of 380–420 day-degrees (around 4 weeks) into mussel larvae, called glochidia, of around 0.07 millimetres in length (Hruska 2001). Mussels with glochidia in the gills are termed gravid. Normally 30–60 percent of individuals at a site are gravid (Young & Williams 1984a, Larsen 2005). However, a Norwegian study found that in some locations 80–100 percent of individuals were gravid (Larsen 2005) and it was proved that the mussels reproduce every year (Larsen & Berger 2009). Bauer (1987b) has shown that in larger populations the freshwater pearl mussel is dioecious, but that the share of females that can fertilise their eggs themselves (hermaphroditism) increases in sparse populations. A large female can produce several million glochidia annually.

The glochidia are released from the female mussel through the excurrent siphon (Figure 7). This is believed to be synchronised and to take place over a period of approximately two weeks, often in August or September (Larsen 1999), depending on the water temperature. But the release of glochidia larvae has been observed as early as the end of July. In Norway, gravid females have been found as late as October (Larsen et al. 2007b).

The released glochidia larvae open and close until they come in contact with the fish gills. Then they close once and for all. The larvae encyst in the gills (Figure 8) and initiate growth in the gill filaments which result in the larvae becoming embedded in the epithelium cell layer within the space of a few hours.

Since the larvae become encysted in the gills, they are subject to the host fish’s immune defence. And because the larvae are attached to the gills over a long period of time, the fish’s immune defence has plenty of time to react. Young fish, underyearlings, have not previously had contact with mussels. Furthermore, they possibly have thinner gill walls and are therefore easier to infect (Bauer 1987b). It is often the case that a fish that has previously been infected cannot function as host for any more larvae. This means that the glochidia that infect a previously infected fish have a much higher mortality rate in the parasitic stage than in the case of a first infection. The mortality rate of mussel larvae can even be high in fish that are infected for the first time (Young & Williams 1984b).
The host fish for the freshwater pearl mussel are brown trout and Atlantic salmon (Young & Williams 1984a; b, Larsen 2005). In Sweden, only brown trout has been observed as a host, but a number of mussel populations in the larger rivers can possibly use Atlantic salmon as a host, for example, the Rivers Lagan and Åtran on the Swedish west coast (Ingvarsson 2006). Norwegian studies have found both salmon and brown trout mussels (Larsen 2006). Salmon is the most common host fish in the large salmon rivers. Brown trout is the most common host in the smaller rivers and also upstream of the distribution of salmon in the larger rivers. It is not believed that salmon can act as host fish to freshwater pearl mussels above the salmon’s natural distribution in the Norwegian rivers (Larsen et al. 2000; 2002, Larsen 2004). This means that freshwater pearl mussels in a water system containing salmon are believed to use only salmon as host fish and that mussels found in waters with brown trout can only satisfactorily be served by brown trout. In Norwegian rivers with both salmon and brown trout as host fish, the “brown trout mussels” release their glochidia 3-8 weeks before the “salmon mussels” (Larsen 2002). In this far-reaching adaptation between the mussels and host fish, it is likely that only certain strains of host fish suit the mussels in a certain watercourse. Studies in Germany show that local strains of brown trout that coexist with freshwater pearl mussels worked best as hosts (Altmüller & Dettmer 2006, Buddensiek 1995). Similar observations have been made in Sweden (Söderberg et al. 2008a) and Norway (Marit Ladegaard pers. comm., Larsen 2009a) where it was concluded that different strains of brown trout differ in their ability to act as host fish to freshwater pearl mussels.

Temperature
Both the glochidia stage and the parasitic stage are dependent on temperature. In the Czech Republic and Germany it has been found that glochidia larvae at altitudes greater than 750 metres above sea level require around 1 350 day-degrees in order to develop into freshwater pearl mussels of 0.4–0.5 millimetres in length (Hruska 2001).

During the first 2–3 months after the larva has first encysted itself on the gills of the host fish growth is slow. Then the larva overwinters without any growth (Figure 9). In the period from April to June, when the water temperature increases, growth accelerates and the transition from larva to juvenile mussel is completed. Thus, the parasite stage lasts for 9-11 months, depending on the local climate, in Scandinavia and the Kola Peninsula in Russia (Larsen 2005, Ziuganov et al. 2000).

In May or June the juvenile mussel (which is then around 0.4 millimetres long) releases its hold on the host fish and floats on the current, finally ending up on the riverbed. Only those mussels that land on a suitable bottom substrate, sandy or gravelly substrates, have a chance of survival. The mussel normally lies buried in the riverbed for the first 4–8 years. This is probably an adapta-
tion to minimise the risk of being washed away and of being eaten up. The mussel also attaches itself to the substrate with a thread called the byssus thread; this helps to reduce the risk of being washed away (Figure 10). The period when the mussel is buried in the substrate is critical; as many as 95 percent of all juvenile mussels die during the first year (Young & Williams 1984a).

The vitality of the juvenile mussels that drop off the host fish is determined by the conditions during the parasitic stage on the host fish (Hruska 2001). Experience suggests that juvenile mussels should be longer than 0.36 millimetres and should grow 250 percent during the first summer, otherwise they risk death. Initially, growth is driven by food reserves, but quite soon the mussel begins to eat microscopic particles with the help of its foot. When the mussel is around 4 millimetres long the filter system develops (Buddensiek 1995). As they grow, the mussels gradually seek to move upwards towards the surface of the riverbed where the availability of food is better.

Growth

It is not clear exactly what the freshwater pearl mussel eats, but the list is likely to include bacteria, fungus spores, fine detritus, small phytoplankton and small zooplankton. It has been proved that the freshwater pearl mussel, like other large freshwater mussels, filters out small particulate organic matter from the water (Figure 11). It is most likely that relatively small particles (<40 micrometres) are generally preferred by freshwater mussels (Strayer 2008).

During the first few years of independent life, growth is relatively slow (1–2 millimetres per year). It then increases gradually, which results in a more or less exponential trend during the early part of a mussel’s life. When the mussels are 4–8 years old and have a shell length over 10 millimetres they start to become visible on the riverbed. Even large (adult) mussels can be completely buried in the bottom substrate. In a study of six Swedish watercourses, Bergengren (2000, 2006) found that on average around 20 percent of the mussel population lay buried. A study of freshwater pearl mussels in eight
Norwegian watercourses found that on average 34 percent of the population was buried (Figure 10, Larsen et al. 2007b).

Results from studies of mussel shells in Sweden show that a mussel with normal growth rate is around 10 years old when it reaches 20 millimetres in length and almost 20 years old when it reaches 50 millimetres (Dunca 2009a). Freshwater pearl mussels have a very long lifetime. The oldest known specimen was found to be as much as 280 years old (from River Görjeån in the county of Norrbotten, Sweden). The freshwater pearl mussel is therefore one of the species in the Swedish fauna that lives to be oldest and is the most long-living species known in the Swedish freshwater environment. It was previously believed that there was a clear correlation between the maximum age of a mussel population and the latitude at which it is located. But new results show that the rate of growth can vary greatly within a geographical area (Dunca 2008b) and that the maximum age does not show any strong correlation to the latitude as previously believed (Österling 2006, Dunca 2009a).

The freshwater pearl mussel in the ecosystem

As a living organism, the freshwater pearl mussel is a component of the water landscape and an important one at that! An adult freshwater pearl mussel can filter up to 50 litres of water per day (Ziuganov et al. 1994). The organic content is filtered out and the inorganic and inedible organic fractions are expelled again. Dense populations of freshwater pearl mussels can tangibly clean the water of particles. In the River Varzuga on the Kola Peninsula, 30–90 percent of the water volume is filtered by the mussels annually. The population of freshwater pearl mussels in this river is estimated to be 140 million individuals.

Consequently, freshwater pearl mussels excrete both inedible material, in the form of so-called pseudo faeces, and waste from feeding: faeces. The latter contains small particles, produced from larger particles, which can be used by invertebrates that are detritus eaters. The faeces also contain a nutrient solution for plants. The organic content in the flowing water is thereby conserved for use by the local ecosystem. Part of the organic content is however, retained in the mussel’s biomass, which can be a dominant constituent of biomass in the benthos over a long period of time.

The mussels are therefore part of the structure that actively retains the organic material in the flowing aquatic ecosystem, both by filtering and by increasing the heterogeneity of the riverbed and in that way acting as a particle trap. Thus, the mussel population provides the habitat with a source of food for a significant quantity of benthos (Strayer 2008). The increased heterogeneity of the riverbed also increases the active surface area, which may lead to increased production of salmonids (e.g. Ziuganov et al. 1994).

Mussels have datable growth bands, just like trees and it is possible to read not only individual growth seasons but even daily periodicity. There are therefore fantastic possibilities to use the freshwater pearl mussel as an environmental archive, indicating the occurrence of metals and trace elements throughout the mussel’s lifetime (Carell et al. 1987, Dunca & Mutvei 2001, Mutvei & Westermark 2001).
Superhabitat needs
A complex life cycle, a long life and the need for a strong host fish population places high demands on the mussels’ environment. The habitat can be divided into four components: super-, meta-, macro- and microhabitats. A short summary of the needs of freshwater pearl mussels on these four scales is described below.

The superhabitat of an organism is defined as the overall factors, in particular temperature and precipitation (e.g. water flow, risk of drought) which define the spread of the distribution of the species across the planet. It is very probably the climate that limits mussels to the northern and western parts of Europe, that is, areas with a predominantly oceanic (maritime) climate, without all too extreme winter and summer temperatures (Figure 1). Hastie et al. (2003) suggest the temperature interval for freshwater pearl mussels to be 0–25 °C. This temperature requirement has the result that mussels cannot survive in all areas of the Scandinavian peninsula. In the northern part of the distribution, recruitment of mussels is dependent on warm summers (op. cit.). Whilst the host fish brown trout is found at over 1 000 metres above sea level, mussels have not been found at altitudes above 575 metres above sea level in Sweden. In Norrbotten, in northernmost Sweden, the highest documented mussel population is at 430 metres above sea level in the Gällivare district. Smith (2001) believes that the distribution of freshwater pearl mussels may also be restricted at low altitudes because of competition from other large freshwater mussels. It is likely that lack of the correct host fish is a contributing factor in low-lying coastal areas because salmonids are replaced by other species in such areas.

Metahabitat needs
The term metahabitat refers to the distribution within the river basin. It is commonly observed that the distribution of mussels is uneven in a watercourse; some stretches seem to suit whilst other stretches which appear to have similar conditions do not suit the mussels. Generally, freshwater pearl mussels in Sweden are often found in the upper, narrower parts of the river basin, often with a stream order of 2–4. The gradient is often high and there is little sediment deposition. In the smallest watercourses there is a risk of drying out or bottom freezing, and consequently mussels are seldom found. There are a number of Swedish populations in the larger Swedish rivers, but the status of these populations is currently uncertain.

Flowing water
Without exception, freshwater pearl mussels live in fast-flowing habitats. The only areas of the River Pärälven in northern Sweden which have rich mussel populations are located directly downstream of large areas of rapids (Hendelberg 1960), which probably provide a better availability of food. On different spatial scales, large freshwater mussels seem to occur in areas of flowing water that provide protection against the most extreme water flows (Johnson & Brown 2000, Hastie et al. 2001, Howard & Cuffey 2003). Several studies of different large freshwater mussels have de-
scribed the negative effects of extremely high flows (e.g. Bolden & Brown 2002, Hastie et al. 2001, 2003, Kleiven & Dolmen 2008) which disturb the substrate. Hendelberg (1960) observed how mussels in strong flows were flushed downstream “with the foot stretched out”. Similar observations have been made in other Swedish waters (Grundelius 1987). In this way, mussels can accumulate in areas with moderate flow speeds or with better conditions, e.g. less acidic water (Henrikson 1996).

**Substrate**

The stability of the substrate is important (Strayer 2008) and is governed by the substrate’s composition, the extremes of flow and the gradient of the watercourse. The gradient in freshwater pearl mussel habitats commonly lies in the interval 0.08–0.3 percent (Skinner et al. 2003). This depends on the size of the watercourse; in small watercourses, larger gradients are necessary for good freshwater pearl mussel habitats.

**Forest prevents leakage of sediment**

It is favourable for the mussels that a large share of the river basin is forested because this has the effect that the water temperature is lower, the water flows are more moderate, the water-retaining capacity of the basin is higher and the risk for leakage of sediment and nutrients is lower (Figure 13). Swedish studies show that mussels often have better reproduction in stretches of water that lie downstream of lakes (Lundstedt & Wennberg 1995), ideally large ones (Söderberg et al. 2008b), i.e. areas where the water flow and temperature is stabilised and the quantity of sediment and organic material is lower. Areas with major sedimentation of silt and plant mass do not contain freshwater pearl mussels (Hendelberg 1960).

**Macro- and microhabitat needs**

The macrohabitat refers to the conditions for life within around 10–100 metres from the mussel site. The microhabitat refers to the conditions for life at the mussel site (0-10 metres). Generally, it has been possible to correctly predict where mussels will be found on a macro scale but rarely on a micro scale (Strayer & Ralley 1993).

Freshwater pearl mussels require a substrate that is stable. The site must also be a fast-flowing area without too much sedimentation, with a good supply of young host fish and with sufficiently low water temperatures. In addition, the risks of drying out and of freezing must be low. Whilst all these general factors are valid for all sizes of mussels, a certain amount of difference can be seen between the habitat needs of juvenile and adult mussels with regards to the substrate (Geist & Auerswald 2007). This difference is probably related to the size of the mussels; the risk of predation and of being washed away are lower the greater the size of the mussel.

The bottom substrate should also be stable on the macrohabitat scale. The stability of the riverbed is greater if it is composed of particles of varying sizes; this also facilitates good water flow in the hyporheic zone. Areas which are stabilised by larger blocks and which contain sand and small gravel make an ideal habitat for juvenile freshwater pearl mussels (Hendelberg 1960, Hastie et al. 2000a, 2001, 2003, Geist & Auerswald 2007). Such areas can have dense populations of mussels (Figure 14).

In contrast to most other large freshwater mussels, the freshwater pearl mussel lives in waters with low organic content, that is to say, areas that are poor in nutrients. Factors that increase the quantity of oxygen-consuming substances are usually negative for the mussels. The oxygen supply to the bottom sediment is critical and is governed by the substrate particle size and the quantity of fine particulate material (permeability), the quantity of organic material (oxygen consumption) and the water temperature (solubility of the oxygen). The share of fine-grained inorganic material (< 1 millimetre) in the bottom substrate should be below 25 percent in order for juvenile mussels to survive (Geist & Auerswald 2007, Ulvholt 2005, Österling 2006). The share of organic material should also be low. In the River Lutter, Germany, work has focused on measures that reduce sediment transport and deposition; in this way the project has succeeded in achiev-
It is important both on the meta- and macrohabitat scale that the area close to the watercourse has a high degree of tree coverage. The optimal habitat for freshwater pearl mussels has shade of 60-100 percent (Moog et al. 1993). The forest provides shade and thereby reduces the water temperature, which is an increasingly important factor the further south the population is located (e.g. Morales et al. 2004). But above all, forests reduce the growth of aquatic plants and filamentous algae. High plant production results in a large mass of vegetation that must be broken down, which can result in low oxygen levels in the sediment. Björk (1962) observed that freshwater pearl mussels are generally found in stretches without vegetation.

**Water quality**

The water quality should be such that the bottom does not become clogged or suffer from lack of oxygen, and that surplus production of vegetation does not occur. This implies that the watercourse does not transport large quantities of sediment. Arvidsson et al. (2006) found that in watercourses without mussel reproduction, the turbidity was on average 3.6 NTU whilst in watercourses with reproduction, it averaged 0.94. Söderberg et al. (2008b) suggested a turbidity limit of 1 FNU for watercourses with good reproduction of freshwater pearl mussels (Figure 15).

It is also important that the humus content is not too high. The quantity of humic substances affects how brown the water is. This is sometimes measured as water colour (mg Pt/l) and in Sweden an upper limit of 80 mg Pt/l has been suggested for recruiting populations (Söderberg et al. 2008b). The total phosphorus level should not exceed 15 µg/l in Swedish waters for successful reproduction (Lundstedt & Wennberg 1995, Söderberg et al. 2008b), whilst levels <30 µg/l have been suggested for British populations (Skinner et al. 2003). In Ireland it has been suggested that the total phosphorus concentration should not exceed 5 µg/l (Moorkens 2007). Based on the Scandinavian and Irish data, a guideline of 10 µg/l is suggested to ensure that a watercourse has good reproduction of mussels. Phosphor is the nutrient that limits vegetation production in freshwater and coastal waters and it is therefore the most important nutrient to keep a check on. Concentrations of nitrogen are often correlated to phosphorus concentrations. Nitrogen concentrations should not generally exceed 1 mg/l (op. cit.). In Ireland, it has been suggested that the median concentration of nitrate of 125 µg/l should not be exceeded (Moorkens 2007). Generally, the conductivity should be <10 mS/m (<100 µS/cm), but freshwater pearl mussels have been reported at higher conductivity. Geist (2005) states that conductivity is usually <20 mS/m.

Due to their distribution in the landscape, which is probably a function of the need for low sedimentation, the presence of Atlantic salmon or brown trout and of competition with other large mussels, freshwater pearl mussels are often found in relatively soft and weakly alkaline waters (Hendelberg 1960, Grundelius 1987, Geist 2005). A small number of populations have, however, also been found in calcium-rich water with pH...
well over 7.5 (Lucey 2006). In the Norwegian freshwater pearl mussel monitoring programme, the average pH in the watercourses varied between 6.5 and 7.7 (Larsen et al. 2007b). In Sweden, a mussel population exists at pH 7.7 in the river Harrån.

Acidification has damaged some mussel populations, either directly or through a reduction in the number of host fish (e.g. Dolmen & Kleiven 2004), and liming has resulted in better status (Henrikson 1996, Larsen 2006). A lower limit for pH is given as 6.1-6.3 and a low concentration of inorganic aluminium (<30 µg/l) (see Söderberg et al. 2008a), but adult freshwater pearl mussels can tolerate pH as low as 5 over short periods of time (Henrikson 1996). When conditions are poor mussels have a certain degree of mobility and can move to another place (Figure 16). Finally, it should be mentioned that many metals can be toxic for mussels, in particular, copper (Young 2005). High concentrations of metals and other environmental toxins have been found in waters with weak populations of freshwater pearl mussels (Frank & Gerstmann 2007).
5. Assessment of the mussel status

Background

A number of standards have been developed to assess the status of mussel populations. These are mainly aimed at assessing the size of the population and whether reproduction is taking place. The latter aspect is often assessed by digging in the substrate to find the very smallest mussels, whilst the Swedish standard, for example, is based on an ocular examination of the riverbed.

On average, 13-34 percent of individuals were buried during the summer in six Swedish mussel populations (Bergengren 2000); it was mainly the juvenile mussels that were buried. This factor often results in an underestimation of the share of juvenile mussels (Hastie et al. 2000b, Larsen et al. 2007b – see Figure 12).

It can be difficult to dig in substrate at locations with mussels, especially when one is trying to be careful not to disrupt the juvenile mussels. The upper layer is usually easy to dig in, but lower down the substrate becomes increasingly compact. The greatest depth to which one practically can dig was found to be 7 centimetres in a study of six Swedish watercourses (Bergengren 2000). The digging itself can result in disruption of the habitat, with increased erosion and siltation of fine material. Furthermore, it is easy to miss the very smallest mussels (<10-15 millimetres) because they are hard to see and they can easily get washed away on the current.

Studies indicate that some small (<20 millimetres) mussels can generally be found on the surface of the substrate if they exist at the site (Bergengren 2000, compare with Figure 10). Generally, the smallest mussels that are visible on the bottom are around 12 millimetres long and are around 4-8 years old in central Sweden (Söderberg et al. 2008a), but the age varies greatly in different watercourses.

The Swedish standard

The Swedish standard method for making an inventory of freshwater pearl mussels is based on observing visible mussels on top of the substrate with the help of an aquascope (Figure 17). A suitable stretch of the watercourse containing mussels is selected and 15 sampling stretches of up to 20 metres length are randomly selected. Within each sampling stretch the numbers of living and dead mussels are recorded and the population density and size is calculated. The lengths of randomly selected mussels outside of the sampling area are recorded. In the sampling area, the measurement of the smallest mussel found is recorded.

Costs

The Swedish standard for making an inventory of freshwater pearl mussels in a watercourse with 15 sampling stretches per watercourse takes around 4–6 days for two people the first time. Subsequent visits after 6 years are slightly quicker (Lundberg & Bergengren 2008). Additional costs are transport and other expenses. Total costs for the first visit are around € 3,500 per watercourse and around € 2,500 for follow up visits.
Criteria for a viable population

Håkan Söderberg and Oskar Norrgrann have developed a classification system for the status of freshwater pearl mussel population based on the number of mussels in the population and the share of the population that are juveniles (Table 1). The classification is based on length distributions in Scandinavian mussel populations where 2 centimetres corresponds to an age of around 10 years and 5 centimetres corresponds to an age of 20 years (Dunca 2009a,b). The share of juvenile mussels (<5 centimetres) should be at least 20 percent for a population to be considered viable.

The distribution into classes is based on Young et al. (2001), and on experience from studies in Varzuga (Bergengren et al. 2004) and has been presented at a national seminar on freshwater pearl mussels in Karlstad, Sweden (Arvidsson & Söderberg 2006). In total the status is divided into six classes, from viable to extinct populations.

Figure 18. A Viable population has a great percentage of small mussels. The slide calliper shows 10 mm. Photo: Lennart Henrikson.

Table 1. The classes of mussel population status according to Swedish standards (mussel status) (adapted from Arvidsson and Söderberg 2006, Söderberg et al. 2008b). The assessment is based on making an inventory of mussels visible through an aquascope.

<table>
<thead>
<tr>
<th>Class</th>
<th>Population Status</th>
<th>Population structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Viable</td>
<td>&gt;20 percent &lt;5 cm and &gt;0 percent &lt;2 cm (&gt;500 ind.)</td>
<td></td>
</tr>
<tr>
<td>2 Viable?</td>
<td>&gt;20 percent &lt;5 cm or &gt;10 percent &lt;5 cm and &gt;0 percent &lt;2 cm (&gt;500 ind.)</td>
<td></td>
</tr>
<tr>
<td>3 Non viable</td>
<td>&lt;20 percent &lt;5 cm or &gt;20 percent &lt;5 cm and &lt;500 ind.</td>
<td></td>
</tr>
<tr>
<td>4 Dying out</td>
<td>All &gt;5 cm, many individuals (&gt;500 ind.)</td>
<td></td>
</tr>
<tr>
<td>5 Almost extinct</td>
<td>All &gt;5 cm, few individuals (&lt;500 ind.)</td>
<td></td>
</tr>
<tr>
<td>6 Extinct</td>
<td>Documented presence that has disappeared</td>
<td></td>
</tr>
</tbody>
</table>

Hans Mack Berger monitoring the freshwater pearl mussel population in River Håelva, Norway. The river is included in the national monitoring programme of Norway. Photo: Bjørn Mejdel Larsen.
In a global and historical perspective, watercourses have served as the cradles of civilisation. Watercourses were transport routes, sources of power, water supplies and places to dispose of waste. They were also expected to be a source of food. The equation just did not balance and it still doesn’t.

Drainage

Ever since the Middle Ages, people have strived to drain the landscape. The building of ditches was required to meet the needs of a growing population and to facilitate agricultural development. At the end of the 19th century people also began to drain the land for forestry. Over time, larger and larger watercourses were modified to increase their capacity to drain the landscape of water. Rich habitats were ripped out of the watercourse and the channel was straightened. This drained landscape results in extremely high flows in the spring and extremely low water levels in the summertime. The extremely heavy flows erode the watercourse channels, with the risk that the sandy or gravelly habitats suitable for juvenile mussels may be washed away. The habitats in the deep and broad channels can be devastating for all forms of aquatic life during the extreme low water flows of the summer.

Obstacles to migration

Since the middle ages many mills have been built on flowing water. The number of water mills was often great, even on small watercourses; these mills and their millponds constituted obstacle for animal migration and for the spread of vegetation. The mills have been part of the landscape for a long time and are a symbol of the growth of industrial civilisation. At the beginning of the 20th century many mills were replaced by small hydroelectric power plants to produce electric current. Hydroelectric power has had an extremely negative effect on the hydrology, geomorphology and ecology of the water landscape. Fish have been unable to migrate past all the dams and dried out river channels that hydroelectric plants create. Natural fish stocks have been replaced through large scale stocking of degenerate individuals, a process that has become increasingly unsuccessful over the years. (The recapture rate of farmed sea trout in the River Dalälven in Sweden has fallen from 20 percent to around 2 percent over the last 50 years.)

Channelization and dredging

Timber has been transported on Scandinavian watercourses for several hundred years. The floating of timber is especially associated with the great breakthroughs in forestry during the 1800s. Different measures were taken on the timber routes to avoid the timber getting stuck. Side channels were closed off, the main channel was channelized and cleared of larger stones, boulders and dead wood and enormous stone and wooden constructions were built to channel and direct the timber. Holding dams were built in the side channels to collect water which could be used to help the floating timber on its way. Watercourses became channelized and important habitats, in particular boulders, disappeared (Figure 19); this also led to the disappearance of freshwater pearl mussels (Björk 1962).

Summary of the Threats to Freshwater Pearl Mussel

- Lack of suitable substrate. Channelization, dredging, water regulation and extreme flows due to wetland drainage all result in the washing or digging away of finer sediments, such as sand and gravel.
- The substrate becomes a poor environment for young mussels, with low oxygen levels and poor flow of water through the substrate. This is due to an excessive supply of inorganic and organic material.
- Lack of suitable host fish for the mussel larvae caused by fragmentation of the water system, low habitat diversity and fish stocking.
- Poor water quality caused by acidification, eutrophication, high turbidity or direct releases of toxins.
- Competition and predators can sometimes be threat.
- Pearl fishing has historically been a threat but is no longer judged to have a negative effect.

6. Identification of threats
Increased sediment transport
Over the last century sediment transport has increased by a factor of 100 in the rivers of northern Europe (Rippl & Wolter 2005) and the landscape has been deforested. The original forest coverage in Europe under the current climatic conditions was approximately 90 percent (Huntley & Birks 1983; Perlin 1989). Nowadays the forest coverage is estimated to be a little more than 30 percent (Mikusinski & Angelstam 2004). The loss of forest has had negative consequences for watercourses in the form of changes to headwater areas, increased water temperature, increased erosion, increased sediment transport and nutrient runoff from farmed land. In Latvia, freshwater pearl mussels only survive in watercourses in large forested areas (Rudzite 2001) and even in Sweden, there is a positive correlation between the share of land that is forested and how successfully the mussels reproduce (Söderberg et al. 2008b).

Mankind has always had a close relationship with water and influenced its form, function, flow, fauna and flora. In assessments of the ecological status of watercourses, based on the fauna (fish and benthos), it has been found that only four to seven percent of Swedish watercourses have high ecological status (Bergman et al. 2006). In Denmark, a similar assessment found that 2.2 percent of watercourses have preserved their natural geomorphological forms (Brookes 1984, 1988).

Figure 19. A dredged Norwegian watercourse containing freshwater pearl mussels. When the large structures are removed the water flow rate increases and finer substrate is washed away. Photo: Bjørn Mejdell Larsen.

Figure 20. Dead wood and large stones create a heterogenic environment in the stream Navarån, which hosts a viable freshwater pearl mussel population. The large structures create many microhabitats with substrates that are suitable for small mussels. Photo: Erik Degerman.

Specific factors behind weak recruitment in freshwater pearl mussels
Large scale change has taken place in the water landscape over recent centuries, as described above. For a complex organism such as the freshwater pearl mussel, it can be hard to identify specific factors in the environment that cause the weakness of a population. We know that most studies find large mussels which have many eggs. These “gravid” mussels release the glochidia and if the right host fish is available they become infected. However, juvenile (settled) mussels are rarely found on the riverbed. This suggests that reproduction is taking place, but that host fish and other factors in the period up to maturity of the settled mussel are impeding recruitment (e.g. Geist 2005, Söderberg et al. 2008a,b).

Deterioration in habitat – lack of large structures and dead wood
General changes in the habitat have been suggested as a reason for the weakness of populations in Ireland (Ross 1990). More specifically, channelization has been blamed (Alvarez et al. 2000). In Scandinavia, watercourses have been palpably changed by clearing to facilitate log transport and hydroelectric power production. This clearage work has often focused on the removal of larger structures such as stones and boulders. The riverbed structure has thereby become less diverse, with fewer suitable, stable habitats for mussels, and in general the flow rate has increased - the watercourse has become a canal. This higher water flow rate results in the washing away of finer substrate - sand, gravel and smaller stones – which are deposited in quieter waters. In this way the habitat of (in particular juvenile) mussels and host fish is destroyed. Dead wood serves a function similar to that of large boulders (Figure 20) and is now also commonly lacking in our watercourses. In Sweden, it has been estimated that in 90 percent of watercourses the quantity of dead wood is so low that it negatively affects the population density of brown trout (Degerman et al. 2004, 2005).

High water temperatures due to insufficient buffer zones and changes in the climate
Amongst the general changes to the habitat, alterations to land use are seen to be a negative factor, especially forestry (Figure 19, Cosgrove et al. 2000, Söderberg et al. 2008b). As shading is reduced, the water temperature increases. High water temperature can have a negative impact on the survival of juvenile mussels (Buddensiek 1995) and free glochidia live much longer at low water temperatures (<15 °C) (Akiyama 2007).

A wooded buffer zone not only provides shade, it also supplies organic material to the waters and stabilises the littoral zone. It is therefore common to find mussel populations in stretches of water in the vicinity of wooded buffer zones (Lucey 1993).

During the last 100 years the earth’s climate has become warmer which has had several negative effects on freshwater
pearl mussels such as increased water temperature and extremes of low and high flows (Hastie et al. 2003). The host fish, Atlantic salmon and brown trout, are cold water species and are both negatively affected by the warmer climate. In general temperatures above 25 °C and 28 °C are lethal for brown trout and Atlantic salmon respectively. The upper temperature limit for these species’ growth is below 20°C (Elliott 1994).

**Increased sediment transport and deposition caused by a poor buffer zone**

When the undisturbed buffer zone is lost, the transport of sediment to the watercourse can increase (Figure 21). The risk of sediment transport into the watercourse increases as the proportion of the drainage basin that is actively cultivated increases. There are often several local sources of the sediment, for example, road crossings, tree felling, wading livestock and an insufficient buffer zone between farmland and the watercourse. The increase in sediment transport in watercourses is a global phenomenon. In a comprehensive study of human impacts on the water ecosystem, Goudie (1993) suggests that increased sediment deposition on the riverbed is the most serious negative factor. Several studies have indicated that high levels of sediment in the water (measured as turbidity) and sediment deposition can be a reason that recruitment is not achieved in freshwater pearl mussels (Geist 2005, Österling 2006, Söderberg et al. 2008b). It is quite likely that water flow in the hyporheic zone is a critical factor; water containing food must reach the mussels, waste products must be removed and the oxygen levels must be good.

**Extreme high flows and low flows caused by drainage**

Both forested and farmed land is drained to increase the area of land that can be farmed. Drainage can cause an increase in the transport of sediment, nutrients and humus to the watercourse and affect the capacity of the soil to retain water. High flows become more extreme and low flows become lower. The enhanced high flows erode the riverbeds that are suitable for freshwater pearl mussels. Other reasons for extreme high flows are forest felling and an increase in the asphalted areas in urban areas. Extreme low flows have become more common due to ditch drainage and asphalting. Runoff is extremely fast and leads to very low flows in the summer months. As a result of this low water flow, the area covered with water becomes smaller, the quantity of particles transported decreases and the water temperature in summer increases. In winter, the risk that the mussels’ habitat freezes increases (see below under “Low water temperature and bottom freezing”).

**Changes to the hydrological regime caused by hydroelectric power**

Ziuganov et al. (1994) and Hastie et al. (2003) point to hydroelectric power generation as an important factor behind several weak mussel populations. The effect of hydroelectric power exploitation is also named above in connection to increased sedimentation and below in connection to fragmentation of the water landscape. In general, it can be said that stretches of a watercourse that are downstream of regulated dams and power stations are put under stress by variations in the water flow (Strayer 2008).

Successful recruitment in large freshwater mussels may depend entirely on the water transport in a specific year. It has been documented that recruitment was strong for the mussel *Fusconaia ebena* in years when a high spring flood was followed by relatively low water flows (Payne & Miller 2000). The high flow may have cleaned out the suitable bottoms and the low flows may have made it easier for the juvenile mussels to settle. When water is regulated for power generation, the natural flow situations are eliminated as far as possible.

**Low water temperature and bottom freezing**

Freshwater pearl mussels generally live in stretches of a watercourse that do not dry out and therefore do not freeze in the winter. However, in extreme conditions comprehensive mussel mortality...
has been observed during periods of extreme cold occurring early in the winter, before snowfall and before the development of a protective layer of ice. Around 10,000 dead mussels were observed in a watercourse in Västernorrland, in central Sweden (Söderberg et al. 2008a). At the same time, the population density of brown trout fell by 77 percent in the watercourses in that area (Hoffsten 2003). The brown trout population has, however, recovered very quickly (3–6 years).

### Pollution and eutrophication

Pollution is considered to be a negative factor for freshwater pearl mussels in several countries (Ross 1990, Cosgrove et al. 2000, Alvares et al. 2000, Bauer 1986). More specifically, eutrophication has often been identified (Buddenstien 1995, Akiyama 2007). Eutrophication leads to increased algal growth and more decomposition products collect on the riverbeds, leading to poor oxygen levels in the hyporheic zone. This adversely affects the buried juvenile mussels and even adult mussels, showing lower growth and survival rates.

Direct emission of toxic substances can also affect freshwater pearl mussels. In western Sweden a small population of freshwater pearl mussels in the stream Blomsholmsbäcken was wiped out by the use of pentachlorophenol for wood impregnation (Eriksen et al. 1986). Norrgrenn (2006) reported the elimination of freshwater pearl mussels on long stretches of Knipjtjärnsbäcken in Västernorrland, Sweden, downstream of a lake treated with rotenone.

### Increased humus transport caused by large scale changes

Humic substances can also contribute to the deterioration of oxygen levels in the interstitial water. The brownness of the water is mainly determined by the quantity of humic substances, i.e. decayed vegetation. Brownness is sometimes measured as water colour (mg Pt/l). Alternatively, the quantity of humic substances is indicated by the quantity of total organic carbon (TOC) in the water mass. Watercourses in boreal areas seem to be becoming browner; this is a phenomenon noted in large parts of northern Europe and North America (Chapman et al. 2005). The increase in water colour is likely to be caused mainly by climatic factors; higher summer temperatures can lead to greater plant growth. But exactly what the process is and how it works has not been clarified. The browner water could also be linked to the acidification situation or to land use (drainage, forestry) – or a combination of these factors and the climate (Chapman et al. 2005, Evans et al. 2006). Monteith et al. (2007) suggests that an increase in DOC (dissolved organic carbon) is linked to a reduction in sulphur deposition in recent years.

### Lack of host fish

Many of the factors that have a negative impact on mussels also affect their host fish. Small changes can have large negative effects since they affect both the mussel and its host fish.

Swedish studies show that at least 5 juvenile brown trout (0+) per 100 square metres are needed for a mussel population to achieve good levels of reproduction (Söderberg et al. 2008b). Only 28 percent of Swedish watercourses with non-anadromous brown trout populations have such a density of underyearlings (data from the Swedish Electric fishing Register, SERS 2008-08-31, n=27 865 surveys). Geist et al. (2006) claims however that brown trout underyearlings are not an absolute requirement; the greater capacity of older fish to carry glochidia can to some extent compensate if the older fish have not previously been in contact with the mussels.

Another change in water quality is caused by the long range transport of pollutants, namely acidification. It causes low pH and high concentrations of metals in the water (for example aluminium, which can flow out of acidified soil; Figure 23). This can have an effect on the mussels directly or on their host fish. Henrikson (1996) demonstrated that it is mainly the aluminium which causes mussel death at low pH. Adult mussels die at pH lower than 5, whilst host fish can be injured by pH in the interval 5.5–6.3. In Norway, acidification is considered to be reason that 94 percent of the freshwater pearl mussel populations in the most southerly region of Norway (Sörlandet) have died out (Dolmen & Kleiven 2004).

In general, surface water in northern Europe can recover from acidification when the precipitation of acidifying substances decreases. However, increased levels of humic substances counteract this recovery since they are weak organic acids.

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In general, surface water in northern Europe can recover from acidification when the precipitation of acidifying substances decreases. However, increased levels of humic substances counteract this recovery since they are weak organic acids.
Lack of host fish has also been pointed out as an important factor for freshwater pearl mussel populations in other studies (Grundelius 1987, Ziuganov et al. 1994, Cosgrove et al. 2000, Arvidsson et al. 2006). The optimal brown trout density, all ages, has been suggested to be 5–10 per 100 square metres.

But perhaps it is not the density of possible hosts that is most important, rather the total number of available hosts. Small and fragmented fish populations have little chance of giving rise to a dense freshwater pearl mussel population, which was shown by Strayer (2008) using a model for large freshwater mussels in general.

**Wrong species or strain of host fish**

In many watercourses attempts have been made to boost the host fish population by fish stocking, mainly with the aim of creating fishing opportunities in watercourses that have been affected by hydroelectric power production. It is not usually checked whether the stocked fish are of the right strain to suit the watercourse’s character and to interact with other organisms such as the freshwater pearl mussel. Studies suggest that some strains of brown trout can have higher resistance to infection by glochidia than others (Larsen 2009a), which is also indicated by differences in infection rate in different strains of brown trout by an upstream mussel population in Galtströmmen’s fish farm in Sweden (Söderberg et al. 2008a).

In Sweden, it is permitted to farm and release rainbow trout in watercourses containing native salmonids, even though it is well known that the rainbow trout can carry diseases and parasites that are lethal to the native salmonids. No consideration is made to the presence of the red listed freshwater pearl mussel or other naturally occurring species.

**Fragmentation**

Dams are considered to be the cause of weakening populations of several species of pearl mussels; *M. luvis* and *M. togakushiensis* in Japan (Akiyama 2007) and *M. margaritifera* in Scotland (Cosgrove et al. 2000). In Latvia, beaver dams have also been identified as a problem (Rudzite 2005). The main ways that the dams affect host fish are by impeding migration and by creating unsuitable habitats of still water with sedimentation and higher temperatures. Road culverts are also a migratory obstacle in smaller watercourses. Several examples of the negative effects of culverts on aquatic fauna are documented in Scandinavia (Degerman 2008).

In a study of the River Ljungan basin in Västernorrland, Sweden, it was found that 6 out of 25 freshwater pearl mussel populations were completely isolated from other populations due to man made barriers (Söderberg et al. 2008a). In general it is estimated that artificial migratory obstacles are located about every 2 kilometres in Sweden (Degerman 2008). Thus, the water landscape is extremely fragmented. The result is that there can be several barriers within the distribution range of a single freshwater pearl mussel population. In a study of the lower reaches of the River Ljungan, an average of 2.8 migratory obstacles was recorded per mussel population (Söderberg et al. 2008a).

The result of these migratory obstacles is that brown trout are unable to migrate to lakes, the sea or long stretches of still water in large rivers. This has the result that both juvenile and adult brown trout inhabit the same habitat and that the adults therefore claim resources that would otherwise have been used by the juveniles. This leads to a radical reduction in the share and quantity of juveniles. Since underyearlings are the most common host fish for glochidia, fragmentation of the water landscape results in fewer suitable host fish per unit area. In Swedish watercourses with river basins <1000 square kilometres, the median density of brown trout underyearlings (brown trout 0+) was 8.2 per 100 square metres in migrating populations, whilst in resident populations the density of underyearlings was 0.6 per 100 square metres (data from SERS, n= 30 913 surveys). In migratory populations, the potential host populations of underyearlings are significantly higher. The fragmented water landscape is therefore a threat to healthy mussel populations.
of studied watercourses (SERS). In 2006-2007, the figure was 10.4 percent. Since the spread of signal crayfish in Sweden is expanding (Degerman et al. 2009) and the populations are also achieving greater densities (Degerman et al. 2007), the effect of crayfish on freshwater pearl mussels can be expected to increase. Despite the lack of direct evidence of predation, it is recommended that signal crayfish should never be allowed to be introduced to a water system with freshwater pearl mussels.

Non-indigenous mussels
Non-indigenous mussels have not actively been introduced in Scandinavia, but are spread in ships’ ballast waters and via aquariums (Lundberg & Bergengren 2008). The zebra mussel (Dreissena polymorpha) has spread from the Black Sea to northern Europe and North America through ballast waters. It lives in entirely different habitats to the freshwater pearl mussel but it is not known which parasites and diseases may be transmitted. In North America, where the two species exist in the same habitat, the freshwater pearl mussel is disadvantaged by the presence of zebra mussels, probably due to food competition (Baker & Levinton 2003).

Pearl fishing
Finally, several studies suggest that pearl fishing was a major factor behind the decline of many populations (Ekman 1910, Young & Williams 1984a, Grundelius 1987, Ross 1990, Beasley & Roberts 1999, Cosgrove et al. 2000). The fishing of pearl mussels is now prohibited in the main distribution range of the species: Finland (1955), Norway (1993), Sweden (1994) and UK (1998). Nowadays, pearl fishing is almost nonexistent in Scandinavia and is therefore no longer considered a threat to the mussels.

How to study the main threats to Scandinavian mussel populations

Based on the summary above as well as Strayer et al. (2004), Direktoratet for Naturforvaltning (2006), Arvidsson & Söderberg (2006) and Söderberg et al. (2008a,b), a number of factors have been identified as posing a tangible threat to freshwater pearl mussel populations. Large scale changes to river basin areas due to the land and water use lie behind many of these threats.

Low oxygen levels in the hyporheic zone
1. Increased sediment deposition
2. Eutrophication & organic pollution
3. Increased levels of humus matter in the water.

Destruction of habitat
4. Changes to water regime (hydroelectric power, drainage)
5. Lack of large structures (boulders & dead wood)

Deteriorating conditions for the host fish
7. Loss of host fish
8. Fragmentation of the landscape
9. Acidification.

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Low oxygen levels in the hyporheic zone (1–3)
Threats 1–3 lead to a lack of oxygen in the hyporheic zone, which makes it harder for the juvenile mussels to survive. The effect of increased sedimentation of fine inorganic particulate matter or eutrophication and organic pollutants can be studied directly by measuring the redox potential or oxygen conditions in the bottom sediment (Geist & Auerswald 2007; Figure 25). The crucial information is whether there is a difference in the redox potential or conductivity between the free water mass directly above the bottom and in the hyporheic zone. In places where reproduction is good there is little difference between the two measurements (op. cit.). It is suggested that 10–15 transects are measured in the area containing freshwater pearl mussels. At least three samples should be taken at depths of both 5 and 10 cm in the substrate in each transect.

Redox potential is measured as the voltage between platinum and a solution

Figure 25. Upper picture: Jürgen Geist measures the redox potential in a Swedish watercourse, assisted by Håkan Söderberg and Askja Wittern. Photo: Andreas Karlberg. Lower picture: Close up of the equipment. This redox sensor can be bought from Elana – Bodenwasser monitoring (email: frank.kruyger@ufz.de). Photo: Håkan Söderberg.
of Ag/AgCl2. The measured redox potential should be corrected for temperature. A measured redox potential of 300 mV in the bottom substrate indicates oxygen rich conditions. Higher values indicate even better oxygen conditions.

It is also possible to measure oxygen levels in the field directly but this is generally more difficult and is not recommended.

The quantity of deposited fine material can be studied using e.g. a sediment trap or a sample of the bottom substrate.

Sediment deposition in the watercourse can be quantified with “sediment traps” placed in the gravel beds. A modified Whitlock-Vibert box (Figure 26), which is usually used for stocking spawning grounds with trout eggs (Whitlock 1977), can be used as a sediment trap. The boxes have the dimensions 145x90x60 millimetres. Canadian (Wesche et al. 1989, Clarke et al. 1998) and Swedish studies (Nyberg & Eriksson 2001, Degerman & Nyberg 2002, Österling 2006) have shown good results when studying sedimentation with this technique. Five transects should be measured per area of mussels. In each transect, 3–5 boxes are placed. This method is, however, considered less cost effective than measuring redox potential.

Undisturbed samples of bottom substrate can be collected with different types of sampling device (e.g. Geist 1997, Ulvholt 2005). Again, measurements of redox potential are recommended over sampling bottom substrate.

As an alternative to these methods, conventional water sampling in the free water mass can indicate the nutrient conditions (phosphor, nitrogen) and organic material (water colour, TOC), even in the hyporheic zone. However, sediment load should not be estimated from measurements of suspended material unless the measurement frequency is very high and measurements include periods of high flow.

Analysis of the landscape’s share of forested and farmed land and land use in the buffer zone using GIS can give a good indication of where problems related to land use can be expected (Söderberg et al. 2008b). However, this does not produce directly applicable and comparable measurement results.

**Destruction of habitat**

The lack of large structures such as boulders, large stones and dead wood has several effects on the watercourse and can cause loss of the finer bottom substrate such as gravel and sand. In Sweden, a standardised biotope mapping method has been developed which, amongst other things, provides a relatively detailed picture of the buffer zone, the riverbed, the occurrence of dead wood and the water flow rates (Read more about biotope mapping of watercourses at www.naturvardsverket.se).

Generally, the impact is judged on a scale from 0–3, where 0 indicates unaffected conditions and 3 indicates a strong effect. Regarding dredging, an impact of 1 is acceptable if the freshwater pearl mussel population’s status is good. If the impact is greater then measures should be taken.

**Deteriorating conditions for host fish**

Electric fishing surveys of host fish are an ideal way to establish whether this problem exists in a watercourse. Electric fishing is usually carried out by wading in rapids and it is in these habitats that both freshwater pearl mussels and the young stages of Atlantic salmon and brown trout are found. Electric fishing is not harmful to mussels (Hastie & Boon 2001), but there is a risk that the mussels are damaged by stepping on them, so the examination should be executed with care. Electric fishing should be carried out according to current standards, e.g. Bohlin et al. (1989) and Degerman & Sers (1999).

**COSTS**

A redox sensor costs about € 1 000.

The costs are estimated to € 1 000 – € 2 500 per 10 kilometre of watercourse.

Biotope mapping (Hallidén et al. 1997) is reported to take two people one day in the field for every 6 kilometres studied. General preparations and the interpretation of aerial photographs takes approximately one additional day. In addition, one more day is needed to compile results, input data and for quality control. In total, the work takes approximately four man days per six kilometres.

Electric fishing surveys cost about € 400 per area studied, usually a stretch of around 50 metres. Two people are needed for the survey.
In Sweden, large areas of land are set aside for the protection of sensitive countryside, but only a few of these areas include freshwater. One of the reasons for this may be that aquatic environments often have a complex combination of threats and that protection of the aquatic environment also requires protection of the surrounding terrestrial environment. Therefore, it may be necessary to protect an extensive area of surrounding land in order to protect one, limited, aquatic area.

Nature reserves
Nature reserves are currently one of the most important forms of protection for freshwater pearl mussel watercourses (Figure 27). These should cover the entire river basin, or at least large parts of it. This is often not possible in practice because forests (and other land types) in the river basin do not have the conservation value needed be included in a nature reserve. Reserves can be designed to ensure that the necessary protection is achieved at the same time as the rights of the landowner and the general public are met. Furthermore, specific rules can be established for the activities that take place on the reserve, and the landowner is often financially compensated for the inconvenience. Thus, the creation of a nature reserve is costly but effective. There are currently 11 Swedish nature reserves that are judged to give adequate protection for freshwater pearl mussels, out of 3 000 existing nature reserves.

Natura 2000
An alternative form of protection is the Natura 2000 system, i.e. the EU’s network of protected areas. There are around 100 Natura 2000 areas containing freshwater pearl mussels in Sweden. Often, it is only the watercourse itself, not the surrounding land, which is included in the protection because landowners do not receive any compensation within the Natura 2000 system. Furthermore, only some stretches of a watercourse are protected; areas upstream may be unprotected. In some cases Natura 2000 can provide adequate protection for a population (depending on which threats it faces). But in other cases, the system in its current form does not provide good enough alternatives to protect freshwater pearl mussel watercourses. It is often the case that some other form of protection is needed as a complement to Natura 2000, for example nature reserve status or biotope protection.

The Forestry Act and consideration rules
Many studies have shown that the most important areas to protect in order to maintain good surface water status are those close to the watercourse; areas further away from the surface water have lower priority. Other important areas to protect are those where ground water is formed, so-called subsurface inflow and outflow areas and sources. Negative effects at the source can accumulate downstream. This means that protection of a freshwater pearl mussel watercourse can be achieved through more limited area protection, e.g. regulation of the use of the buffer zone next to a watercourse and sensitive key biotopes. This method of protection (general rules of consideration) already exists in a general form in the Swedish Forestry Act (but such regulation does not exist in any form for agricultural land). It can be noted that this legislation, in its current vague formulation and application, has not been successful. The status of freshwater pearl mussels continues to deteriorate in Sweden (Söderberg et al. 2008a).

Three main principles
We recommend that preservation of freshwater pearl mussel watercourses follows three main principles:

- setting aside large parts of the river basin area as a nature reserve,
- better general rules of consideration for forestry and agriculture,
- water regulation should take the mussel population into consideration and a free migratory path for fish should be ensured.

Of course, it is not possible to protect all freshwater pearl mussel watercourses as nature reserves. But much better consideration should be shown in Scandinavia regarding land use. The general guidelines that we would like to implement are reflected in the following chapter. They require renewed and improved legislation and information activities.
All measures for freshwater pearl mussels are based on restoring the watercourse to its more or less pristine and natural state. We should not create new disturbances, nor believe that we can “improve” on nature. The interactions between the mussels and natural watercourses are millions of years old.

**Vision**

Before restoration work can begin, a vision should be developed for the watercourse (Figure 28, and also Figures 13 and 14). This can best be achieved by visiting an undisturbed watercourse of the same size and gradient.

Restoration should not be aiming to achieve a fixed, stable state; it should be aiming to reach a state where the natural processes maintain a dynamic and varied environment. Note that all restoration measures aim to restore, not to modify, a watercourse from its natural state.

It is also important to take the cultural environment of the watercourse into consideration. Restoration should cause as little disturbance as possible to the cultural environment. There are many examples of good collaboration between culture and nature conservation. Always make contact with the conservation authorities to discuss the cultural environment.

Of course, it is vital that land owners and other stakeholders are consulted before any measures are implemented. This consultation process and the legislation that applies to it in Sweden (The Environmental Code, Miljöbalken) are discussed by Degerman (2008). Always consult the relevant authorities before planning and implementing restoration measures.

Naturally, it is vital to check whether there are already large freshwater mussels or other protected aquatic fauna in the stretch of river where restoration measures are planned. If large freshwater mussels are present they should be moved (explained in the information box in the following page). Do not forget that permission to move the mussels must be granted by relevant authorities (County Administrative Boards in Sweden), according to national fishing legislation. Since freshwater pearl mussels are also included in the EU’s habitat directive, it is also necessary to seek an exception to this legislation.

In which situations is it necessary to remove freshwater pearl mussels before restoration work? It is difficult to give a general answer, but it is above all when
the work involves digging or driving vehicles in the watercourse, or when there is risk for increasing the turbidity of the water. When restoration work takes place in the littoral zone it is generally not necessary to remove the mussels. The fewer individuals present in the watercourse, the more important it is to remove the mussels. It is judged to be fairly simple to move the mussels when the population is below 500, but where the risk that the mussels are greatly affected is high, it may be necessary to move populations of up to 5 000 mussels (see the information box). Mussels can be temporarily stored in weakly flowing, shaded water for 10–20 days without mortality. For shorter periods (a few days), the mussels can even survive on land in cold and damp conditions.

Work in the watercourse, or other measures that increase the water’s turbidity, should ideally be undertaken at low water in June or early July. This minimises the risk that the turbidity spreads, whilst avoiding sensitive periods for the mussels. It should, however, be emphasised that it is sometimes necessary to accept short term disturbances to the mussels during restoration in order to achieve the long term positive effects of the measures.

It is important to try to limit the muddying of the waters because there is a risk that sediment deposition can occur in areas containing juvenile mussels. In addition to working at low water, it is important to think about how vehicles are driven in the littoral zone and in the watercourse. Never drive on soft bottoms where silt can be stirred up. When increased turbidity is hard to avoid one can try to limit the spread of the muddied water using booms, hay bales in the water, or similar methods (see Degerman 2008).
9. Measures in the river basin

Restoration measures in the river basin focus on hydrological restoration, measures that restore the landscape’s capacity to retain water and reduce sediment leakage.

This report does not discuss liming of acidified water. However, it is emphasised that liming activities are a prerequisite for the survival of many Scandinavian freshwater pearl mussel populations. In fact, work with Swedish freshwater pearl mussels first started with the liming of acidified surface water. During the inventory work in conjunction with liming, it was discovered that many of the freshwater pearl mussel populations did not have recruitment (e.g. Henrikson 1996, Eriksson et al. 1998). The positive effects of liming on freshwater pearl mussel recruitment have been proved both in Norway and Sweden (Larsen et al. 2006, Söderberg et al. 2008a) (Figure 31). In a summary of the status of Swedish freshwater pearl mussel populations, it was found that the status of populations in limed waters did not deteriorate, whilst the populations in waters without liming did deteriorate (Söderberg et al. 2008a). The shell growth improved significantly in mussels in limed waters in Västernorrland (Sweden) compared to shell growth in other populations (E. Dunca, pers. comm.).

Figure 31. The distribution of shell lengths in the River Ogna, in Rogaland county, Norway which was limed in 1991. Only mussels that were visible on the surface of the riverbed were counted. A gradually increasing share of small mussels demonstrates the effect of liming measures on mussel reproduction, and thereby also on the total population. From Larsen et al. 2006.
In Sweden, the total length of ditch drainage is longer than the total length of natural watercourses. Many of these ditches are cleared regularly in order to maintain their function – to drain water from the land. It is important to improve understanding and consideration in the forestry and agricultural sectors so that dredging of ditches is reduced. In Scandinavia it is illegal to clear a ditch deeper than to the bottom of the existing ditch. It is often also the case that a deeper ditch results in a decrease in tree growth.

- **Work at low water; the land can bear weight better and less sediment is flushed out.**
- **Do not clear any wetland through which the ditch passes. Do not allow machinery to disturb the ground cover in wetland areas. Otherwise there is a risk that humic substances containing methyl mercury are released.**
- **Wherever possible choose a small machine with caterpillar tracks and grab bucket, or another type of bucket that does not damage slopes.**
- **Ensure that slopes remain intact, with low gradient and preferably with vegetation cover. Otherwise, the ditch can give way, causing serious erosion.**
- **Avoid felling trees to improve access for machinery alongside the ditch. The trees suck up water and thereby reduce the future need for ditch clearance.**
- **In cases where trees must be felled, they should preferably be removed from the northern side of the ditch. If the ditch becomes exposed to direct sunshine it becomes overgrown more quickly and must be cleared more often.**
- **Try to clear selectively from agricultural ditches by removing only those sediment banks and vegetation that cause problems. Selective clearing of vegetation is recommended because it causes less disruption and even quite limited clearance work usually achieves good results. When 20–30 percent of vegetation is removed, the water flow increases by 50 percent of the amount that it would increase if all vegetation were removed (Thiel-Nielsen et al. 2005).**
- **Never remove the hard bottom from a ditch.**
- **The quality of the runoff water should never be worse than the criteria requirements freshwater pearl mussels (Chapter 4).**

**Suggestions for adjusted ditch renovations**

**MAKE A SEDIMENT TRAP!**

1. Allow the ditch to finish with a the water flowing onto wetlands or even dry land, not directly to surface waters.
2. If regular maintenance and oversight is possible, build a silt trap (Vandré 2006). Make the trap big enough to reduce the water speed (Figure 32). These traps are often best at ‘filtering’ sand, not finer fractions.
3. Create shallow areas of wetland to clear the finer particulate sediment from ditch water (Figure 33). Never build shallow wetlands in the watercourse because they become migratory obstacles for host fish.

**Figure 32.** A man made sedimentation trap in the form of a silt trap in a small ditch that flows into River Bränsån, Sweden, containing freshwater pearl mussels. Ensure that the shape of the trap’s bottom is suitable for clearing with an excavator. Cost approx. € 500. Photo: Håkan Söderberg.

**Figure 33.** A sand trap (left picture) and a fine sediment trap (right picture) built in a ditch that flows into the River Lutter, Germany. The traps are part of a comprehensive set of measures to reduce the sediment load, led by Reinhard Altmüller. Photo: Lennart Henrikson.
Blocking ditches – hydrological restoration

Any ditches that are no longer necessary for forestry and agriculture should be blocked off. This can be done with the help of a so-called “forwarder” in conjunction with other forestry tasks in the area (Figure 34). Alternatively, the measure can be undertaken manually; a plug made of pulp wood and soil works well (Figure 35). Manual work is generally only effective in small ditches, 0.5–1 metre wide. Ideally, several plugs should be built in each ditch with a maximum water fall of 10–20 centimetres between plugs.

The plugs will rot away with time. In general, the sediment that has meanwhile accumulated usually causes the ditch to be blocked. By covering the plug with geotextile the lifetime and efficiency of the plug can be improved.

Of course, hydrological restoration must take into consideration the landscape perspective. There are often certain ditches that are more important to block than others. But naturally, decisions must also take land use into consideration. Caution should be taken in blocking ditches in sandy and silty soils because this can lead to increased erosion of fine particles into the surface water. A geotextile should always be used in these conditions to prevent particle transport.

COSTS

Using a guideline value of two man hours per plug, it can be estimated that each manually built plug (Figure 35) costs around € 40–80.

If a forwarder is used (Figure 34), the time taken is around 30 minutes per plug and the cost is of the same order of magnitude as for a manually built plug.
Freshwater pearl mussel waters in Europe

River Lutter, Germany
Photo: Lennart Henriksson

River Our, Luxembourg
Photo: Lennart Henriksson

Stream Strikjupe, Latvia
Photo: Lennart Henriksson
Shade in the buffer zone reduces the solar radiation that reaches the watercourse and thereby reduces the water temperature, prevents the watercourse from becoming overgrown with vegetation and stabilises the banks so that unnatural erosion is reduced (Figure 36). Furthermore, trees and other plants supply the watercourse with nutrients in the form of leaves, which are eaten by benthos, that are, in turn, eaten by fish.

**Establishing and maintaining a buffer zone**

The buffer zone is defined as the littoral environment along watercourses and lakes and the dry land which directly affects the surface water. Since the ecological function of a watercourse is affected by shade, deposition of organic material and the soil’s filtration of several components (sediment, nutrients, water) above the high water mark, these are also included in the buffer zone. The width of the buffer zone can vary greatly according to the area’s topography, the size of the watercourse, the hydrological regime, the geomorphology of the water channel, the groundwater level and to what extent the vegetation in the forest and on the banks affects the water through falling plant material and shade. The buffer zone can therefore be as narrow as a few metres or as wide as several hundred metres (see Bergquist 1999). Despite the great ecological importance of the buffer zone as a habitat for plants and animals and its importance for the watercourse, the littoral zone (riparian area) is the ecosystem that is most commonly disturbed by human activity (Nilsson & Berggren 2000, Nilsson & Svedmark 2002, Swift 1984). The most important step in maintaining and designing the buffer zone is to establish which functions it must meet and then to decide how wide it should be, in other words the width and design should be sufficient to constitute a buffer zone against negative impacts from human activities. Since many buffer zones should meet several functions, the term ecologically functional buffer zone has been developed. This is defined as a zone that is sufficiently wide to create good ecological conditions in the water, in the littoral zone and on surrounding land to enable species that are dependent on close proximity to surface water to survive (Henrikson 2007).

Here, we focus on shading the watercourse, stabilising the littoral zone to ensure that sediment transport is reduced, and limiting the flow of nutrients. Measures aim to benefit from the leaves that deciduous trees generate for the watercourse, which make up the base for many food webs. Coniferous, and to some extent deciduous trees, are also important for supplying dead wood to the watercourse. An ecologically functional buffer zone based on these criteria can generally be established with a 10-30 metre wide corridor alongside the watercourse. In steeper terrain, especially on fine-grained soils, the whole of the slope down to the water must be protected. The protection can be achieved through better consideration from forestry and agricultural stakeholders, and through the development of nature conservation agreements, biotope protection and nature reserves.
Maintenance of an existing buffer zones in forest land

An ecologically functional buffer zone on forested land should resemble a natural buffer zone in terms of the plant habitat. It is often made up of a mixture of tree varieties, including deciduous (Figure 36). There is usually also variation in the height and age of vegetation (low plants, shrubs, bushes and trees). Regarding the age composition of trees, dead and dying trees should be left standing in order to emulate natural forest. It is often recommended to exclusively favour deciduous trees and eliminate planted spruces (Figure 37, 38). The leaves from deciduous trees constitute an important energy source to forest brooks and also counteract soil acidification. However, it is also important to retain large spruces because dead wood from spruces lasts much longer in water and can thereby compensate for the low supply (in terms of volume) of dead wood.

It is generally not necessary to perform any maintenance on the buffer zone; it should be left to develop freely. In some situations, for example when the buffer zone is made up of densely packed spruce forest and lacks variation in age, height and tree variety, thinning and clearing may be necessary.

It is often discussed whether a buffer zone needs to be intact along the full length of the watercourse. It is likely that in the past the landscape was dynamic due to fires and storm damage, which created openings in the natural riparian zone. Furthermore, certain sections of the watercourse may naturally have a lower share of tree shade and bushes. So a few openings in the buffer zone is not necessarily negative. However, letting in more light can encourage the primary production of algae. Therefore, if the freshwater pearl mussel population is under threat then the buffer zone should be kept intact.

Maintenance of an existing buffer zone in agricultural land

In general, buffer zones in the agricultural landscape nowadays are often an untouched grass embankment. A stratified buffer zone with trees, bushes and ground level cover increases the uptake of sediment and nutrients. If thinning or clearing of bushes or trees is necessary in the buffer zone it may be appropriate to save plants with berries or important sources of nectar and pollen in order to increase the richness of species. Examples of species to save are sallow, sloe, hawthorn, roses and blackberries. Trees whose leaves easily decompose should be favoured, for example grey alder, common alder, wild cherry, elm, lime and ash. In all other respects, the recommendations given for forested land also apply, that is, to aim for natural variation in age and species composition.
Creating a new buffer zone in forest land

A new buffer zone should ideally be established through natural regeneration, but to speed up the process, deciduous trees and bushes can be planted. The aim should be to recreate the buffer zone that would naturally have existed in the local conditions. Along watercourses and lakes that regularly flood, the littoral zone benefits from deciduous trees (e.g. alder and downy birch) and bushes. If flooding occurs less frequently then a greater the abundance of silver birch, elm, lime and spruce is appropriate. Pines grow in dry buffer zones. These factors mean that it is important to take the current and future water level fluctuation into consideration when establishing a new buffer zone.

The simplest method is to let the forest in the buffer zone regenerate naturally through the seeds and cover trees left standing after felling, or by allowing the existing trees in the area to grow. Pines are suitable for areas with moist conditions, even those that are sensitive to frost. However, the survival relatively low due to competition from other vegetation and the risk of seed trees getting blown down. Spruces have the additional risk of spruce bark beetle. In general, pine is not recommended, in particular because it is very dominant, which can lead to a single species population.

In order to ensure strong regeneration, certain deciduous trees such as alder and ash can be planted. Pine can be used in drier areas. Planting is expensive, but has a more reliable result than self seeding. Of course, planting or sowing seed is necessary when introducing new species in the area; of course, the planted species should be among those that naturally occur in the area but that have been disadvantaged by recent land management. Seek the advice of forestry experts and plant nurseries.

- A new buffer zone is most easily created by natural regeneration in the areas closest to the water.
- Whilst the new buffer zone is getting established, only gentle regeneration methods should be used, such as shelter wood, self regeneration or manual plantation.
- During felling and other forestry activities, save any small, naturally regenerated saplings, even if they appear to be in poor condition. When given space, they can often grow into fine trees.
- Suitable species for planting manually, closest to the water in healthy soil, are grey and common alder. Pine is suitable for drier patches. Willows and downy birch are also good alternatives closest to the watercourse.
- Plants that have been chemically treated against pine weevil should not be planted in, or close to, surface water.
- No mechanical ground preparation should take place in the buffer zone.
- If conifers are planted (pine), they should be planted sparsely. This allows a strong root system and thick trunks to develop, which reduces the risk of windthrow.
- No machinery should be used in the buffer zone within 20 m of the surface water. Never drive in areas with groundwater outflow or swampy areas. In areas with lots of grass, it may be necessary to clear grass around the plants for the first 1–4 years.
- During summer droughts it may be necessary to water very dry and exposed areas.
- Animal grazing is a problem for most plants, with the possible exception of alder. It is very expensive to put fences around the plants, but protection in the form of plastic piping or plastic spirals may be worth considering.

Creating a buffer zone in agricultural land

Work should be taken in several steps. The first step is to set aside sufficiently wide buffer zones between the watercourse and the fields and to sow grass on these areas. The next step is to plant bushes and trees in the buffer zones. After that, it is possible to create small wetland areas (habitat for fauna and nature’s own water treatment system) at suitable locations within the buffer zones, close to the watercourse. In order to achieve an ecologically functional buffer zone there should be a variety of vegetation in several strata (grass, bushes and trees).

When creating a grass embankment between the farmland and the surface water, it is easiest to sow nutrient “catch crops” in the spring.

The low vegetation in the buffer zone should be allowed to develop naturally, but in areas with prolific vegetation due to nutrient leakage it may be necessary to harvest the vegetation to reduce the risk that it gets washed into the watercourse. The plant nutrients in the soil will gradually deplete over time and the buffer zone will contribute more to self-cleansing. The harvested grass can be used as fodder. Should one instead choose to allow livestock to graze in the buffer zone, it is important to have comprehensive fencing to keep livestock away from the water. It is also important that the animals do not access the land when it is damp, e.g. late autumn. The buffer zone and floodplain can become overgrown with reeds or bushes if there is no grazing, depending on how moist the soil is. However, grazing is a difficult measure to manage due to the risk of overgrazing and erosion. Many watercourses in the agricultural landscape currently have heightened erosion due to grazing. Internationally, the most common restoration measure in the buffer zone is to fence off grazing livestock.
Figure 39. A buffer zone created along a watercourse in agricultural land. Photo: Erik Degerman.
Minimising unnatural erosion close to the surface water

Erosion is a natural process in a living watercourse. However, erosion has increased greatly due to hydroelectric power generation, changes in land use and drainage. When the erosion in the water system is unnaturally high it must be addressed, mainly through tackling the primary causes.

If the erosion has been allowed to take place for a long time and is unnaturally high, it may be necessary to protect the littoral zone from the erosion. This can be done using a number of different techniques:

1) indirect methods,
2) shaping the littoral zone,
3) reinforcing the littoral zone,
4) fencing off sensitive areas,
5) consideration in forestry and agricultural activities to avoid damage from the driving of vehicles.

1) Indirect methods are ways of redirecting water from sensitive stretches by placing structures in the water. Large stones or dead wood can be used (Read more in Degerman 2008).

2) The risk of erosion and subsidence can be reduced by shaping the littoral zone, in particular through changing the slope gradient. The floodplain is an element that has to a great extent disappeared from the landscape. In such low-lying areas close to the watercourse, the high flow can spread itself out, sometimes for several months at a time. Wading birds flourish in the littoral zone, as do all sorts of vegetation, from sedge to high grass, which take care of sediment and nutrients. In many cases the floodplain disappeared when agricultural watercourses were regulated or deep channels were dug with embankments around. At the same time, erosion and sand transport increased in the watercourse. In an agricultural landscape, every running metre can contain hundreds of kilos of eroded material, mainly sand.

The function of the littoral zone as a habitat and filter can to a certain extent be restored through enabling the creation of wetland by flooding. Try to find locations where the high water can be made to flow out and remain in the floodplain (Figure 40). The floodplain must be broad enough and the slope must be shallow enough to cushion the water’s energy. This results in a greater habitat, a larger area for self-cleansing and sediment control.

Suitably formed floodplains function as wetland meadows, which are alternately flooded and drained. The wetland meadow acts as a pump. In drained, oxygen-rich conditions organic material is oxidised and ammonia compounds are nitrified (oxidised via nitrites to nitrates). In oxygen-poor conditions, the nitrates are converted to nitrogen gas. The cycle is repeated for each period of dry then wet conditions. The periodically flooded floodplain has a great capacity for self-cleansing and furthermore high biodiversity; it is a natural element of the landscape.

3) The littoral zone is often reinforced with large stones (Figure 41). This often gives an unnatural appearance and should be disguised where possible in the landscape. A low row of stones built on the river bank or a suitably placed piece of dead wood often suffices. A compact grass embankment, preferably stabilised with trees, is often the simplest and cheapest protection. Fibre blankets, for example made from coir, are attached to the land and can be sowed with grass seeds. The greatest difficulty can sometimes be attaching them securely. If the river bank is higher than around 2 metres a landslide analysis should always be undertaken.

4) Grazing cows that trample on the edge of streams can cause considerable turbidity and sediment transport (Figure 42). In a watercourse with good recruitment of freshwater pearl mussels in Västernorrland (Sweden), a farmer was given financial support for measures to keep cows out of the brook. A total of 600 metres of fencing was raised to stop the cows from trampling in the water, and a bridge was built to allow the cows to cross the watercourse (Karlberg 2006). Another way to reduce turbidity is to make the bottom of the watercourse solid in the area where the livestock trample (Figure 42). In general, fencing off the littoral zone to avoid trampling by livestock is the most common way internationally to reduce erosion (Figure 43).

5) Damage from driving vehicles often occurs when felling takes place on land that is not frozen. This can be avoided by using machinery with low surface pressure, felling when the ground is frozen or very dry, planning the driving route to ensure that the softer areas are avoided and by a variety of measures to spare the land, e.g. laying out wood constructions (Figure 44). Special light, transportable bridges for forestry vehicles have also been developed in Sweden. The bridges are made of steel, can be transported on forestry vehicles and may quickly be adjusted to suit the watercourse.
Figure 41. Bank protection in the River Viskan (Sweden) reduces the risk of subsidence and reduces the sediment transport in the watercourse. Note that natural erosion should be permitted. This watercourse has freshwater pearl mussels both upstream and downstream. Photo: Erik Degerman.

Figure 42. The bottom of a watercourse in Südsiche Regnitz, Germany, has been hardened with concrete to minimise erosion from trampling animals. Photo: Lennart Henrikson.

Figure 43. Livestock have been prevented from drinking from the watercourse by fencing (Anlier, Belgium). Instead the animals drink from water pumped up using solar cells. Photo: Lennart Henrikson.

Figure 44. Damage caused by forestry vehicles during felling results in increased sediment transport and increased mercury concentrations in the watercourse. Wood constructions may be used on sensitive soils or as bridges. The cost for one element is € 150-200. Photo: Lennart Henrikson.
Large structures

Large structures such as boulders are nowadays in short supply in the water landscape due to human influences. Hendelberg (1960) observed that large boulders stabilise the bottom and provide mussels with shelter from high flow rates. The same observation has been made by others and it is not only large boulders that stabilise the bottoms; even larger stones, piles of stones and dead wood have a stabilising effect. Host fish and other natural fauna and flora are important for species diversity. By placing large stones in the watercourse, new microhabitats are created with different properties, for example, the accumulation of finer fractions behind or in front of large stones or boulders.

Before starting to return large structures to the watercourse it is important to make an inventory to find out the degree of habitat disruption that has taken place. Generally, a lot of stones can be returned to the water from the edges of the watercourse. Sometimes stones are found piled up in stone jetties and piers. Even stone-lined edges and piles of stones can be of cultural environmental interest. The stones should not be moved before discussing with the authorities responsible for the cultural environment.

The very biggest boulders have usually been broken up and removed. Originally, there may have been boulders of up to two to three metres in diameter. If it is clear that the watercourse used to contain large boulders then it is important to recreate this environment, even if the measure is expensive.

Placing boulders and stones in the water

If the stones and boulders that were cleared have not been discarded close to the watercourse, then it is necessary to transport new structures to the site. Research is needed to find a quarry with boulders, stones and gravel of the right dimensions. The material must then be transported to the watercourse and stored temporarily in an appropriate place. This requires research and scouting of the area.

The decision whether to work manually or using machinery is dependent on the size of the watercourse, the possibility to drive up to, and into, the water, the natural availability of material and the scale of the work. Manual work is common in watercourses with widths below three to seven metres, especially when the measures need to be undertaken with great care, or when it is difficult for heavy machinery to access the area (Figure 45). But in general, excavators are to be recommended from cost and efficiency perspectives. If it is possible to drive machinery to the watercourse, and even into it, or if large structures need to be moved or dug up, then an excavator should be used (Figure 46).

Distribute the boulders and stones randomly, but in areas with natural rapids the stones should be placed in a way that reinforces them. It is important that groups of stones are not too densely packed. The water must be able to flow through the piles; this creates good environments for freshwater pearl mussels.
between the stones and the structure has a more natural appearance.

It is generally best to place out stones during periods of low water. This helps to ensure that the position of the stones does not lead to sediment deposition in the target area at low water levels. It is also easier to move in the water at low water and the structures that are established can be seen more easily. Furthermore, it can be difficult to position the stones firmly during periods of high water. And it is normally the case that stones placed in the watercourse have greatest effect on the water flow at low water. At high water, the bottoms curb the flow of water less. So it is easiest to see the effects of the stones on the water flow at low water. When working with larger structures, groups of boulders and heavy steps, in larger watercourses, work can sometimes be done at the normal water flow level, but it is often necessary to make adjustments later at low water.

Try to use stones and boulders of the same size as those that would originally have been found in the watercourse. Look at the river banks, the surrounding terrain or a reference watercourse.

If you are unsure, the structures should be dimensioned for the expected highest water flow rate to ensure that the large structures do not get washed away (read more in Degerman 2008). However, do not deliberately over dimension the structures. In general it is not a problem if there is some degree of movement.

Start work at the upper end of the stretch of watercourse and gradually work downstream. In this way you can see how the water flow structure changes as you work; you “take the water with you”. By gradually working downstream the quantity of stones and the height of structures can be adjusted in order to achieve a pronounced fast-flowing channel, or ideally several such channels.

Generally, a few of the larger structures such as boulders should be allowed to stick up above the water level at normal water levels.

Ensure that the stones are firmly secured in the bottom. Large stones and boulders should be placed with 1/3 of the stone submerged in the substrate. When the structures are secured in this way the aim is that finer material will settle around to the large structure.

The larger the watercourse and the steeper its gradient, the more stones and boulders that should be placed together in a group. Stones and boulders placed in groups are more likely to result in pools than when placed separately. The greatest effect can be gained from structures in a watercourse above 0.5 cubic metres per second as an average flow rate. In small watercourses (average flow rate <1 cubic metres per second and a gradient below 2 percent) stones can be placed individually.

When placing a group of boulders or stones together it is often a good idea to try to place the larger boulders together with a hole in the middle and then try to create suitable substrate for freshwater pearl mussels between the boulders and stones.

**Supply of dead wood**

The term dead wood is used to describe entire tree trunks, bits of trees or thicker branches where the life functions have ceased and the wood has started to decompose. It is usually specified that the pieces should be at least 0.5-1 metres long and at least 10 centimetres in diameter. The trunks and branches that end up in the water usually grow within 15–20 metres of the water. The trees may have died due to windthrow, drought, fire, parasitic attack, erosion of the river bank, natural aging and occasionally forestry activities. In some regions beaver activity can also be a factor.

**Dead wood fulfills several functions in a stream or lake:**

- creates a more varied environment, e.g. bottoms suitable for juvenile mussels
- forms a “reef” that can be colonised by algae and then by different benthos
- creates sheltered microhabitats for invertebrates and fish
- can help to stabilise the river banks by breaking the water flow and waves
- creates pools downstream, or erosion of river banks
- retains organic material and sediment
The function of retaining sediment, for example sand and gravel, means that dead wood can be important to freshwater pearl mussels, even if this has not been documented. Dead wood is an important large structure, especially in stretches of watercourse which have few large stones or boulders.

The dead wood should be collected from the local area, but not from the buffer zone (unless it is, for example, a spruce that needs to be removed to support deciduous trees; Figures 37, 38). Trees in the littoral zone are otherwise important to leave alone so that they can fulfil their function by providing shade, leaves and soil stability.

Conifers generally last longer in the water than deciduous trees. Conifers can survive for decades or even centuries. Pines survive for a long time, especially slow growing pines that have died standing and have then become dried out by sun and wind. The disadvantage of fresh conifers is mainly that the needles are initially relatively toxic. Fish do not usually collect around newly felled pines or spruces and the effects on mussels are currently unknown. It is therefore not recommended to place dead trees with needles on in stretches of the watercourse with mussels.

Some deciduous trees, such as oak and alder also last a very long time in water, whilst birch quickly rots away. Naturally, it is also the case that larger (thicker) pieces of wood last longer because the decomposition takes place on the outer surface of the wood. Larger trees have a greater volume relative to surface area. In addition, larger trees are less likely to be pushed around by the water and therefore less physically affected by the water.

In general it is said that dead wood should only be used in watercourse restoration when it can be left there permanently and when it affects the flow of water (read more in Degerman 2008). Do not place dead wood all over the watercourse as a routine measure. The fewer the natural stones that remain, and the more uniform the bottom is, the greater the need for dead wood. Dead wood is especially useful when placed close to the floodplain where it can divert water over the floodplain, or when placed above an island to stabilise the river banks and to divert the water flow. It is also especially useful in places where the water flow is sufficient for the dead wood to create erosion of the bottom and can retain sand and gravel for mussels.

Studies in the USA have shown that “digger logs”, i.e. complete trees that are placed in the watercourse with the root system remaining for stabilisation, were the most cost effective way to increase habitat diversity for fish in flowing water (Figure 47). Trees placed in this way also proved to last a long time. Wrench the tree from the ground with its root system with the help of an excavator or scooter. The root system provides good anchorage. It is also possible to use cables and a tractor with a front winch to pull the tree into the water. Wait for the needles to wither away on land before placing the tree in the watercourse.

Figure 47. Dead wood is a natural component of streams. It has several ecological functions, e.g. hiding places for young brown trout. Photo: Lennart Hemkaon.

PLACING DEAD WOOD

Placing dead wood in the watercourse should be considered a temporary measured undertaken whilst waiting for a natural buffer zone to be established. Before any wood is placed in the water, an analysis of the possible consequences on the water system, the littoral zone, outdoor activities, property and other installations should be made.

Guidelines when placing dead wood in the watercourse:

- the wood should mainly be placed in stretches that lack a natural supply of dead wood
- the need depends on the variation in bottom topography and substrate; the more uniform the conditions, the greater the need for dead wood
- avoid areas that are steeply sloping (5 percent) or where the bottom is composed of large boulders
- in waters wider than one tree length (10-20 metres), only trees that are well anchored in the littoral zone should be used.
- trees should be placed in the water over a period of years so that there is variety in the aging material.
- there should be variety in the dimensions of the material used, but thicker dimensions (>30 centimetres) are rare and should be prioritised.
- if it is important that the wood remains where it is placed, the length of the wood should be somewhat longer than the width of the watercourse at high flow.
Habitats for juvenile mussels

Juvenile mussels require stable riverbeds with suitable substrate (sand, gravel and small stones) in flowing aquatic environments. Such habitats have declined rapidly because of the clearing of watercourses. Shallow areas with somewhat weaker currents than the main channel are important for the juveniles of many aquatic species, including the freshwater pearl mussel, which prefers stable substrates that are not exposed to a low water level.

These shallow areas can be created by adding coarse or fine structures to the watercourse. It is always important to stabilise finer substrate (sand, gravel, small stones) with larger stones and boulders, and ensure that the fine substrate is varied. Uniform gravel is too mobile. Chapter 12 provides more details about how to establish such areas. In general, it can be said that riverbeds that are suitable for mussels have the same characteristics as spawning grounds for brown trout and Atlantic salmon, but with a somewhat higher share of gravel or even coarse sand in the fine sediment.

It is important to try to avoid adding very fine material to the watercourse, which could clog up the hyporheic zone. If possible, the finest fractions should be washed away on land before the stones are placed in the watercourse. A simple solution is to leave the piles of gravel to stand by the watercourse for a month or two before use, so that they are washed by the rain.

Björklund (2006) described the riverbed suitable for juvenile mussels to settle in, created in the River Vramsån in southern Sweden. One hundred tons of gravel was laid down in 15–40 centimetre thick layers in three areas, covering a total of 350 square metres. The fraction size was 4–100 millimetres, where 20 percent was 4–16 millimetres, 70 percent was 15–50 millimetres and 10 percent was greater than 50 millimetres. A follow-up report has not yet been published.

In the LIFE watercourse called Rastälven (Grängeshytteforsen), 40 cubic metres (70 tons) of gravel was spread out over an area of 240 square metres with the aim of creating a habitat for mussels and a spawning ground for brown trout (Figure 48). The work took three days for four people to achieve. The labour cost was around € 5 800, the gravel cost around € 2 000 and the machinery and driver cost around € 1 600. The total cost was around € 9 400, or around € 4 000 for 100 square metres of riverbed.

Measures to reduce sediment load

Measures to reduce sediment load should generally take place in problem areas, often in the buffer zone (see chapter 10). If it is not possible to reduce the flow of sediment then sediment traps can be created in smaller watercourses (Figures 32, 33). Sediment traps are essentially pits dug in the watercourse that are so large that the water flow rate is reduced and the sediment is deposited. Sediment traps and silt traps normally require regular cleaning and should therefore be situated in places that are easily accessible to an excavator and lorry/dumper truck. The length of the sediment trap should be several times longer than the width of the watercourse. The watercourse should be widened and the depth should be considerably greater than the normal bottom depth.

When the cause of high sediment transport has been addressed, the bottom will be rinsed clean after a number of high flow periods. In some watercourses, however, water regulation ensures that there are no high flow periods and it may be necessary to take extreme measures in order to ensure the survival of the juvenile mussels. In the LIFE project “freshwater pearl mussels and their habitats” a manual clearance of the riverbed in the Bratteforsån watercourse was undertaken (Figure 49). Similar measures were performed in a watercourse in Südliche Regnitz in Germany. The substrate was removed using an excavator and placed in a container where it was washed clean of sediment and returned to the watercourse.
In general, restoration of flowing water is beneficial to mussels, fish and other fauna. So even if a measure focuses on the host fish, Atlantic salmon and brown trout, the measure will also benefit freshwater pearl mussels. The techniques used to improve reproduction of host fish and to create free migratory paths are presented below.

**Spawning grounds**

Salmonid spawning beds, i.e. the bottom where roe are deposited, should provide protection to the roe during the winter months - from being washed away, frozen or eaten by predators. The bottom should be stable enough that it does not move; otherwise it could crush the roe. Furthermore, there should be a good flow through the substrate so that fresh water can flow in and particles and waste products are flushed away. The needs are the same as those of juvenile freshwater pearl mussel on their first habitat. The reestablishment of spawning grounds for salmonids are therefore also beneficial to mussels both directly (by creating new habitat) and indirectly (by leading to more young host fish).

There are several methods for recreating and restoring salmonid spawning grounds, described in more detail by Degerman (2008). In this manual only the most common methods are described. These methods deal with returning suitable substrate to the watercourse and stabilising the substrate.

We would like to stress the importance of carefully assessing the areas that will be dug up or covered with spawning substrate (chapter 8). Dense populations of large freshwater mussels should not be disturbed. Sparse populations without recruitment can be moved by hand before the work begins and returned afterwards.

There are two main methods for establishing a spawning ground: the substrate is either placed in a hole dug in the riverbed or placed next to rapids (steps).

If one chooses to create spawning beds in *dug out holes*, the bottom should be 0.3–0.5 metres deep and in an area where, at low flow, the water “makes the top of your rubber boots flutter” (around 0.3 metres per second). The work should take place at low water flow. A bowl-shaped hole is carefully dug using an excavator. It should be at least 3 metres long and at least 1 metre wide. The entire hole should be filled with a suitable substrate up to the height of the rest of the riverbed (Figure 50). It is important that the spawning bed does not stick up above the level of the rest of the riverbed; otherwise it may collect sediment or wash away. The largest holes dug have been around 300 square metres. The bowl shape ensures that the surface water naturally flows down into, and then up out of, the hole. And the spawning bed is protected from high flows. The spawning bed can be stabilised by placing a number of standing stones downstream, and even to the sides of the bed. These stones also help to force the water downwards into the bottom, i.e. to ensure a good flow of water through the substrate.

Of course, it is not necessary to dig in the bottom if there is a natural site against some *rapids* where the gravel will not be washed away. Alternatively, rapids/steps can be built up and suitable spawning substrate can be placed immediately upstream of them (Figure 48, chapter 11). It is common that spawning substrate laid out in this way is not sufficiently stable, so it is important to be particularly thorough with measures to improve stability. Start by establishing a step of large stones and fill the gaps with smaller stones. It is recommended to exaggerate the use of coarser fractions in the spawning substrate to improve stability and to add some extra larger stones that protect the bed from high water flow.

**Costs**

Natural gravel costs around € 30-60 per cubic metre. However, there is large regional variation in the price according to natural availability. There are additional costs for transport, digging and placing out the gravel, etc. The total cost can be of the magnitude of € 60–125 per cubic metre. If the work is done manually. As described in chapter 11, when these bottoms are built primarily for mussels, the cost can be expressed as € 4 000 per 100 square metres.
Spawning beds for Atlantic salmon and brown trout should be at least 39 centimetres deep. For safety’s sake the bed can be built to be 50 centimetres deep. For resident small brown trout, 15-20 centimetres can be sufficient.

The coarseness of the material used should lie in the interval 10-50 millimetres, with some coarser material to stabilise the bottoms. Common fractions available from quarries are 8-16 millimetres, 16–32 millimetres and 32–64 millimetres. A suitable spawning substrate could be a mixture of 15–32 millimetres and 32–64 millimetres, in the proportion 2:1.

It is important that the gravel is not too rounded; otherwise, it can move too easily. It is also important for the substrate’s stability that it contains a variety of fractions.

Material that has been crushed or blasted should not be used because there is risk that it can injure spawning fish. Furthermore, there is a lot of fine sediment on such material.

The water depth should be between 0.1 and 0.7 metres for brown trout. It can be somewhat deeper for large sea trout and Atlantic salmon.

Suitable locations for creating spawning grounds are those where the material will not be washed away, but where there will be a good flow of water through the substrate. Good locations are: upstream of rapids, in the shelter of large stones, in stream outflows, in side channels and downstream of lakes and ponds.

It is preferable to choose a location high up in the fast flowing stretch, so that gravel that is washed away can create new spawning beds downstream. Another advantage is that fry often spread downstream.

The spawning ground should ideally be located close to a place of shelter for the spawning fish, for example, a pool, stones or large piece of dead wood. Furthermore, there should be shallow and weakly flowing areas that are suitable as rearing habitats for fry and underyearlings in the vicinity and downstream.

In order to ensure that the water flows well through the substrate, measures should be taken that promote hyporheic flow. This can be achieved by establishing the spawning bed in an area where the ground water flows up, or, more commonly, by steering the water and forcing it down into the substrate using stones and other structures.

The water flow rate over the bottom should be in the interval 0.2-0.5 metres per second, but for the very smallest mussels 0.2-0.3 is preferable.

Aim for at least one spawning bed (ideally at least 1x3 metres, that is, an area of 3 square metres) per rearing habitat and at least one spawning bed of this size per 50 metres of fast-flowing water. In wider watercourses (>5 m) it is likely that more and larger spawning grounds are necessary. Guidelines suggest spawning beds of 3–5 metres long in small watercourses and 5–15 metres long in larger watercourses. Based on these sizes, spawning beds should be created at 100–200 metre intervals.

All spawning beds that are created should be revisited after a year to see how well the structure survived high flows. This should be included in the project plan.

In general, the work should be done during periods of low water. This ensures that the structures created are such that sediment deposition does not take place in the gravel beds, and that the spawning beds never normally dry out.

A good spawning ground should not fill with sand. If the bottom does fill with sand then the location was not appropriate. It may be possible to avoid the collection of sand by steering more of the water flow over the bed, or by building a sediment trap (Figure 32, 33).
Free migratory paths

Free migratory paths are needed to maintain biodiversity. In this manual we focus on salmonids, because these fish are important for the continued existence of freshwater pearl mussel populations. The focus lies on ensuring free passage for the fish upstream, but it is also stressed that it is often necessary to improve conditions for passage downstream, especially in watercourses with hydroelectric power stations.

There are four main ways to create nature-like solutions to help the salmonids’ migration (nature-like fishways):

- removal of the obstacle and creation of short rapids,
- rocky ramps to create rapids over the obstacle,
- naturelike channels bypassing the obstacle within the watercourse (bypass through the dam),
- natural channels bypassing the obstacle outside of the watercourse (bypass).

Furthermore, there are a number of technical solutions (technical fishways). These are not addressed in this manual, but can be found in Degerman (2008). In general, building technical fishways requires special expertise and the constructions require regular maintenance.

The nature-like solutions should always be prioritised because, when built properly, these solutions enable most aquatic species to pass. Technical fishways are mainly used for large obstacles such as power station dams, where there is a large fall in the water level.

The aim of a fauna passage / fishway should always be to enable all species in the watercourse, fish, benthos, mammals and amphibians, to travel past the obstacle. Fishways should be passable and attractive; these two aspects define their function. The functions are to a great extent dependent on the water flow and velocity through the fishway.

Figure 51. Removal of a dam (Kubadammen) in River Nättraån, Sweden. The watercourse has a sparse freshwater pearl mussel population. Photo: Håkan Söderberg.

The power to attract fish to the entrance of the fishway is crucial to its success. The entrance must be well designed and modifications may be necessary downstream to ensure that animals are lead towards the fishway. The mouth of the fishway should be strategically located so that existing migratory paths downstream in the watercourse naturally lead the fish to the fishway. It is common that there is a competing, often stronger, attractive force coming from the dam outflow or turbines. The water that flows out of the fish passage, the lock water, should be directed so that it flows to the place where fish migrate or collect downstream of the obstacle. It should flow out at a suitable depth, somewhere between the surface and around 2 metres deep.
Removal of the obstacle

When a dam or other obstacle is removed (which, of course, requires an environmental permit, see chapter 8) a passage is created in the existing channel, normally encompassing the whole watercourse (Figure 51). This is therefore the solution that works best for most species and most sizes of watercourse. The work to remove the obstacle is usually followed by work to build up a naturally fast-flowing stretch where the obstacle previously stood. In general the measures do not require maintenance and are relatively cheap to implement. The new rapids often become an important habitat for species that live in fast-flowing water, such as freshwater pearl mussels.

One problem associated with removing a dam is that it is hard to predict the hydrological and geomorphological results of the change. Many worry that the risk of flooding will increase downstream; this is not generally the case. The dam’s function as a sedimentation basin will disappear, which can sometimes be a negative effect. A dam provides protection from careless behaviour upstream in the river basin which can result in increased sediment transport.

Many people do not like change, such as the change involved when a dam is removed. It is advisable to prepare pictures from the same or similar watercourses with free-flowing stretches to be shown at public meetings.

It is important that the removal work is done at low water and that it causes as little increased turbidity as possible. It may be necessary to build a smaller, temporary dam upstream of the dam to be removed, in order to redirect water past the work site. Gabions (metal mesh sacks filled with stones) or blasted rocks can be used to build it. The former has the advantage of being easier to remove after work is completed. The water can also be redirected past the dam in plastic piping. In small watercourses, it is also possible to build a dam out of wooden panelling, with an outlet for a pipe that redirects the water. Care must be taken to ensure that the riverbed downstream containing freshwater pearl mussels does not dry out, i.e. the piping must be positioned so that the water continues to flow over every part of the watercourse downstream. It is sometimes necessary to make small adjustments to the riverbed downstream to disperse the water appropriately.

In larger reservoirs, the sediment normally remains in place during normal conditions, whilst in small dams with low storage capacity some of the sediment can wash away during high flow. The removal of a dam can lead to higher sediment transport at times. Before removing the dam, the thickness of the sediment in the reservoir should be investigated.

Depending on the quantity of sediment, the conservational value of the watercourse downstream and any toxic compounds in the sediment, there are three ways to deal with the sediment: allow it to wash away, remove it by digging it out or stabilising it on site. Sediment should never be dug out when there is water in the reservoir; this leads to excessive turbidity and the mass of material to remove is great. The sediment mass should be allowed to dry out for three to four days before it is dug out.

The cheapest alternative is to allow the sediment to wash away in the watercourse, but this is, of course, not a good solution in watercourses with large freshwater mussels. It may, in some cases, be reasonable to accept this disturbance to the watercourse since the measure as a whole will lead to long-term positive effects. Fish and mobile benthos usually recolonise quickly, but larger molluscs and vegetation can be greatly disrupted. When a dam was removed from the river Vessingeån, Sweden, in 1993, parts of the riverbed downstream were covered with 0.5 metres of sand during the following summer. Two years later, the areas had been washed clean and the fish density had returned to normal levels (Hans Schibli, pers. comm).

The best solution is often to create an artificial, stabilised channel through the sediment (Figure 52).

Figure 52. A channel has been created through the sediment store, where the dam pond was previously located. The sediment and the channel are stabilised. Vegetation soon develops which covers the sediment, thereby stabilising it further. Photo: Erik Degerman.

COSTS

The median cost of removing a dam is cited as € 10 000 per meter fall in the river (6 200 – 30 000).

It is considerably cheaper to remove a dam than to build a nature-like passage from the point of view of guaranteeing the function and of requiring minimal supervision and maintenance. The cost of removal increases with expensive waterfall rights, difficult (toxic) sediment conditions, larger watercourses, important cultural heritage that demand a cautious approach, inaccessible terrain, the need for complementary measures for biotope conservation and increased risk of landslides in the area.
12. Measures for host fish

Stepping
Stepping is used to raise the water level downstream whilst maintaining the existing water levels upstream, so that a passage past the obstacle is created in the form of a ramp (continuous or in several parts). Stepping is a suitable method for dams that have a lot of sediment, which can then be left untouched. It is also used to raise the water level downstream of road culverts that have been placed incorrectly so that fish cannot pass (Figure 53).

Bypass through the dam
A bypass through the dam is a natural path built into the watercourse itself. This is different from an external bypass (see below), which is a path around the obstacle that is built outside of the existing watercourse. The bypass through the dam can be designed so that it takes a given quantity of water at different levels of water flow. It is suitable to use in situations where it is difficult to lay claim to the land around the obstacle. Since it is built within the watercourse and is given a natural bottom, it is easy for migrating animals to find. The spread of vegetation downstream is also facilitated. It is likely that a bypass through the dam is a more effective passage than, for example, an external bypass, but little research has been done in this area. However, bypasses through dams are more expensive and more difficult to build. There is some uncertainty over the maintenance needs and durability of the structure.

The tongued and grooved or casted separating wall to the watercourse must be very stable (Figure 54). In soft sediment a tongued and grooved solution can be sufficient, but casting must be used with coarser sediment or rocky outcrops.

External bypass
External bypasses are nature-like passages that are built to divert water around the obstacle. They are normally built with a low gradient and a stony littoral zone (Figure 55). Atlantic salmon, brown trout and other strong swimmers can pass without problems through an external bypass with a gradient of three to nine percent if standing stones are placed appropriately to create sheltered areas. However, a gradient of two percent is generally quoted as the greatest slope suitable for all species and sizes of fish in short external bypasses (<50 metres). The gradient for longer external bypass is a maximum of 1.5 percent. The gradient can be greater (but preferably not more than five percent), if the channel is built with an uneven bottom with areas that are sheltered from the current close to the bottom and the edges. External bypasses with a gradient of five to nine percent have been built in the form of short rapids; in this case large stones should be used to create sheltered areas. External bypasses with steep gradients work best at low water flow. When the flow is high the water flow rate becomes too great for the fish.

One disadvantage with external bypasses is that they are sensitive to variations in the water level upstream. The external bypass tolerates greater water level variation if the inflow is narrow and sharply v-shaped. An alternative is, of course, to install a spillway in the upper end of the external bypass; these are available prefabricated.

The external bypass can be built with natural sections of rapids and can thereby also function as a rearing habitat for mussels, fish, insects and other invertebrates. In Denmark, it is common to create spawning grounds for brown trout in the external bypass. The external bypass is often the only remaining stretch with areas of hard bottom in the channelized agricultural watercourse. Of course, the external bypass should also be built with suitable habitats for freshwater pearl mussels.
External bypasses that have a meandering path are sensitive to erosion. The flowing water is constantly forced to change direction, resulting in high erosion of the banks. There is a large risk that the external bypass floods at high water levels if the water inlet is not regulated; it is therefore necessary to have a spillway. Furthermore, there is a risk that the water seeks a way out through the ground and creates new paths leading more directly down the slope. The bottom should be secured with a sealing layer, e.g. a geotextile.

COSTS

In general, the total cost of constructing a bypass is around € 20 000 per meter drop in water level, but the costs can vary greatly.

The omlöp shown in Figures 58 & 59 cost € 20 000 in total, excluding project planning and management. The prefabricated spillway that regulates the water inflow at the upper end cost around € 4 000 and was included in the figure above.

Figure 55. Construction of an external bypass past a dam at Fågelfors in the LIFE stream Nötån, Sweden. Photo: Sofi Alexanderson.

Figure 54. Bypass through a dam at Hotagens outflow in the Härkan watercourse, Jämtland, Sweden. Note that the water level in the dam is maintained by the separating wall, whilst the upper part of the bypass through the dam has rapids that determine the water level in the lake. Photo: Erik Degerman.
13. Reintroduction of host fish

As previously mentioned, there is good evidence that only the right strain of host fish can successfully be infected by mussel larvae. Buddensiek (1995) and Söderberg et al. (2008a) give several examples of how different strains of brown trout have different susceptibility to infection. The situation is further complicated by the fact that fish that have already been exposed to infection are immune to further infection. Host fish which are reintroduced must always be of the closest possible, suitable strain.

It is generally recommended that reintroduction of Atlantic salmon or brown trout is achieved through the release of fertilised roe or hatched fry. When the fry hatch they have a large yolk-sac filled with a food supply that lasts for two to three weeks, during the period that they learn to eat other food (Figure 56). The best reintroduction results with fry are often achieved with yolk-sac fry that have started feeding. The reintroduction should take place in the period March-May, depending on the geographical location, sometimes in conditions with ice coverage or during the spring flood.

A licence is always required from the County Administrative Board for the reintroduction of fish. The eggs or fry should come from a fish farm with health controls.

If there is no roe or fry is available from hatcheries then the reintroduction can be done using juvenile brown trout or Atlantic salmon that have been caught by electric fishing. This requires a balance between ensuring that the juveniles are large enough to avoid negative effects from electric fishing (they should usually be at least 40–45 millimetres long) and that the reintroduction should take place when the glochidia larvae have been released into the watercourse.

Recommended quantities for releasing are 500–1 000 roe-corn per 100 square metres of rearing area, 200–500 yolk-sac fry per 100 square metres. For yolk-sac fry that have started feeding, 50–300 per 100 square metres is suitable, depending on the production capacity of the water (Degerman et al. 1998). One can assume that around 30–40 percent of feeding yolk-sac fry survive to become one summer old brown trout (0+). Typical published densities of one summer old brown trout (40–80 millimetres) in Swedish waters (Sers et al. 2008) are generally of the magnitude of 10–50 per 100 square metres. The quantity of material for releasing can be estimated from the expected mortality rate of feeding yolk-sac fry and the desired density of underyearlings.
Freshwater pearl mussel waters in Europe

Stream in Morvan, France.
Photo: Lennart Henrikson

Stream in Anlier, Belgium.
Photo: Lennart Henrikson

River Spey, Scotland.
Photo: Lennart Henrikson
14. Reintroduction of mussels

Mussels should only be reintroduced if all of the above restoration measures have failed to produce a positive result. The reason for the weak status of the population should be identified and measures should be taken before reintroduction of mussels is attempted. Criteria for when reintroduction can be considered have been compiled from Ziuganov et al. (1994) with some additional points (see the information box).

Some advice has been formulated by Kleiven & Dolmen (2008) to accompany the above criteria:

a) Avoid intensively regulated watercourses and stretches that risk drying out.

b) Place the mussels in a stable substrate, preferably close to large stones and boulders.

c) The substrate should consist of sand and gravel.

d) Do not place the mussels in areas where the current is very strong because this can make it difficult for them to collect food.

e) Place the mussels in shady stretches.

f) Pools in the current that do not dry out at low water are a good habitat for the mussels.

g) Avoid stretches of the river with banks that are liable to subside or with lots of algal growth.

It is therefore important to look for suitable substrate in areas that are stabilised by large lakes upstream, or by large boulders or stones. Stable substrates often have moss growing on them – this is an important indicator.

Reintroduction is often achieved by placing the mussels in groups in a suitable substrate. Reintroduction on the Kola peninsula was done by placing mussels in groups of 100-250 individuals around large stones in the river, in order to establish a structure that was similar to the original colonies (Ziuganov et al. 1994).

In areas of low water flow rate, the mussels can be gently placed on the bottom (Figure 57). They will quickly dig themselves down into the substrate. If the water flow rate is higher, the mussels should be gently inserted into the substrate. Try to push aside the substrate first with your fingers to create a gap for the mussel. Do not push the mussel directly into the substrate; place your hand or a few fingers under the mussel to protect the edge of the mantle from damage.

The survival rate appears to be good when mussels are moved within a watercourse. In the summer of 1996, 12 mussels that had survived a catastrophe downstream and marked with an X on the shell (watercourse in Västerbotten, Sweden). One year later, 11 of the mussels remained. Finnish studies have found that reintroduction of mussels from another watercourse have generally not been successful, with a mortality rate of around 50 percent within three years. On the other hand, moving mussels within a watercourse seems to be more successful with around 90 percent of mussels surviving in the short term (Valovirta 1990). In 1991, 250 adult freshwater pearl mussels were moved from the river Ulsetelva (Nordmøre) to the Audna (Vest-Agder), both in Norway. In the following year there was a period of extremely high flow which washed many of these mussels away from two of the four reintroduction sites. However, at the remaining two locations, 18 percent and 68 percent were found respectively when revisiting the sites, up to the year 2007 (Kleiven & Dolmen 2008). So survival rates were not good, even at the most suitable reintroduction sites. Reproduction has not been observed; a possible reason for this may be high concentrations of metals caused by acidification.

In Sweden, ten attempts have been made to reintroduce freshwater pearl mussels. Only one attempt has been successful. However, the conditions described above have not been met in these attempts, that is to say that the underlying reason for the weak population has not been identified and addressed before the reintroduction attempt.

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**CRITERIA FOR REINTRODUCTION OF FRESHWATER PEARL MUSSELS**

1) Reintroduction should only be attempted in areas that are within the mussels’ natural distribution in terms of region and watercourse.

2) Reintroduction should only be attempted if the previous population is extinct.

3) Before reintroduction, measures must be taken to ensure that the proposed criteria for water quality and presence of host fish are met in the watercourse (Chapter 4).

4) Any human influences that could impede the mussels’ survival must be eliminated.

5) The mussels used for reintroduction should be taken from waters that are as nearby as possible, preferably from the same water system.

6) It may be appropriate to check that the host fish in the watercourse can be infected by mussel larvae from the mussel population which is planned to be used for the reintroduction.

7) If older mussels still exist in the water then alternative restoration methods must always be weighed up before reintroduction is attempted.

8) If older mussels still exist in the water then a genetic analysis should be undertaken to ensure that the mussel strain for reintroduction is as close as possible to the existing strain.
Within the LIFE project 1 000 mussels were re-introduced to stream Silverån (Figure 57, 58). The freshwater pearl mussel population Silverån had gone extinct. Mussels were collected in stream Sällevadsån in the same water system. The mussels were transported in plastic boxes, covered with mosses. The time between collection and introduction was 1-2 hours, which apparently did not affect the mussels. The mussels were marked and then placed in groups at different places in the stream. Silverån has been physically restored, which means that the freshwater pearl mussel will have good opportunities for recruitment.

Figure 57. Peter Johansson and Thomas Nydén re-introduces adult freshwater pearl mussels to the Stream Silverån, part of the River Emån water system (LIFE project). Photo: Jakob Bergengren.

Figure 58. Mussels were transported in plastic boxes from a neighbouring stream and placed in stream Silverån by Peter Johansson and Sofi Alexanderson. Photo: Lennart Henrikson.
15. Artificial infection of brown trout and rearing of mussels

When a mussel population is very weak, it may be appropriate to try to strengthen the population. This has rarely been attempted in Scandinavia because restoration measures for more viable populations have been given higher priority. In other parts of Europe, however, attempts to strengthen weak populations are more common. Two methods have been tested:

- Releasing brown trout that have been artificially infected with glochidia
- Releasing mussels reared in a laboratory

Artificial infection of brown trout

The release of artificially infected brown trout is only appropriate when the threats to the juvenile mussels’ survival have been removed. Furthermore, the host fish must originate from the watercourse to which they are re-released. (see Chapter 3; Altmüller & Dettmer 2006, Buddensiek 1995, Söderberg et al. 2008a, Larsen 2009a). It is common to find glochidia-infected brown trout in a watercourse without finding any small mussels in the substrate. In this case it is likely that the small mussels have been suffocated by silting up of the substrate. If this is the case then releasing infected fish is not an appropriate measure.

A successful example

Altmüller & Dettmer (2000, 2006) collected gravid mussels and brown trout from the River Lutter in Niedersachsen, Germany. The host fish were infected with glochidia in the laboratory and then returned to the river. This process was repeated each year at the beginning of the 1990s. The Lutter now has a healthy mussel population. At the same time, measures were taken to reduce the flow of sediment into the river and buffer zones were purchased along the river. These measures created good conditions for the small mussels. The Lutter is the only example where restoration measures have succeeded in stimulating recruitment. The project also proved that artificial infection was only successful with brown trout from the Lutter, not from farmed brown trout. Similar experience was reported from Südlische Regnitz, Germany (Robert Vandré, pers. comm.)

Stream Hyttkvarnsån in Sweden

In Sweden, Bergengren & Törnblom (2005) reported a simple attempt to infect glochidia infection in the river Hyttkvarnsån in Dalarna, Sweden. Farmed brown trout (1+ and 2+) were released into a water mill channel which had a large population of freshwater pearl mussels. The fish spent one year in the headrace before being released. Studies showed that they carried glochidia larvae. An inventory taken six years later did not find any juvenile mussels. The reason for the failure was judged to be that there was too much fine particulate matter on the bottom, and that the fish may have been of the wrong strain.

Simple systems for field use

In cases where it is known when the glochidia larvae are released from the mussels, simple systems can be set up in the field. In order to strengthen the brown trout and mussel populations in a small Norwegian brook outside of Trondheim, a method was developed whereby juvenile brown trout that were infected with mussel larvae were released (Larsen 2009b). The mussel population in the brook is critically threatened; only 25 individuals remain. 1 250 underyearlings (one summer old, so-called 0+) from a local strain were placed in a rearing tray at the end of July (Figure 59). Gravid mussels were placed in plastic baskets with suitable substrate in the rearing tray together with the juvenile brown trout (Figure 60). The fish became infected in August and at the beginning of October the fish were returned to the brook. 93 percent of the fish were infected; on average each infected fish carried more than 100 glochidia. The plan is to repeat this process for two more years.

A question that arises is how host fish are affected by glochidia infection. Treasurer et al. (2006) studied Atlantic salmon underyearlings infected with glochidia and found that there was an initial dip in the rate of growth in the length and weight of the fish. This effect soon disappeared. The mortality was not found to be higher in infected fish than in noninfected fish. However, Smith (2001) reported that juvenile (30 millimetres) salmonids died as a result of a bacterial infection after having had over 100 glochidia on the gills. Grundelius (1987) reported that brown trout in fish farms/hatcheries died of glochidia larvae. This problem is, however, considered small and negligible.

Figure 59. July 2009: A rearing try is placed next to a Norwegian brook with a very threatened population of freshwater pearl mussels. 1 250 underyearlings (one summer old, so-called 0+) from a local strain of brown trout were placed in the vessel. They were fed on conventional fish food.

Figure 60. Gravid mussels were placed in plastic baskets with suitable substrate.
Rearing mussels

Rearing of mussels may be necessary for watercourses with small populations and an unfavourable water environment. Small mussels are more sensitive than large ones. The population can be strengthened by rearing mussels up to a size where they are better able to survive in poor conditions.

In the Czech Republic, Hruska (2001) developed a method for rearing mussels. Brown trout are infected in a laboratory and are held until the glochidia have developed into juvenile mussels and fall off into the laboratory vessel. These mini mussels are collected and sorted by size. The larger ones are kept in a small vessel (Figures 61 and 62). They are fed with water from a wetland; the fine roots of grass have proved to be a source of microorganisms that are suitable food for the mussels. Food and water temperature appear to be the most important factors for the mussels’ growth. When they have grown larger, the mussels are placed out in net baskets in small dug channels (Figure 63). They can grow there until they are large enough to place out in the watercourse.

Using this method, the mussels’ survival during the most critical period can be secured. This method has since been applied in several other European projects with some small variations.

Several advanced, semi-natural systems to infect young brown trout with freshwater pearl mussel glochidia have been developed in recent years. The basic idea is that natural water, which naturally contains food for the mussels, is used in the system. Preston et al. (2006) and Scriven et al. (2007) have also added a component to the system where the juvenile mussels can settle in the bottom substrate. The system developed at a fish hatchery in Mawddach in Wales was described by Scriven et al. (2007). The adult mussels are kept in trays outdoors and fed with unfiltered water from the River Usk. Atlantic salmon and brown trout are kept in separate trays and infected with glochidia from trays upstream. The juvenile mussels are collected in a net filter on the outflow water (mesh size 0.15 millimetres). A problem with the system is that this filter quickly clogs up with fine gravel from the bottom substrate, making the process of collecting the juvenile mussels difficult. The water supply therefore enters the trays both at the water surface and from below. The flow is around 6 litres per minute. The water is filtered in a coarse filter. After about six months, the mussels are transferred to a larger tray with a coarser net bottom and coarser substrate (about 5 millimetres in diameter).
In general, the follow up on watercourse restoration measures is limited and is rarely reported (Bash & Ryan 2002). This makes it difficult to evaluate the effectiveness of the measures and to improve methods. Measures should always be followed up!

It is often not enough to simply follow up one particular object before and after restoration measures because there is large natural variation. Other factors can lead to temporarily weak fauna (mussels/host fish) or variation in the chemical properties of the water, even after a successful restoration project. It is therefore good practice to always have a reference site to compare results with, which indicates natural variation. The reliability of results is further improved by analysing several parameters, i.e. measuring several ‘impact area – control area’ pairs. BACI design (Before-After-Control-Impact) is a suitable method for follow up. The method is based on the use of control (reference) waters, and involves taking samples from the control and treated waters both before and after measures has been taken. Analysis of variance (ANOVA) can be used to identify changes that only take place in the treated waters. Further reading can be found at e.g. Underwood (1996).

The effects of measures regarding mussels should be controlled within five to ten years of implementation. Water quality measures should be controlled immediately after the work is completed. The quantification of host fish can be done in parallel with control of the mussel status, or after one to three years.

It is very important to follow up the restoration measures with a well documented methodology because many years may elapse between the preliminary and the follow up study. Unfortunately, restoration projects are often closed before it is possible to expect to see any small mussels on the riverbed. It may be possible to see results sooner by digging in the substrate for small mussels, but there is currently no standardised methodology for this in Scandinavia. It is therefore often necessary to initiate and establish a free-standing follow up project.

Ensure that data from all standardised studies are recorded by the national data host for each study type.

A GOOD FOLLOW UP PLAN SHOULD:

- Include clear and well-defined quantitatively measurable goals.
- Ensure that goals address both the measures (i.e. evaluate project implementation) and the status (i.e. evaluate conditions for freshwater pearl mussels and control the criteria for water quality and host fish, chapter 4).
- Be based on standard methodology wherever possible.
- Include suggestions of which actions to take depending on the results of the follow up analysis (part of adaptive management where measures are gradually adapted according to the results obtained).
- Where possible, include surveys before measures are taken, both in the stretch of water in question and in reference stretches.
- Have a long-term approach, because the effects of measures may only become evident after >5 years.

WE RECOMMEND THAT THE FOLLOWING STEPS ARE UNDERTAKEN IN ALL RESTORATION PROJECTS:

- Establish the status of the freshwater pearl mussel population in the impacted and reference waters both before and after the restoration measures.
- Measure the chemical properties of both waters, listed in chapter 4.
- Undertake an electric fishing survey to establish the quantity of host fish before and after the restoration measures.
Freshwater pearl mussels often arouse great interest from the public due to their complex life cycle and fascinating cultural history with their precious pearls. For this reason, mussels have been used as an umbrella species, together with other species that are well known to the public such as Atlantic salmon and otter. In the past, information about the location of mussels was often restricted; the risk of illegal pearl fishing was considered too great. However, current experience in Sweden and Norway suggests that the availability of information about mussels creates heightened interest from local inhabitants, who then act as caretakers to the mussels and consideration increases. It is therefore especially important the stakeholders are informed about the existence of freshwater pearl mussels and in what ways they should be taken into consideration.

Where is the information found?
The Swedish Species Information Centre’s Clam gateway (musselportal, www.musselportalen.se) contains information about freshwater pearl mussels and other large freshwater mussels. Any mussel populations found in Sweden can be reported to the database, and it is possible to search the database for populations in all Swedish watercourses. The database is currently under construction (2009). WWF Sweden has published a brochure in Swedish entitled “Flodpärlmusslan – skogsvatten nens skatt” (Freshwater pearl mussel – the treasure of forested watercourses) (Figure 64). Information about this and the LIFE project can be found at www.wwf.se/fpm. You can also view two short films – one about the freshwater pearl mussel as a species and one about restoration of habitats. The Swedish Museum of Natural History Museum has a series of factsheets about large freshwater mussels (in Swedish). (http://www.nrm.se).

Information on two levels
Information about freshwater pearl mussels is needed on two levels: nationally, to stress the importance of restoration measures for the species, and locally, to those who live and work close to mussel populations. There are several cases where a population of mussels has been damaged due to lack of knowledge about the presence of mussels in a watercourse. The owner of the land and the watercourse is, of course, an important person to keep informed. Awareness of the value of the watercourse and the responsibility that this carries usually leads to increased consideration. Our experience is that landowners are proud to have such a fascinating species in their waters.

National information is managed in Sweden by the Swedish EPA, the Swedish Board of Fisheries and the Swedish Species Information Centre. There is a national action plan for freshwater pearl mussels (Schreiber & Tranvik 2005) which addresses these issues, amongst other things. The County Administrative Board of Västernorrland has responsibility for implementation of the action plan.

On a local level, information about the presence and needs for consideration of mussels must be communicated to everyone who could affect (or preserve/restore) the watercourse, including:

- Land and watercourse owners (and leaseholders).
- Forestry stakeholders: planners, forestry contractors, road contractors, timber buyers, electricity providers (who manage the distribution network), etc.
- Fishery conservation areas, fishery conservation area associations, fishing clubs etc.
- Public authorities: district councils, county administrations.
- Nature conservation organisations.

It is important that the presence of freshwater pearl mussels is taken into consideration in physical planning, in order to ensure that no mistakes are made. The district council has an important role in this; nature conservation plans should point out the presence of the mussels in watercourses. The most important measure is to ensure that any waters containing freshwater pearl mussels are included in the general plans used to define a district council’s political plans for land and water use. These plans are in turn used for the more formal and prescriptive detailed plans. The presence of freshwater pearl mussels must also be documented on a regional level, e.g. in county-wide nature conservation planning, not least to ensure that an effective liming strategy is achieved.

As mentioned in the introductory chapter, specific action plans for mussel waters should be developed. The action plan should outline the threats and the actions needed and should include information to all stakeholders.

Since most freshwater pearl mussel waters are found in forested areas, informing and educating landowners and other forestry stakeholders is extremely important. This has been tested by the Swedish Forest Agency and County Administrative Boards in the LIFE project.

A suitable approach could be to invite stakeholders to an evening meeting where the fascinating biology and cultural history of freshwater pearl mussels is described, along with the threats and suitable measures for consideration and restoration of populations. Information material can be handed out and films shown. The evening activity could be followed up by a half-day or evening excursion where participants can look for, and study the mussels themselves, and where restoration measures can be demonstrated Of course, these two activities could be combined as a full day event.


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Cover photo: Lennart Johansson is searching for juvenile mussels in a new “mussel bed” in the LIFE project stream Pauliströmsån. Photo: Jako Bergengren.

Text: Erik Degerman (erik.degerman@fiskeriverket.se)
Sofi Alexanderson (sofi.alexanderson@wwf.se)
Jakob Bergengren (jakob.bergengren@lansstyrelsen.se)
Lennart Henrikson (lennart.henrikson@wwf.se)
Bo-Erland Johansson (bo-erland.johansson@skogsstyrelsen.se)
Bjørn Mejdel Larsen (bjorn.larsen@nina.no)
Håkan Söderberg (hakan.soderberg@lansstyrelsen.se)

Translation: Emma Henningsson has translated the main part of the original Swedish text.

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July 2009 © WWF Sweden
Two Latvian children are fascinated by the freshwater pearl mussels in River Rauza, Latvia.

Photo: Sofi Alexanderson.

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WWF Sweden
Ulriksdals Slott
SE 170 81 Solna
Tel +46 8 624 74 00
Fax +46 8 85 13 29
E-mail: info@wwf.se
Website: www.wwf.se
Plusgiro Account: 90 1974-6
Bankgiro Account: 901-9746