Chapter 4
Silver Eel Migration and Behaviour

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4.1 Introduction

After their first transatlantic migration, larvae metamorphose into 'glass eels' and swim into estuarine areas of river deltas. The glass eels develop into the so-called elvers (~65 mm) which swim up the rivers. They enter inland waters of northern Africa and Europe during different periods; Morocco: September–October; Spain, Portugal, South France: November–December; North France: January–March; British Islands and the Netherlands: February–April and Scandinavia: April-May. After reaching a length of 30 cm, elvers become known as yellow eels. These specimens have moved inland to coastal seawater or inland freshwater and continue to grow for some 8–15 years (males) up to 10–18 years (females), but they even may become much older.

After their period of growth, in preparation of their return trip to the spawning grounds, the eels transform into silver eel. Once the eel has undergone pre-puberty or "silvering", which is accompanied by marked changes in morphology, body constitution and other features (see Chapter 2), it is ready to start its spawning migration. Its lifestyle changes radically. As we have seen in Chapter 2, silver eels stop feeding, they have already acquired salinity tolerance while still living in freshwater and finally they have begun their puberty. As European eels, *Anguilla anguilla*, spawn in the Sargasso sea, the silver eels must migrate from inland or coastal waters over a distance of about 6,000 km to reach this area. Somehow silver eels are triggered by environmental factors to start their migration.

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Downstream migration has been subject to investigations on physiological and ecological topics for many years, not only to resolve the mysterious life-cycle of this catadromous teleost species, but first and foremost to understand the reason for its global decline. During their downstream migration in river systems, silver eel have to pass many types of barriers such as large barrages, flood-control dams, flood gates, weirs, hydropower stations, sluices, pumping stations and fisheries. Such barriers are abundant in the many regulated European river systems and inland waters. These barriers are clear obstructions for downstream movement and cause a risk for the survival of the silver eel. They also have a clear impact on river flows with much diversity in flow patterns. For better understanding of the impact by barriers on downstream migration of silver eels and the development and implementation of technical and management measures, improved detailed knowledge of silver eel behaviour at barriers is necessary.

As with many diadromous fish species, eels are threatened by the presence of dams and hydroelectric facilities in rivers. Turbine entrainment as well as impingement of silver-phase eels on the screens causes massive mortality of eels (Travade and Larinier 1992; Hadderingh and Bakker 1998). Up to 100% of the eels entering the intakes may be injured (Larinier and Travade 1998), depending on the type of turbine and flow conditions. The situation has become critical for eels and management solutions on a European level are urgently needed. With respect to eel behaviour, information can be used to develop techniques to protect silver eels at turbine intakes of hydropower facilities. Knowledge of eel behaviour around barriers and timing of migration events may lead to successful protective measures (Richkus and Dixon 2003; Durif et al. 2003; Bruijs et al. 2003) (Durif and Elie 2008).

In 1996, the Committee of Ministers of the Benelux Economic Union decided to guarantee free fish migration in the hydrographic river catchments of the Benelux countries by 2010. This has already resulted in the construction of fish passages at weirs and hydropower stations in the Belgian and Dutch parts of the river Meuse. The European Water Framework Directive (EC 2000) requires undisturbed migration for fish in European river systems, and the European Commission has mandated the preparation of a European eel action plan (EC 2005, 2007). These developments will increase pressure for measures that protect eels and other species during their downstream migration. The need to manage the European eel fisheries has been recently addressed under the Common Fisheries Policy. A major stumbling block is the inadequate knowledge on the basic biology of the eel, crippling the attempt to set up rational management strategies. Furthermore it is well known that substantial mortality appears with downstream migrating eels passing the turbines of hydropower stations. Hydropower stations are widespread in many European rivers and might have detrimental effects on the population level of the European eel.

The objective of this chapter is to bring together existing and new information on the behaviour of downstream migrating silver eels related to environmental

migration triggers, migration events in rivers, obstructions in migration routes and behaviour when silver eels encounter mechanical and behavioural barriers designed to guide them towards safe bypasses at hydropower plants.

4.2 Migratory Behaviour of the Silver Eel

Eels migrate in large groups during narrow specific periods: they gather from streams and small river systems in the catchment area of large European river systems like the rivers Rhine, Meuse, and Loire. As Lowe (1952) wrote, downstream runs of silver eels "will depend on three things: the number of silver eels available in the lake or river, the external conditions, and the responsiveness of the eels to these external conditions". In many biological phenomena it is important that physical events (i.e. environmental factors) coincide with biological ones. Once the eel has undergone its "pre-pubertal" metamorphosis (i.e. silvering) it is ready to start its spawning migration. Its behaviour changes and it becomes receptive to certain environmental factors which will trigger the downstream movements. The urge to migrate is apparently so strong that they will even leave the water to escape if necessary (Tesch 2003). Runs of silver eels typically occur at night and during heavy rainfall (Bertin 1951). This has long been described by fishermen. Consequently migratory movements have been correlated with environmental factors that result in increased discharge (rainfall, flood events, dam openings) and low light conditions (wind, increased turbidity, atmospheric depression, moon phases) (Otamura 2002). Migration also coincides with the decrease of temperature in the autumn. In this section, we will review existing literature on the effect of environmental factors on downstream migration. Habitats of eels are extremely variable. They are found in freshwater and saltwater, lakes, ponds, marshes, rivers and estuaries, and yet they must rely on the same cues for the onset of migration. The relative influence of environmental factors is seemingly different according to the type of habitat. Their effects on eel are not clearly understood.

4.2.1 Downstream Migration Period and Timing

Most of the knowledge on the timing and dynamics of downstream migration comes from the commercial fishing industry. Downstream runs of European silver eels typically start in the autumn and may last until early spring. Authorized fishing periods centre on the time of major runs. In France, fishing for silver eels is allowed from 1 October to February 15. Although little is known about possible runs in September, the majority of silver eels in the Loire River migrate in November (Durif and Elie 2008). The first migratory movements obviously

depend on the timing of the silvering process. Silver migratory individuals (at stage V, see Chapter 2 for details of classification) first appear in August and September.

There are reports of downstream runs occurring in the spring. These often occur in areas regulated by dams such as in the study by Feunteun et al. (2000) and Acou et al. 2008 an or in the Dutch canals (in Deelder 1954). Spring migrations of eels, in addition to the autumn runs, have also been reported in Lake Fardume in Sweden, but these silver eels often had food items in their gut (Westin 2003). The downstream migration of silver eels has been extensively investigated by means of telemetry in the Dutch part of river Meuse by Bruijs et al. (2003) and Winter et al. (2006). The downstream migration occurred predominantly during October to November 2002 and January to February 2003. However, some eels were found to start their downstream migration a long period after their initial release. These 'slow migrators' were detected during March 2003 and even up to November 2005. Eels migrating beyond winter are probably latecomers for the autumn migration. In southern Norway (river Imsa) migration can start as early as July but the main peak is in September and October, and most individuals have migrated by November. (Hvidsten 1985; Haraldstad et al. 1985;Vøllestad et al. 1986). Timing of migration is similar in Ireland with an early start in July–August and a maximum in September and October (Poole et al. 1990). From these studies, it appears that eels start migrating earlier at northern latitudes, such as in the river Imsa in Norway (Vøllestad et al. 1986). Bergersen and Klemetsen (1988) studied eels from the northern limit of its distribution area, along the north Norwegian coast. Silver eels mostly migrated in August starting in July. By leaving earlier, these eels, which have more distance to cover, will likely reach the spawning grounds at the same time as other subpopulations.

Downstream migration generally occurs within narrow timeframes. It was found at the Lith-Alphen fisheries on the River Meuse that during most years about 20 days yielded 50% of the total silver eel catches, and in 1 year just 10 days yielded more than 60% of the total catch. Because this fishery does not operate when discharge is too high, it is likely that >50% of the total number of eels passing this location occurs in less than 20 days, i.e. the migrating silver eel population in one season passes during <20 downstream migration events (Bruijs et al. 2003; Winter et al. 2006).

Investigations described by Oberwahrenbrock (1999) in the River Mosel at the Fankel hydropower station (Germany), showed that during 3 months of nightly samplings (by means of one anchored stow net (10×5 m) in the tailrace of the hydropower station), a migration peak was observed during 1 night (during waning of the moon + increase of river discharge) in which 67% of all migrating eels passed and 90% of all eels passed during the 10 days of largest catches (i.e. 10 days of highest migration activity).

Monitoring of silver eel migration was carried out between 1999 and 2001 on the River Nive in France (Durif 2004; Durif et al. 2003; Gosset et al. 2005). In 1999 migration occurred over a period of 19 days out of 60 sampling nights. 75% of the

total number of eels caught in the trap was captured during 8 consecutive nights. In 2000, migration was monitored for 75 days and eels migrated during 20 of those days. Thirty six percent of the silver eels migrated during 2 consecutive nights. Finally in 2001, monitoring took place during 90 days and eels were caught during 22 days with 40% of the eels being captured over 4 consecutive days.

4.2.2 Water Temperature

The effect of temperature is not clear and the range of temperatures during which migration takes place is extremely variable according to different studies. Overall, downstream runs occur when the temperature decreases. In Norway, on the River Imsa, eels migrate between 4°C and 18°C (Vøllestad et al. 1986). Maximum migration was observed at a water temperature of 9°C and migration decreased at both higher and lower temperatures. Hvidsten (1985) gives a maximum threshold of 14°C for silver eel movements. In Spain, the range is between 10°C and 16°C (Lobon-Cervia and Carrascal 1992). Vøllestad et al. (1986) found that eels migrated earlier when summer temperatures were lower.

On the River Nive, eels migrated between 7°C and 17°C (Fig. 4.1). Data obtained from a commercial silver eel fishery on the Loire River in France showed that eels migrated between −3°C and 21°C; most migration occurred however between 6°C and 15°C. Runs at both sites occurred during both increases and decreases in temperature.

These data show that the temperature range at which eels migrate is fairly wide and it is not possible (and maybe not relevant) to set a threshold. It is probable that temperature acts more on the physiology of eels (i.e. silvering), than on migratory movements. In any case, what the individual eel perceives is probably more a temperature difference rather than a definite value.

4.2.3 Photoperiod

Vøllestad et al. (1994) showed that photoperiod affected downstream migration using tagged silver eels. They observed that eels would migrate faster as the daylight decreased. They suggested that photoperiod had an effect on silvering. Durif et al. (2005) also hypothesized that photoperiod (or the decrease in temperature) activates the last stages of the silvering process in a similar way that these environmental factors affect smolting in Salmonids. The obvious advantage would be to synchronize the onset of migration via physiological preparation, so that the future spawners would be physiologically ready for migration at the same time.

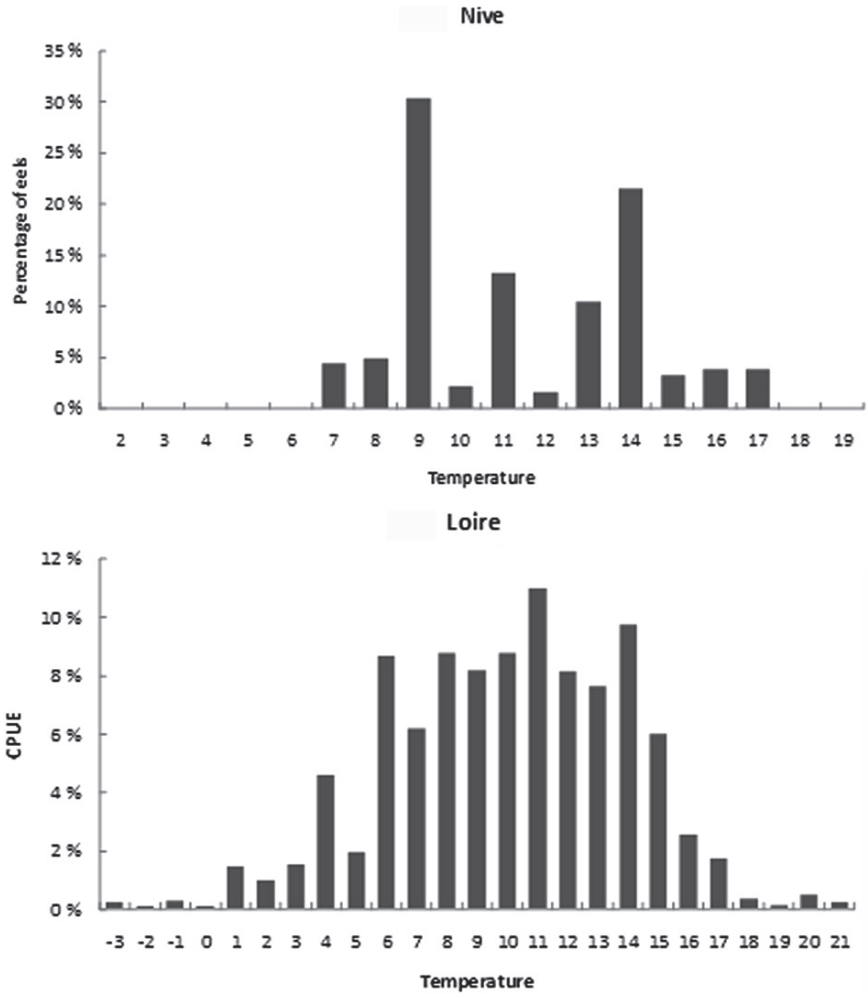

Fig. 4.1 Percentage of silver eels caught in the downstream trap on the river Nive and CPUE of the silver eel commercial fishery on the Loire vs. water temperature (pooled data for the periods 1999–2001 for the Nive and 1990–2001 for the Loire)

4.2.4 Discharge

River discharge has an influence on the migration of the eel. During high discharge the catch is larger than during low discharge (Tesch 1977). Jens (1952–1953) assumed that it is not the discharge, but a high water level that stimulates eel migration. Vøllestad et al. (1986), Jonsson (1991), Deelder (1954) and Lowe (1952) did not agree with this. The water level in the Dutch polders is kept at a constant level.

When the water level rises at another location, the water level within the polders remains the same, only the water current increases. When this happens, the migration of silver eel also increases (Deelder 1954; Durif et al. 2003).

Figures 4.2a–c show the results of the Nive River study in France (Gosset et al. 2005). During all three migratory seasons, close links between discharge and runs of eels were observed. Eels were caught in the downstream trap either during the flood or the day after. Data from the commercial silver eel fishery, located downstream of the much larger catchment, the River Loire (117,000 km^2), were also analysed for comparisons with the Nive catchment (1,030 km^2). The relationship between CPUEs (calculated as number of eels/the hours spent fishing) and discharge was not as clear every year, probably resulting from different perspectives due to the size of the catchments, i.e. longer distances between the start off point of the eel and the observer (fishery), (Figs. 4.2a–c). CPUEs were generally not proportional to discharge, and during

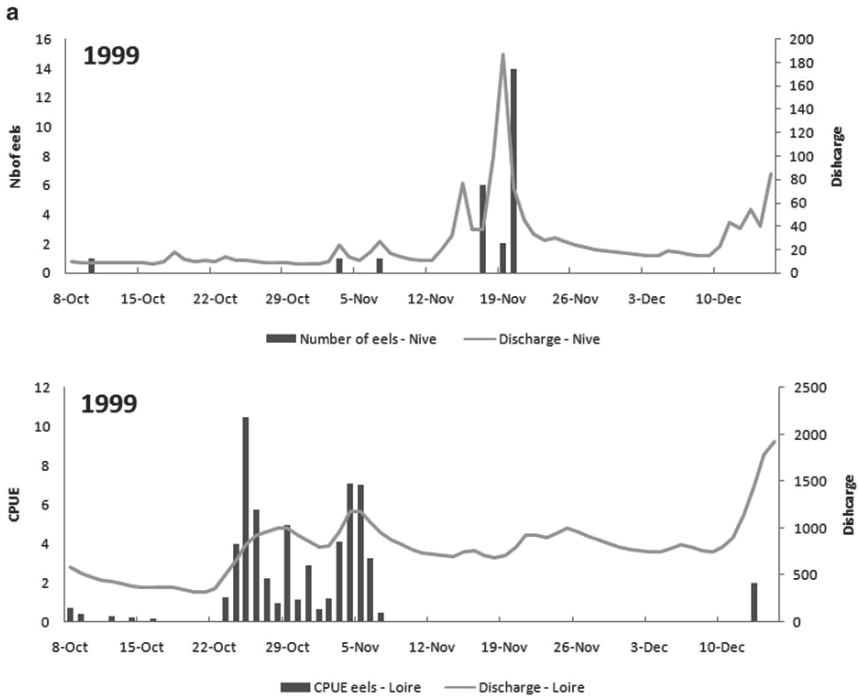

Fig. 4.2 (**a**) Comparison of downstream runs of silver eels and discharge on the Loire and Nive rivers in 1999 (Durif et al. 2003; Durif and Elie 2008; Gosset et al. 2005). Runs are expressed as number of eels caught in the trap on the Nive and as CPUEs on the Loire. Discharge is in m^3 s^{-1}. (**b**) Comparison of downstream runs of silver eels and discharge on the Loire and Nive rivers in 2000 (Durif et al. 2003; Durif and Elie 2008; Gosset et al. 2005). Runs are expressed as number of eels caught in the trap on the Nive and as CPUEs on the Loire. Discharge is in m^3 s^{-1}. (**c**) Comparison of downstream runs of silver eels and discharge on the Loire and Nive rivers in 2001 (Durif et al. 2003; Durif and Elie 2008; Gosset et al. 2005). Runs are expressed as number of eels caught in the trap on the Nive and as CPUEs on the Loire. Discharge is in m^3 s^{-1}

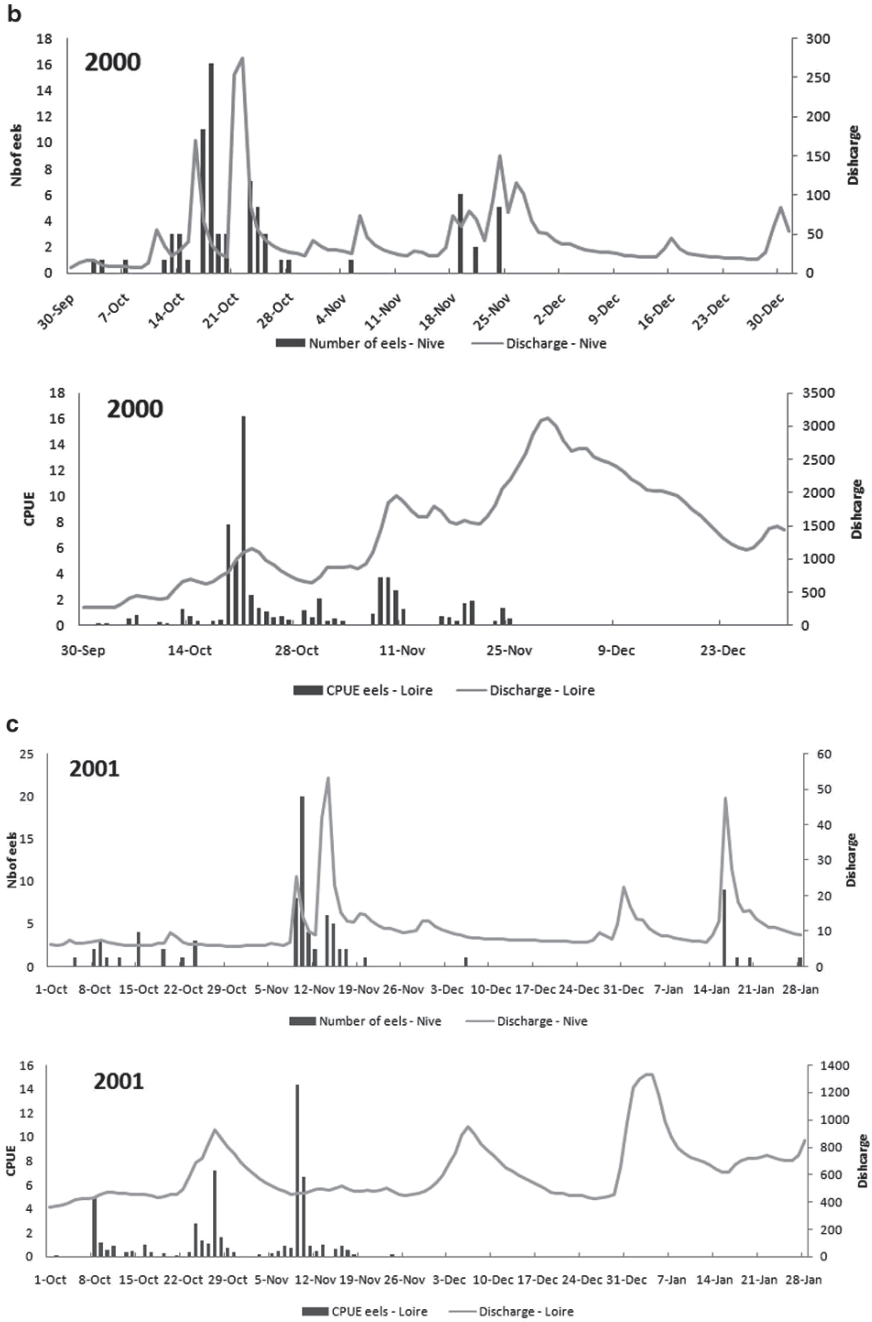

Fig. 4.2 (continued)

the 12 years of data few migration events were actually associated with high discharge (Durif and Elie 2008). In 2001, three main runs occurred and only the second run could be associated with a flood event. Data from 1996 is also shown (Fig. 4.3) when a major run (28% of the total catch of the season in 1 night) occurred without any variation in discharge at the fishery or in the Loire tributaries. The only event that occurred prior to migration was heavy rainfall, but which did not have any effect on discharge.

Migration of silver eels in the River Meuse, as shown by the cumulative passage of eels at detection stations (Fig. 4.4), showed that most of the eel migration events took place at distinct moments during a couple of weeks in autumn when the river discharge started to increase (Bruijs et al. 2003; Winter et al. 2006). The main event occurred between 25 and 28 October 2002 during the first increase of river discharge. This migration event started upstream and reached the lower part of the river about 3 days later. Further analysis of the results showed that river discharge affects the migration route of silver eel in the downstream area of the River Meuse, where eels follow the route of highest discharge (Jansen et al. 2007). This is in accordance with the results found for distribution of eels over the alternative ways near a hydropower complex. Both results provide a clear indication of equal distribution of eels over the different migration routes in accordance with the river flow.

Migrating during high flow is clearly advantageous as it takes less energy. The dynamics of downstream migration are obviously linked to discharge since the swimming speed of the eel will necessarily depend on flow velocity. However, whether discharge constitutes an actual trigger is questionable. In any case, it is not necessary for the simple reason that many areas present no perceptible current and therefore this factor is probably not the essential trigger.

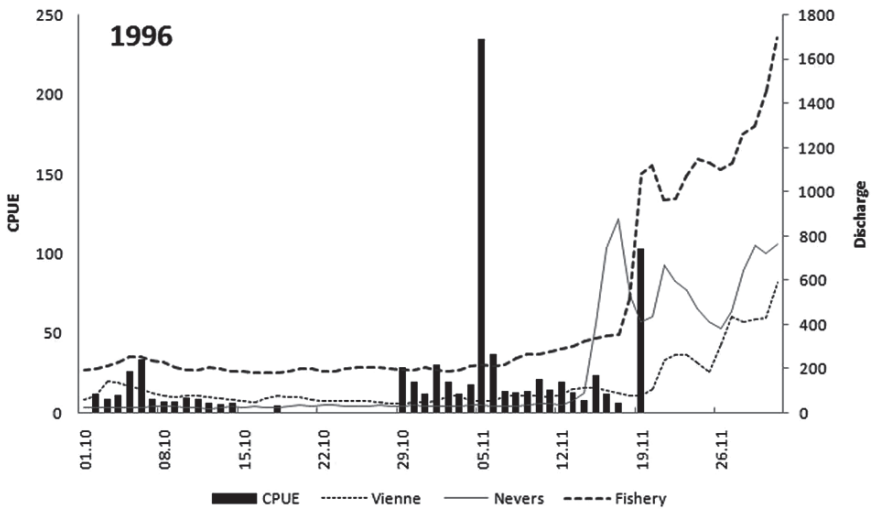

Fig. 4.3 Comparison of downstream runs of silver eels on the Loire River and discharge ($m^3 s^{-1}$) of several tributaries in 1996

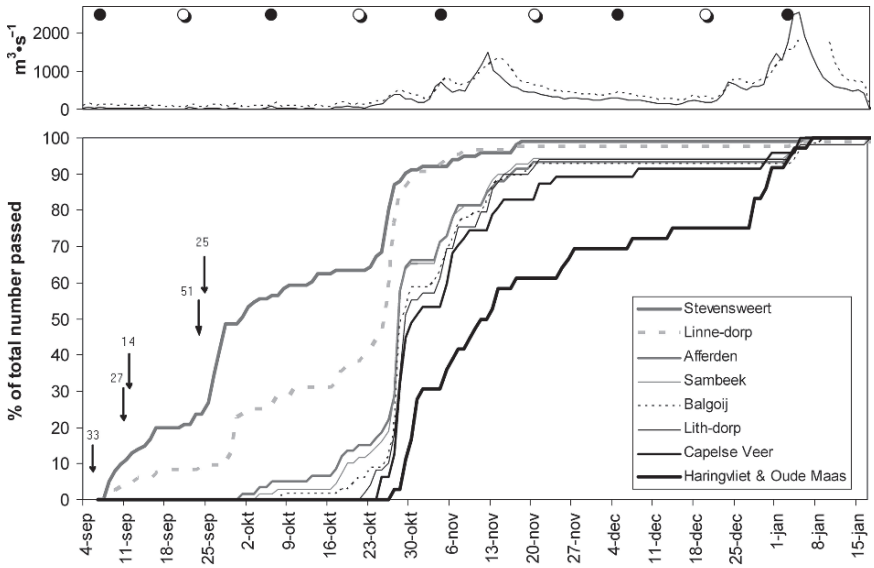

Fig. 4.4 Cumulative percentage of total passages of tagged silver eel per detection station (bottom panel). Arrows indicate the timing and number of eels released. River discharge ($m^3\ s^{-1}$) at Linne (—) and Alphen (- - -) and lunar phase (○ full moon; • new moon) are shown in the top panel (Bruijs et al. 2003)

4.2.5 Moonlight and Light

The effect of the moon appears to be dual. It is well known that eels are strongly photophobic, and a full moon will inhibit migration. There seems to be indeed an internal rhythm, but which can be obscured by hydrological or meteorological factors (Cullen and McCarthy 2003). From research and from experience of professional fisherman, it appears that silver eel are most active around the last quarter (Tesch 2003). Increased catches are observed in a period ranging from about 4 days prior to the last quarter, up to 2 days after the last quarter. Boetius (1967) and Jens (1952–1953) state that it is not the moonlight, but the moon phase that is the influencing factor. This is because eels in a closed tank also showed increased activity at the same time that eels in the river were active (Boetius, 1967) and because during cloudy nights the moon also had an influence. Lowe (1952), Deelder (1954), Hain (1975), Haraldstad et al. (1985) and Vøllestad et al. (1986) disagree with this. During a study by Haraldstad et al. (1985) it was observed that the migration was highest during the first quarter and stopped completely during full moon. The conclusion was drawn that migration is not influenced by phase, but depends on light. Deelder (1954) argues that the eel is exposed to the moon all of its life and it cannot be assumed that its preference is not continued when it is cloudy. Also, a night with new moon is always darker than a night with full moon, even when it is cloudy. Korringa (1947) suggests that moonlight triggers an internal

rhythm that is present whether there is light or not, such as is also observed for other animals. In that case the moonlight is the influencing factor. Around the last quarter the night is darkest. At new moon the sun and moon go down and set at the same time. A few days later the moon goes down later, so that during the first hours there is light. At full moon it is light during almost the full night, but from a few days after full moon the moon comes up a while after sunset and then the first hours are dark (Hain 1975). Independent statistical studies by Deelder (1954) and Jens (1952–1953) show that the migration of silver eel is largely influenced by the moon. That effect is however not the same everywhere. In the upper part of the Rhine, migration occurs before the last quarter, in the Baltic Sea and in Dutch inland waters after the last quarter.

Commercial fishery data from the Loire River (Durif and Elie 2008) showed that runs of eels were higher during the last quarter and the new moon (respectively 36% and 29%) compared to the full moon (17%) and the first quarter (18%). Although these differences were statistically significant (χ^2 test, $p < 0.001$), Analysis of Variance showed that the moon phase factor only explained 3% of the variability in CPUEs. No significant differences were found on the Nive River; eel runs occurred equally during full moon.

It is difficult to come to a conclusion on the effect of the lunar cycle. Endogenous activity has been shown (Jens 1952–1953; Boetius 1967), but it is clearly obscured by other factors (i.e. water turbidity, cloudy skies) that suggest that luminosity is the factor mostly affecting the runs.

4.2.6 Atmospheric Pressure

Professional fisherman and researchers have observed that the migration of silver eel often occurs during storms (i.e. atmospheric depression). In a similar way to the effect of the lunar phase, atmospheric pressure has often been cited as having an effect on the eel's behavior when they are in captivity, in a lake or in a closed water body (where no flow is perceptible). Eels become more active (active swimming and escapement behaviour) during thunderstorms (Lowe 1952). Deelder (1954) found a strong correlation between runs and the occurrence of microseismic oscillations (due to passage of depressions). Hvidsten (1985) also indicated that atmospheric pressure is statistically correlated with migration peaks. According to Okamura et al. (2002), atmospheric depression would trigger eel seaward migration (i.e. estuarine migration) where no rainfall or variation in flow can be detected.

4.2.7 Turbidity/Darkness

As mentioned above, eels are strongly photophobic and the inhibition caused by light surpasses the stimulatory effect of flow according to Hadderingh et al. (1999). They avoid bright lights. This strong behaviour is used to deflect eels from

hydroelectric turbines (see below). From the commercial fishery data on the Loire, it was observed that low light levels resulted in early migration, as did decreasing temperatures. All the events that tend to decrease the light level can be considered as favourable for downstream migration. During the silver eel study on the river Nive, downstream runs were mostly correlated with turbidity ($R^2 = 0.67$, Durif et al. 2003). Many authors indicate the positive effect of wind, which also increases turbidity. Eels usually stop migrating during daylight hours: commercial silver eel fishing always takes place at night. Eels sometimes pause for several weeks if there is an obstacle or when the light level is too high (Lowe 1952; Vøllestad et al. 1994; Durif et al. 2003; Watene et al. 2003). In the Middle Ages, silver eels were caught by lighting fires on the riverbanks, thus stopping the movements of downstream migrants (Bertin 1951). Bertin (1951) also mentions the experiments of Pedersen in 1906, who observed that eels stopped swimming when a beam of bright light was shone on the river.

4.2.8 Relevance of Migration Parameters

The migration of silver eel mainly occurs during the period after full moon and increases of river flow, often due to rainy periods in autumn. The main downstream migration events occur after sunset and before midnight. The most important parameters that induce the migration of silver eel therefore seem to be river flow and darkness/turbidity. These triggers are found to be significantly related to the start of migration in most studies. However, although silver eels commonly descend rivers when discharge rises (Euston et al. 1997; Bruijs et al. 2003; Durif et al. 2003), not all discharge events are accompanied by migration events. Also, darkness seems not always to be a prerequisite. Behrmann-Godel and Eckmann (2003) found during a study at a hydropower dam that the onset of migration coincided with the first flood event that followed the full moon, but was independent of daytime, because migration and turbine passage occurred during both day and night. These factors are thought to play a role in the efficiency of energy use by the animals and in protection from predators during the downstream migration.

4.3 Migration Barriers and Their Effects

4.3.1 Migration Barriers

During their downstream migration, silver eels meet many, principally manmade, obstacles that need to be passed before they reach the mouth of the river and the sea. Different types of barriers for downstream migration of silver eels exist all over Europe, presenting problems through obstruction of downstream movement as well

as risk for survival of silver eels. Such barriers are, for example, large barrages, flood-control dams, flood gates, weirs, hydropower stations, sluices, pumping stations and fisheries, which are abundant in many European river systems and inland waters. Most are built to enable water management, for example to control the water discharge and water level in rivers to ensure shipping, water conservation for irrigation etc. Such structures have an impact on river flows with much diversity in flow patterns. River systems like the Rhine, Meuse, Loire and Gironde are especially highly regulated. But the mouths of rivers into the sea are also often closed by dams and sluices, such as in the Netherlands, for protection against floods. Estuaries provide a gradual transition zone in salinity and temperature. Before entering the sea, the silver eel has the time for the necessary physiological adaptation to marine conditions. However, flood control sluices provide a sharp division between fresh and marine water. There is no brackish water zone for the fish to adapt to changing osmotic conditions. Silver eels and other fish are directly confronted with marine conditions which may have physiological consequences.

All these barriers significantly hinder the migration of silver eels and other migratory fish species. On a diurnal scale, timing of migration activities shows a higher number of detections at night, especially during the first half of the night. It was found by Bruijs et al. (2003) that the diurnal differences were stronger at the hydropower stations where 63% of all detections took place between 19 and 24 h, than at the river stations with 35% between 19 and 24 h. This is a clear indication that eel show hesitation to pass hydroelectric facilities and wait until flow conditions are more favourable. Moreover, pumping- and hydropower stations cause mortality among downstream migrating silver eels that pass through the pumps and turbines. When silver eels migrate all barriers present in the main river need to be passed before reaching the sea. Silver eels that live far upstream obviously need to pass more obstacles. Also, when an eel is living at distance from the main river course, such as in river branches, small streams and polders, it may need to pass extra barriers such as weirs and pumping stations. For better understanding of the problems of barriers for downstream migration and technical measures, improved detailed knowledge of silver eel behaviour at barriers is necessary (Kroes et al. 2006).

During downstream migration in rivers, eels appear to use the direction of stream flow as an orienting stimulus (Carton 2001; Jansen et al. 2007). This behavioural response to water currents is known as rheotaxis. Barriers in river systems are specifically built to alter the water flow: the main river flow is stopped and any excessive water is spilled in a controlled manner over the weir or spillway. If enough head is present at such a location, a hydropower station is often present. In that case the main river flow is directed through the turbines in order to produce energy. It is clear that migrating eels, following the direction of the main river flow, are hampered in their migration and are directed mainly through a turbine or alternatively over the adjacent weir.

It is not only through causing difficulty in finding a proper route to pass that barriers, hydropower stations, pumping stations and fisheries cause mortality among migrating eels which is potentially of great significance to overall eel stock. Fisheries and modern pumping stations are though to be most lethal for eels as in

principle all specimens that enter the fishing nets are landed and modern pumps are 100% lethal. Passage through the turbines of hydropower plants is lethal to a lesser extent, however, up to 50% of the turbine-passing eels may be killed depending on the type of turbine and when a series of stations is present in a river system, cumulative mortality may rise up to 100% (Dönni et al. 2001; Dumont et al. 2005; Dumont 2006).

The problem of downstream migration has been known for more that 200 years (Gerhardt 1893). However, only recent publications summarise the worldwide knowledge and technology standard for fish protection and downstream bypasses, i.e. to protect fish from entering intakes and to provide a safe bypass (Larinier and Travade 2002; Richkus and Dixon 2003; ATV-DVWK 2004; Dumont et al. 2005). Facilities to protect fish from entrainment and to enable a safe downstream migration have been installed at about 50 European hydropower stations (Gosset and Travade 1999; Hadderingh et al. 1999; Adam et al. 1999; Adam 2000). While there are cases that provide ample experience on the implementation and efficiency of fish protection and bypass facilities, the transfer of this knowledge to other water systems is yet to be done.

For a long time, many barriers have been impassable for any migratory fish species, both up and downstream. In recent years, fish passages are planned for many weirs and hydropower facilities in European rivers, at least to facilitate upstream migration. Even more protective measures for fishes can be expected as a result of the EC Water Framework Directive (EC 2000) which requires an undisturbed migration for fishes in river systems. Also, the EU has published guidelines for the protection of eels (EC 2005, 2006). For downstream passage, eels may use a fish passage, or in some cases specific downstream bypasses. Although upstream migration facilities are being installed at many barriers, only at a very limited number of hydropower plants are functional downstream migration facilities in operation.

4.3.2 Effects of Barriers on Downstream Migrating Silver Eel

In large regulated river systems, weirs and hydropower facilities are the most important barriers as they not only hinder migration, they also cause mortality among downstream passing fish populations. Next to the danger of hydropower plants, silver eels may also be affected by large drops over weirs or spill ways (Kroes et al. 2006) and by impingement and entrainment at pumping stations and industrial cooling water intakes. Increased flow velocities in front of intakes may act as an attraction flow for downstream migrating fish, or when the intake flow is higher than the maximum swimming capacity, fish may not be able to escape from the intake flow velocity. But especially pumping stations, which are used for water management in lowland polder areas in the Netherlands, Germany and Flanders, are thought to cause major damage to fish when these try to leave the polder area. Mortality due to passage through pumping stations is thought to be much higher

than with hydropower stations. In most cases no alternative routes, i.e. fish passages or weirs, are available, thus the pumping station is the only route. Also, the pump types that are in use cause 100% mortality. In summary, depending on the type of barrier, different types of damage to fish can occur (Adam and Bruijs 2006):

- In dams with heads over 10 m and/or an impact of hard structures in the tail water region, fish may suffer lethal injuries.
- Screens and trash racks in front of water intakes cause damage when fish are impinged and pressed against the racks by the approach velocity.
- Turbines and pumps cause mortality by direct contact with turbine blades, shear stress, cavitation and pressure differences.
- Fish that are entrained through the screens at cooling or potable water intakes die in the following zone.
- Fish that have passed and survived hydraulic structures are easy prey for predatory fish and fish-eating birds in the tailwater.
- A fast change of osmotic conditions at flood control sluices in coastal areas may provoke high mortality rate among the fish, especially when freshwater fish species are discharged into marine water.

However, a major cause of direct mortality among downstream migrating silver eels are hydropower stations, of which many have been built in European rivers in combination with a weir. These stations cause problems for downstream migrating fishes, in particular for the diadromous species which maintain a two-phase life-history involving extensive migrations between sea and freshwater. In many European rivers like the Rhine and Meuse numerous hydropower stations have been installed. The types of turbines used in European rivers are Kaplan, Straflo or Francis turbines. In the larger rivers these stations can have a capacity from 5 up to circa 100 MWe, like Iffezheim in the River Rhine.

The operation of hydropower stations in rivers produces potential injury to downstream migrating fishes if they become entrained in turbine-intake flow and pass along fast moving turbine blades. Early reports of fish mortality at European hydropower stations were published by Raben Von (1955, 1957) and by Berg (1986). In these studies, the average mortality rates for the European eel, which is very susceptible to injury of turbine blades, ranged between 15% and 38%. However, eels are not only entrained through the turbines; impingement on the trash racks may also cause severe mortality (Adam and Bruijs 2006). Trash racks prevent the intake of debris. When the approach velocities towards the trash rack or screens are higher than the swimming capacity, fish are impinged on the screen (Fig. 4.5).

In the period 1990–2002, several investigations on downstream fish migration at hydropower stations have been carried out or are underway all over the world. On the first International Catadromous Eel Symposium held in St. Louis (USA) in 2000, several presentations dealt with problems of eel passage at hydroelectric power stations in Canada, the United States, New Zealand and France (Dixon 2003). In Germany, Holzner (2000) studied the impact of fish passage through the turbines of Dettelbach hydroelectric power station on the river Main, a tributary

Fig. 4.5 Eel collected from the trash rack at the Wahnhausen power station at the river Fulda in Hessen, Germany (photo by Adam B)

of the river Rhine. In the Netherlands fish passage mortality was studied at Linne hydroelectric power station on the river Meuse in 1990/1991 (Hadderingh and Bakker 1998) and in 1999, as well as in 2001 and 2002 (Bruijs et al. 2003).

Injuries and mortality are established directly after collecting the fish; this mortality can be defined as direct mortality. Delayed mortality, for example mortality after 24 h, cannot be excluded but in many cases was not investigated. The most frequent type of injury of eel are bisections (chopped), broken backbones and internal haemorrhages. Other fish species show considerably lower mortalities. This difference is probably caused by the relatively great length of the eel resulting in a higher strike probability of the turbine blades during the passage through the turbines.

In Europe, most applied turbine types are Kaplan turbines. Different eel mortalities are found: at Linne, the highest lethal injuries, up to 30% of the fish that pass the turbines, have been found for eels, 38% mortality at Neckarzimmern Germany, 22% mortality at Dettelbach Germany, 20% at Obernau Germany, 24% at Beauharnois Canada, and 37% at Raymondville USA (Hadderingh and Bruijs 2002). Of special importance for silver eels is the cumulative mortality due to passage through a series of hydroelectric power stations. Typically, 15% to 25% of silver eels passing through the turbines of a hydroelectric power station in a large river, such as the Meuse or the Mosel, are fatally injured. Therefore, the average survival rate amounts to 80% or 0.8 per facility. The passage through a second facility leads to an average rate of 0.8*0.8 = 0.64. The total survival rate of downstream migrating silver eels after the passage of five hydroelectric power stations drops to approximately 30%. A higher number of obstacles virtually prevent all silver eels from reaching the sea. Dönni et al. (2001) made a calculation of the cumulative

mortality of downstream migrating silver eels for the River Rhine between Lake Constance and Basel. The cumulative mortality of downstream migrating silver eels, passing the maximal number of 11 hydroelectric power stations in this stretch of river, amounted 93%.

Bruijs et al. (2003) investigated the cumulative mortality of silver eels in the River Meuse by means of telemetry. In September 2002, 150 silver eels were surgically implanted with Nedap-transponders and released at the catch site, upstream in the River Meuse. Of these, 121 started to migrate downstream of which 37% successfully reached the North Sea (Winter et al. 2006). Hydropower mortality was at least 9% and assessed to be 16–26%. Fisheries mortality was at least 16% (reported recaptures) and estimated to be 22–26%. Also a difference was found in diurnal pattern; 63% of the eels that passed through the turbines did so during the first 5 h of the night after sunset, whereas for the stations on free-flowing sections this was only 35%.

4.4 Eel Behaviour at Barriers

4.4.1 Hesitation at Trash Racks

In order to investigate the technical possibilities and efficiency of mechanical systems in front of the intakes of hydropower stations, a number of laboratory studies have been performed focusing on eel behaviour, including Adam (1999), Amaral (2003), Adam et al. (2002). Only a few studies have investigated the specific behaviour of eels during their natural downstream migration and passage of hydropower stations (Haro et al. 2000; Durif et al. 2003; Bruijs et al. 2003; Behermann-Godel and Eckmann 2003).

It was found during investigations in model flumes, that eels react differently to mechanical barriers than do other fish species (Adam and Schwevers 2001; Amaral 2003). When eels approach the intake area of hydropower stations they show hesitation when confronted with the trash racks. Although the main river flow that is used by silver eels to migrate downstream in general runs through the turbines, the majority stop and try to seek alternative routes. Some eels even return in an upstream direction and come back only weeks or months later (Bruijs et al. 2003; Winter et al. 2006; Jansen et al. 2007). When no alternative routes are available or when these are difficult to find, the eel eventually will pass through the trash racks. The eel may swim close up to the trash rack, without passing, and stay there for a while, swimming up and down.

It can be concluded that eels show a clear hesitation to pass the trash racks at hydropower station as well as an upstream-orientated escaping movement in front of trash racks. The upstream-orientated escaping movements of eels in front trash racks were clearly observed in flume tank experiments and described by Adam (1999, 2000) and Adam et al. (1999) (Fig. 4.6).

The typical behaviour of the silver eel in front of trash racks has also been observed the field. For example, during fishing efforts in the headwater with fyke

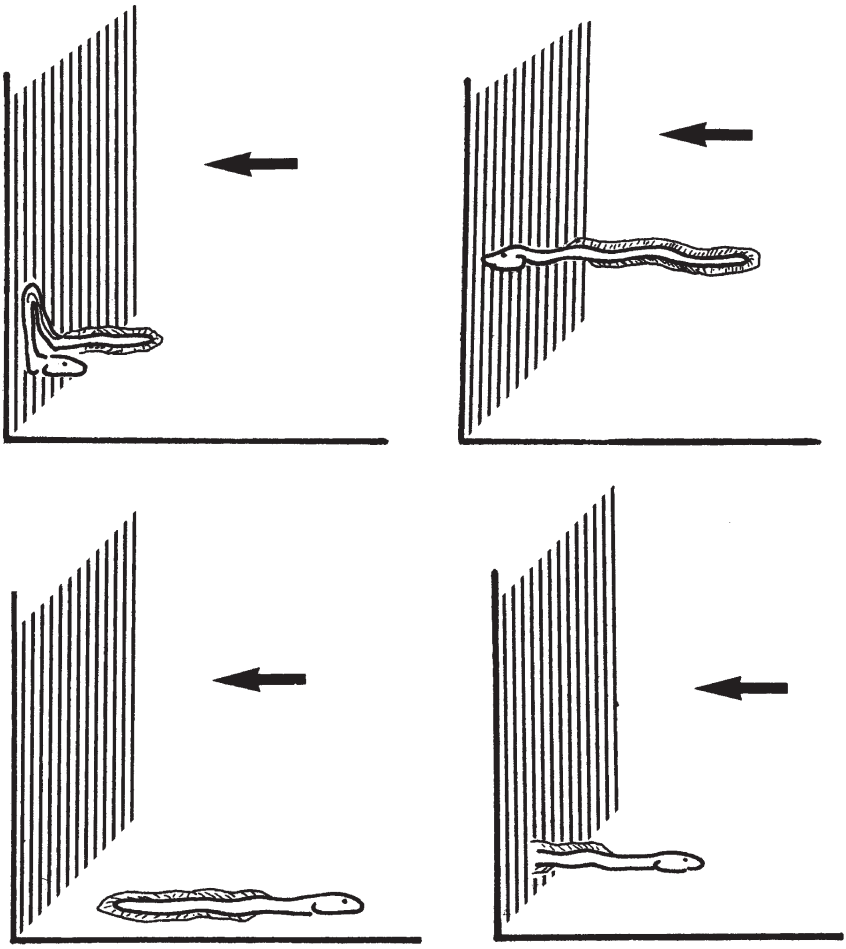

Fig. 4.6 Different phases of the reaction of eel (return behaviour) in front of a mechanical barrier (Adam et al. 1999)

nets placed with the opening in a downstream direction, eels that have returned from the trash rack entered the fyke nets in an upstream direction (RH Hadderingh, 2000, personal communication). The observations of the upstream-orientated escaping movements of eels in front of trash racks are furthermore confirmed by investigations of Holzner (2000) at the hydropower station of Dettelbach on the river Main in Germany and by Haro et al. (2000) at the Cabot hydropower station on the Connecticut River (USA). Figure 4.7 (Brown 2005; Brown et al. in press) provides a clear example of the movement of eels in the fore bay. The eels were found to move around at a range of depths, spending much time at or near the bottom. The eels are also found in the main flow in the fore bay for most of the time.

Bruijs et al. (2003) found clear differences between tagged eels in passage behaviour at hydropower stations, i.e. eels showing hesitation in front of the intakes; 40%

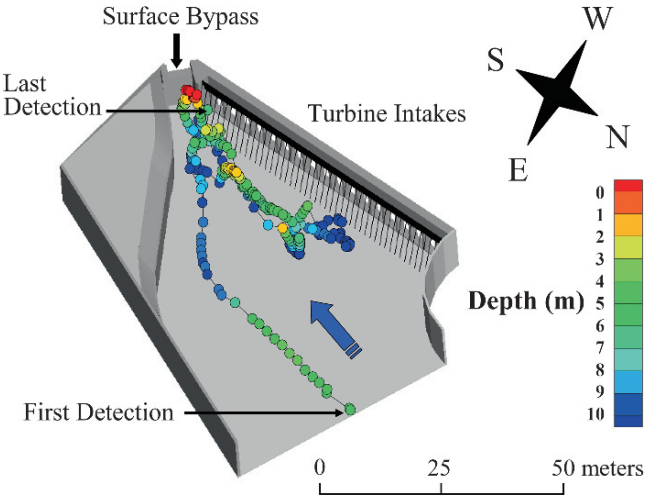

Fig. 4.7 Track of depth-telemetered eel in Cabot Station fore bay, Connecticut River, Massachusetts. The depth of each detected position is colour coded; dark blue is at or near the bottom, green is in the mid-water column, and red is at or near the surface (see legend) (Brown 2005; Brown et al. 2008)

of the eels showed recurrence, in contrast to the river stations where this hardly occurred, indicating a hesitation to pass the trash rack (Winter et al. 2006; Jansen et al. 2007). Eel passage of the river stations was characterized by usually only one or a series of detections with 2 min intervals, whereas the passage of the detection stations at the intakes of hydropower stations showed a different pattern (Winter et al. 2006). Apart from eels that were detected once, one group showed recurrence with intervals above 2 min, varying from several hours to several weeks. Another group showed stationary behaviour indicated by a series of detections with 2 min intervals. Eels showing odd behaviour might seek alternative routes to pass the hydropower station, for example by migration through the fish passage or over the weir.

Behrmann-Godel and Eckmann (2003) found that when migrating eels arrived at the hydropower station, they either passed through the turbines immediately or stayed upstream of the powerhouse for up to 8 days, showing a characteristic circling behaviour. Circling eels repeatedly approached the trash rack, sprinted upstream, and finally passed through the turbines with the next high water discharge.

4.4.2 Making Use of Silver Eel Behaviour to Bypass Hydropower Stations

The damages caused to silver eels occur during the passage of turbines, where they suffer mechanical injuries as a result of being hit by the runners and turbine blades or from pressure fluctuations and turbulences (shear stress) due to the flow condi-

tions. In addition, in the long term, fish-friendly turbines are not expected to replace the old ones at the many existing hydroelectric power stations. In order to prevent damage of eel by turbine passage, several types of barriers, which are basically divided into mechanical and behavioural screening techniques, can be applied.

4.4.2.1 Mechanical Barriers

Laboratory and field research studies carried out all over the world have proved the suitability of mechanical barriers mounted in front of turbines to physically prevent eels from entering the turbines. Laboratory experiments (Adam et al. 1999; Schwevers 1998) showed that eels are able to escape at velocities $<0.5\,\mathrm{m\,s^{-1}}$. Eels that come in direct physical contact with the trash rack react by turning and swimming upstream. In addition, Adam (2000) concluded, based on laboratory observations, that eels show an initial period of hesitation to pass the trash rack and searching behaviour but at a later stage tried to pass the bars. Eels of 70 cm length have been found to pass trash racks with a bar width of 2 cm, and 40–50 cm eels passed through 18 mm racks (Jens 1987).

Under certain conditions, the silver eel is thus very capable of maintaining itself in front of trash racks at water intakes for a certain period of time. Field observations of this behaviour have been made by Haro et al. (1999) at the Cabot hydropower station on the Connecticut River. Eels of up to 90 cm showed a strong hesitation to pass racks of 102 mm bar width, but in the end did pass the trash rack. This behaviour was also observed by professional fisherman in the river Mosel (R Eckmann, 1999, personal communication) and at investigations in the river Main (Holzner 2000) as well as by Bruijs et al. (2003) in the River Meuse.

Gosset et al. (2005) investigated the behaviour of eels in the forebay by means of radiotelemetry. Almost half of the eels returned upstream of the headrace after their release, and most eventually migrated downstream over the adjacent dam during appropriate environmental conditions. Upon arrival at the power plant, eels displayed foraging behaviour in the forebay with frequent displacements interrupted by long resting periods in zones with low current. The repulsive effect of the trash rack located in front of the turbine intake increased with increasing turbine discharge. The study indicated that a trash rack with a smaller bar-spacing (around 20 mm), associated with an appropriate bypass, could deflect a large proportion of the female eels from the turbines. However, the risk of mortality due to impingement on the trash rack was not investigated. This behaviour can be used as a way to divert silver eel from turbines, which must be combined with altered turbine management and the availability of appropriate bypasses or alternative route over an adjacent weir.

Results obtained in laboratory and field studies show that the following values for mechanical barriers should not be exceeded (DWA 2005):

- Internal width of mechanical barrier: $d <= 15\,\mathrm{mm}$
- Approach velocity before the barrier: $v <= 0.5\,\mathrm{m\,s^{-1}}$

Middle-sized and large hydroelectric power stations usually employ barriers with d = 50 to 150 mm and the approach velocity may reach up to 1.0 m s^{-1}. In most hydroelectric power stations, the construction of a 15 mm barrier would create serious technical and economical difficulties. Furthermore, there exist to date no appropriate devices for the removal of the accumulated debris at such fine barriers. Today the employment of the described barriers is limited to hydroelectric power stations with a maximum discharge rate of 20 m^3 s^{-1}, whereas normal facilities, such as those in the rivers Meuse, Rhine and the Mosel reach levels of up to 400 m^3 s^{-1}. Mortality among downstream migrating silver eels can therefore only be prevented if passage through turbines is avoided.

4.4.2.2 Behavioural Barriers

Fish protection at water intakes has traditionally been achieved by fine physical screens. However, such systems are costly to purchase, operate and maintain. They may become blocked easily by debris, restricting water flow resulting in loss of effectiveness. Behavioural deterrent systems are an alternative, used where mechanical fish screening is impracticable. Fish have a number of well-developed senses and are able to detect and react to light, sound, temperature, pressure change and many other stimuli. The relative sensitivity and capacity to react to any of these stimuli varies with species and life stage. To be effective, the stimulus must be strong enough to repel fish at a range where they are not at risk of being involuntarily drawn into turbines by the strength of the water current. For eels, light is an effective stimulus. In general, several reactions to light can be expected including general behaviour towards natural light, such as the diurnal rhythm of fish in relation to the surrounding illumination level where the activity of the fish changes with the illumination level. Reactions of fish as a result of observing artificial light sources absent in their natural environment can be exploited with fish deflection systems.

With respect to the development of a suitable deflection method at water intakes, two behavioural characteristics of eels are very important. Firstly, eels are negatively phototactic. During the day eels hide in the bottom. They are nocturnal and the downstream migration of most silver eels occurs at night (Haraldstad et al. 1985; Tesch 1977). This behaviour is demonstrated by the catch of eels in the cooling water sieves of Bergum thermal power station (situated at a lake) where eels almost exclusively impinge during the dark period (RH Hadderingh, 2001 personal communication). The downstream migration of silver eels takes place almost completely during the night. Van Drimmelen (1951), Lowe (1952), Bräutigam (1961, 1962) and Hölke (1964) used the light-avoidance reaction of eels for commercial fishery purposes and increased their catch by directing eels to fishing nets by means of underwater lamps. Secondly, eels are strongly attracted to water currents; the highest commercial catches are achieved in the main stream of rivers (Tesch 1977). The preference of migrating eels for areas with the highest current might be explained by the saving of energy as the need for active swimming is reduced (Hansen and

Jonsson 1985) and a shorter migration period is required to reach the sea (Thorpe et al. 1981). The application of light barriers has been extensively investigated by Hadderingh (1982) and Hadderingh et al. (1992, 1999). The results (i.e. the effectiveness) of a light system are varying and strongly depend on different factors such as: the angle between the barrier and the flow direction, the water velocity, turbidity and the availability of an effective bypass.

4.4.2.3 Bypasses

Most of the described observations on eel behaviour are discussed with respect to the design of appropriate downstream passage facilities. The eels' behaviour clearly indicates that it is possible to provide a safe passage facility near the trash racks. As the eels are not willing to pass the trash rack they will seek for an alternative route, provided the conditions are appropriate. Such an alternative passage or bypass must be found by the eel through a clear attractive flow. Investigations on designs for the effectiveness of such bypass facilities will increase in the near future as it may provide cost-effective solution for eel passage at hydropower plants.

To achieve good results in deflecting fish, both the deflecting part and the bypass part of the system has to be successful. Till recently little attention was paid to the design of bypasses. A properly functioning bypass has to fulfil a number of conditions such as: dimensions of the opening, water velocity and illumination level. Intensification of laboratory and practical research on bypasses is therefore recommended. To be successful the bypass must comply with a number of requirements. In France, much research has been done on this aspect by Larinier et al. (1996) and harinier (1998) but these did not concern eels.

Gosset et al. (2005) tested the efficiencies of two potential bypasses for downstream migration. These consisted of a surface and a bottom sluice installed on the spillway of a small hydroelectric power plant in France. Total efficiency of both bypasses, evaluated on the basis of downstream movement of radiotagged eels, ranged from 56% to 64%. However, preferred passage through the bottom bypass for both tagged and untagged eels was confirmed by telemetry, as three to four times as many eels transited through the bottom bypass compared to the surface one.

After entering the bypass system, the fish must be transported through a tube or drain system. To prevent damage, sharp angles, rough walls and shocks must be prevented. Also, the maximum current must be 12 m s^{-1} and the diameter of the tubes/drains must be large enough to prevent clogging. In order to prevent damage at the outlet, the outlet must be located in a horizontal plane. Also, the maximum height must be 1–3 m.

At non-lethal barriers, such as weirs and dams, a spillway or small bypass with sufficient attraction flow will do. The eels search for possibilities to pass the barriers and will make use of the flow through such facilities, as these are the only routes. At hydropower stations, where the main river flow runs through the turbines, directing eel towards the bypass is more difficult. The findings described above regarding the hesitation reaction of eel in front of a hydropower

facility, combined with the observations of their searching behaviour, indicate that there are good possibilities to divert eels from trash racks and inlet channels of hydropower facilities. The simplest way is through an existing fish pass. However, in many cases the entrances are not optimal: they are often located too far away from the area in which the eels search and the attraction flow is too small to attract them. A bypass needs to be located close to the power station inlet. The entrances could or should be located at the bottom, mid-depth and at the surface.

The behavioural pattern of eels in front of passable and impassable trash racks up to an approach velocity of 0.5 m s^{-1} is characteristic for eels. It has led to the development of alternative bypass systems, such as the so-called Bottom Gallery® (by Floecksmühle and IFÖ, Germany). It consists of a bottom-oriented bypass system crossing the inlet of a hydropower station. However, it has not been tested yet under real conditions in front of a hydropower station. Also other bypass constructions that enhance the passage of silver eel through alternative routes have been designed, but so far no real implementations have been made.

4.4.2.4 Prediction of Downstream Migration

As an alternative to mechanical and behavioural fish protection systems, protection can be achieved by means of turbine management that takes into account the migration behaviour and migration timing of silver eels. To operate an effective turbine management system, information is needed on the timing of silver eel migration, i.e. a prediction tool is required. Attempts at modeling downstream migration have been made (Hvidsten 1985; Vøllestad et al. 1986; Vøllestad et al. 1994; Euston et al. 1997; Haro et al. 2003), but results in terms of prediction of number of migrating eels are low because models have to take into account not only environmental factors, but also the number of eels physiologically ready to migrate (i.e. silver-phase eels) in a given year as well as the type of hydrosystem (river, lake, marsh) and the presence of obstacles (dams and hydropower stations). Another approach relies in using the innate locomotor activity of eels at the time of downstream migration to predict the runs (Durif et al. 2008). Such a tool may be modelled information or an early warning system.

A tool to assess the distinct periods with silver eel peak migration is the Migromat system (Adam 2000). The Migromat predicts migration events in free-living eels by monitoring activity of eels held in tanks close to the river. The system contains two tanks, each with five connected compartments, which are continuously supplied with river water (Fig. 4.8). Each tank is stocked with 60 silver eels. Displacements of PIT-tagged eels between the compartments are detected by frame antennae around the openings between compartments. Increases in activity level, i.e. eel passages between compartments, indicate pre-migratory restlessness and predict migration timing. For its application, the Migromat systems should be installed on the riverbank close to the hydropower stations. The warnings provided by the system allow for turbine management, i.e. the turbines can be closed down during migrating peak periods of silver eel to offer them a save passage over the weirs and bypasses.

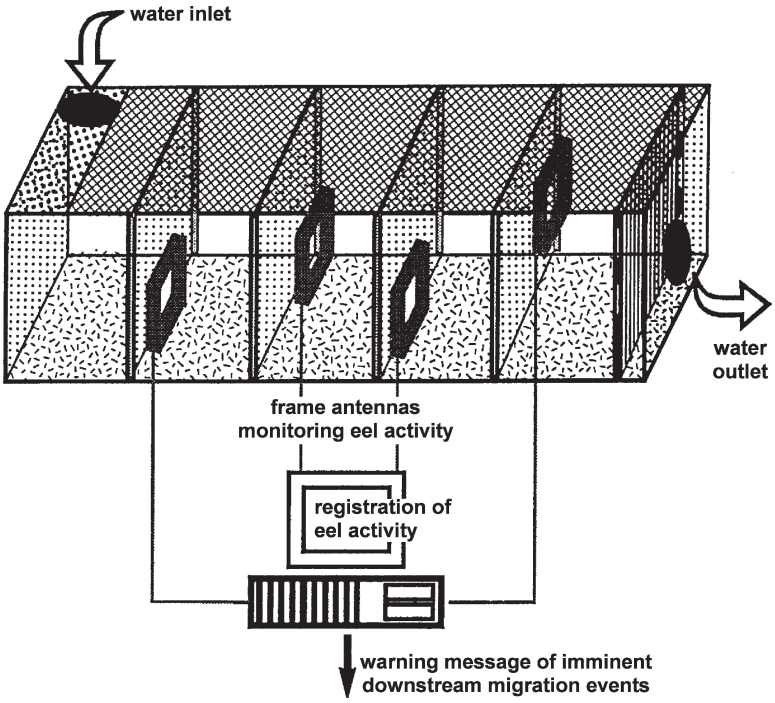

Fig. 4.8 Schematic overview of the Migromat system. Only one of the two tanks is shown

Bruijs et al. (2003) investigated the application of the Migromat at Linne hydropower station in the River Meuse. The correspondence of migration events in the river found by the different monitoring experiments with the warnings provided by the Migromat verify that the system accurately registers the pre-migratory restlessness of eels, thereby predicting the downstream migration events of silver eels with high precision (Adam and Bruijs 2006; Bruijs et al. in press). An example of this prediction is shown in Fig. 4.9. The increase of activity within the Migromat corresponds with an increase of turbine passages as monitored by means of telemetry. This increased turbine passage occurs only several hours after the warning is sent out by the system, leaving sufficient time for the hydropower station operator to adjust the turbine operations.

The prediction of migration events by this early warning system enables an eel-friendly turbine operating management of hydropower plants, by which a high percentage of downstream migrating eels can be saved. Application of the Migromat throughout the migration season of 2002, would have reduced the total mortality by hydropower in the Dutch section of the River Meuse by a maximum of 69.4%, assuming that all eels pass over the weir or through the fishpass without hesitation (Bruijs et al. in press). Closing down the turbines for longer migration periods e.g. a number of months during the autumn, being the main migration period for silver eel, means a substantial loss of electricity production for the electricity companies. Closing down the turbines during short periods with peak migration will be a better option.

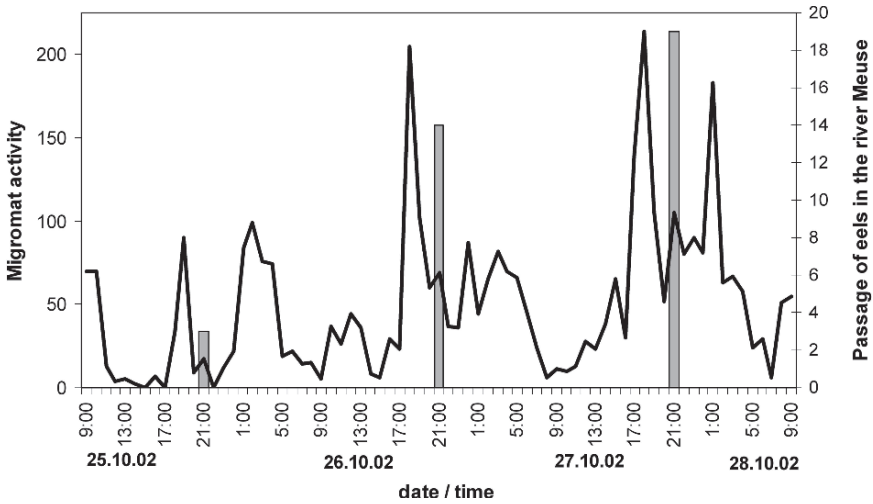

Fig. 4.9 Number of eels passing the Linne hydropower station as determined by the telemetry system (bars) and eel activity index in the Migromat system (line), 25–28 October 2002

The Migromat system is applied as a protective measure at the Wannhausen hydropower station in the river Fulda in Germany. Due to the limited bar width of 2 cm and the high approach velocity of ~1 m s^{-1} silver eels impinged on the trash rack, leading to damage of vertebrae and organs (Schwevers 1998), see also Fig. 4.3. Based on the warnings by the Migromat, the flow of the turbines of the Wannhausen hydropower station is halved in order to maintain an approach velocity of 0.5 m s^{-1}. This enables the eels to escape from the trash rack. By implementing this measure, the damage was decreased significantly (Adam B and Dumont U, 2007, personal communication).

Similar experiments were carried out during the silver eel monitoring study on the River Nive (Durif et al. 2008). PIT-tagged eels were placed in tanks fitted with a flat board antenna (Fig. 4.10). Eels showing escaping behaviours and bursts of activity were automatically recorded by the antenna. Counts of activity (i.e. number of detections) were compared with the number of wild migrating eels caught in the trap as well as changes in environmental factors. Results showed that activity of eels was always high during the first 3–4 days after they were placed into the tank. After this acclimation period, they only showed peaks of activity during specific periods, and sheltered under the clay tiles for the rest of the time. Video observations showed that during active periods, eels would either swim in circles along the walls of the tanks at moderate speed or try to escape by jumping above surface level towards the water inflow.

Although correlations between the number of eels caught in the trap and the activity counts were not statistically significant, both were closely related (Fig. 4.11, top panel). Most migratory eels in 2000 were caught between 13/10 and 25/10 when captive eels were most active. During this period, the four peaks of activity

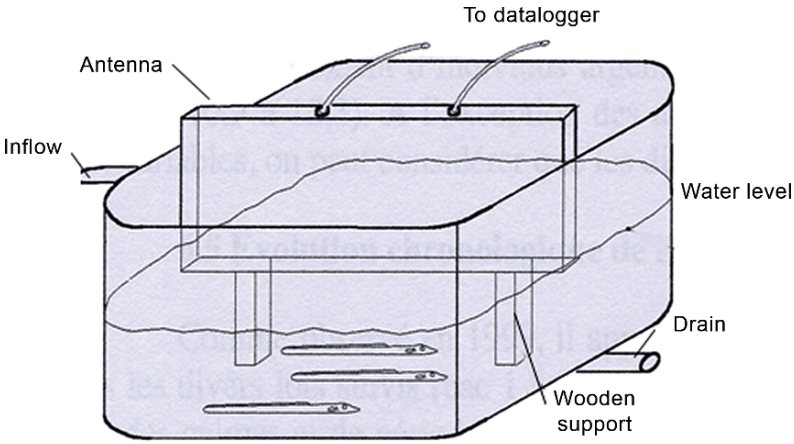

Fig. 4.10 Schematic of the eel activity detection tank

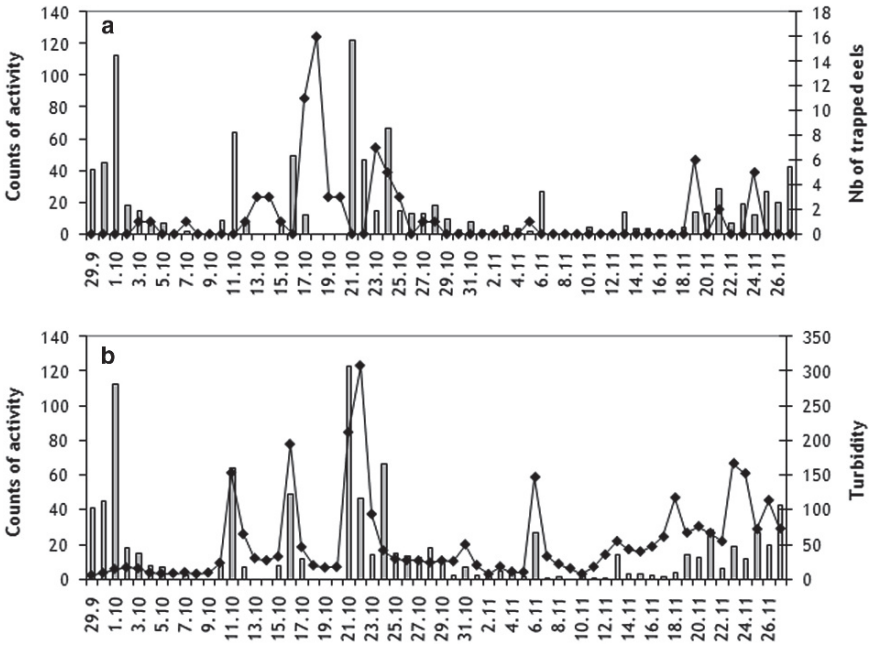

Fig. 4.11 Results of the study on locomotor activity of silver eels on the river Nive in 2000. Counts of activity (bars) are compared with the number of wild silver eel caught in a trap

were closely followed, approximately 24 h later, by captures of migrants in the trap. Activity in the tank was then reduced until 18/11, when eels became agitated again concurrently with a second wave of downstream migration. These activity peaks

were also closely related to increases in turbidity (Fig. 4.11, bottom panel) and both were highly correlated ($R^2 = 0.45$ when the acclimation period was removed).

4.5 Conclusions

Worldwide, populations of the eel, *Anguilla anguilla*, are undergoing a severe decline. The causes for this are not clear because a large part of the eel's life cycle remains unknown (i.e. transatlantic migration and spawning). However, it is quite clear that inland, anthropogenic impacts have a disastrous effect. Indeed, the result of human activities, such as obstruction of downstream migration causes great mortality. Hydropower has a clear and significant effect on the total survival and escapement of adult silver eel. To implement efficient mitigation measures, we need to understand what triggers the eel to migrate.

Recent studies on the silver phase eels have shown that it is important to differentiate the physiological modifications that lead to the silver stage (i.e. silvering, see Chapter 2) from the actual migratory movements. Eels are physiologically ready to migrate at the end of summer and this will probably determine for the most part the onset of migratory movements. Temperature and photoperiod variations appear to trigger silvering in fish that are physiological ready (length, age, fat content). However, migratory movements seem to depend on other factors. Habitats of eels are extremely variable. They are found in freshwater and saltwater, lakes, ponds, marshes, rivers and estuaries, and yet they must rely on the same cues for the onset of downstream movements. River flow is usually well correlated with runs of eels, but it is probably not a necessary trigger since many water bodies do not present any variation in flow. Knowledge obtained from the Migromat early-warning system as well as the study of locomotor activity of silver eels on the river Nive, also support this, since eels in the tanks could not perceive the flow (Durif et al. 2008). A decrease in light level is essential for eel migration. Increased turbidity causes greater activity in silver eels. More research on sensory mechanisms of eels is needed to understand what causes the increased locomotor activity.

The European Commission has published a regulation to establish a framework for the protection and sustainable use of the stock of the European eel (EC 2007), which, among other measures, includes the target that management actions must allow an escapement of 40% of the silver eel population from each European river basin. These developments will increase pressure for measures that protect eels and other species during their downstream migrations.

Obstructions in rivers may cause significant delay and mortality among downstream-migrating silver eel. To investigate the relative role of, in particular, hydropower stations, research on eel behaviour in relation to dam and turbine passage has been conducted, but much work is needed still. The knowledge obtained in laboratory studies and field observation on the eel's specific behaviour can be used to develop methods to guide silver eels along obstructions. As they migrate in groups and collectively react to environmental cues, a combination of protective measures based on their behaviour is thought to be optimal.

References

Acou A, Laffaille P, Legault A, Feunteun E (2008) Migration pattern of silver eel (*Anguilla anguilla*, L.) in an obstructed river system. Ecology of Freshwater Fish 17: 432–442.

Adam B (1999) Aalabwanderung – ergebinsse von Versuchen in Modellgerinnen. Arbeiten des Deutschen Fischereiverbandes 70: 37–68.

Adam B (2000) MIGROMAT® – ein Frühwarnsystem zur Erkennung der Aalabwanderung. Wasser and Boden 52(4): 16–19.

Adam B and Bruijs MCM (2006) General requirements of fish protection and downstream migration facilities. Investigations on the river Meuse system. In Free Passage for Aquatic Fauna in Rivers and Other Water Bodies. Proceedings of the International DWA Symposium on Water Resources Management. April 3–7, 2006, Berlin, Germany.

Adam B and Schwevers U (2001) Planungshulfen fur den Bau funktionsfahiger Fischaufstiegsanlagen. Bibliothek Natur and Wissenschaft, Band 17: 64S.

Adam B, Schwevers U and Dumont U (1999) Beiträge zum Schutz abwandernder Fische – Verhaltensbeobachtungen in einem Modellgerinne – Solingen (Verlag Natur and Wissenschaft), Bibliothek Natur und Wissenschaft 16: 63S.

Adam B, Schwevers U and Dumont U (2002) Rechen- und Bypassanordnungen zum Schutz abwandernder Aale. Wasserwirtschaft 92(4–5): 43–46.

Amaral SV, Winchell FC, McMahon BJ and Dixon DA (2003) Evaluation of angled bar racks and louvers for guiding silver phase American eels. American Fisheries Society, Symposium 33, pp. 367–376.

ATV-DVWK (2004) ATV-DVWK-Themen WW-8.1: Fischschutz- und Fischabstiegsanlagen – Bemessung, Gestaltung, Funktionskontrolle. Hennef (ATV-DVWK – Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V.) 256S.

Behrmann-Godel J and Eckmann R (2003) A preliminary telemetry study of the migration of silver European eel (*Anguilla anguilla* L.) in the River Mosel, Germany. Ecology of Freshwater Fish 12: 196–202.

Berg R (1986) Fish passage through Kaplan turbines at a power plant on the River Neckar and subsequent eel injuries. Vie Milieu 36: 307–310.

Bergersen R, Klemetsen A (1988) Freshwater eel *Anguilla anguilla* L. from North Norway with emphasis on occurrence, food, age and downstream migration. Nordic Journal of Freshwater Research 64: 54–66.

Bertin L (1951) Les anguilles. Variation, croissance, euryhalinité, toxicité, hermaphrodisme juvénile et sexualité, migrations, métamorphoses, Vol. Paris: Payot.

Boetius J (1967) Experimental indication of lunar activity in European silver eels, *Anguilla anguilla*. Medelelser fra Danmarks Fiskeri og Havundersøgelser 6(1): 1–6.

Bräutigam R (1961) Über Versuche zur Intensivierung des Blankaalfangs durch die Kombination von Lichtsperren und Großreusen und ihre grundsätzlichen Bedingungen. Fischereiforschung; 4; (1/2); S. 19–25.

Bräutigam R (1962) Intensivierung des Blankaalfangs mit Hilfe von Lichtsperrketten und Bedingungen der gewerblichen Anwendung. Fischereiforschung: 5: 6: S. 8–15.

Bruijs MCM, Polman HJG, Van Aerssen GHFM, Hadderingh RH, Winter HV, Deerenberg C, Jansen HM, Schwevers U, Adam B, Dumont U and Kessels N (2003) Management of silver eel: Human impact on downstream migrating eel in the river Meuse. EU-Report Contract Q5RS-2000-31141.

Bruijs MCM Hadderingh RH, Schwevers U, Adam B, Dumont U, Winter HV (In press) Managing human impact on downstream migrating European eel (*Anguilla anguilla*) in the River Meuse. In Eels at the Edge science, status and conservation concerns. Casselman JM and Cairns D (eds). Bethesda, MD: American Fisheries Society, Symposium 58, Bethesda, Maryland.

Brown LS (2005) Downstream passage of silver phase American eels at a small hydroelectric facility. M.Sc. thesis, University of Massachusetts, Amherst, 122 pp.

Brown LS, Haro A and Castro-Santos T (2008) Three-dimensional movement of silver-phase American eels (*Anguilla rostrata*) in the forebay of a small hydroelectric facility. In Casselman JM and Cairns D (eds) Eels at the Edge. Bethesda, MD: American Fisheries Society, Symposium 58 (in press).

Brown LS, Haro A and Castro-Santos T (in press) Three-dimensional movement of silverphase American eels (*Anguilla rostrata*) in the forebay of a small hydroelectric facility. In Eels at the edge: science, status, and conservation concerns. Casselman JM and Cairns DK (eds.) American Fisheries Society, Symposium 58, Bethesda, Maryland.

Carton G (2001) Do fish have feelings? Discovering how fish detect water flows. Water & Atmosphere 9(3): 10–11.

Cullen P and McCarthy TK (2003) Hydrometric and meteorological factors affecting the seaward migration of silver eels (*Anguilla anguilla*, L.) in the lower River Shannon. Environmental Biology of Fishes 67: 349–357.

Deelder CL (1954) Factors affecting the migration of the silver eel in Dutch inland waters. Journal du Conseil Permanent International Pour I'Exploration de la Mer, 20: 177–185.

Dixon DA (ed) (2003) Biology, Management, and Protection of Catadromous Eels, Vol. Bethesda, MD: American Fisheries Society, Symposium 33.

Dönni W, Maier KJ and Vicentini H (2001) Bestandsentwicklung des Aals (*Anguilla anguilla*) im Hochrhein. Mitteilungen zur Fischerei Nr. 69. Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern.

Dumont U, Danderer P and Schwevers U (2005) Handbuch Querbauwerke. Düsseldorf (Ministerium für Umwelt und Naturschutz, Landwirtschaft und ländlichen Raum NRW), 212S.

Dumont U (2006) Report on the restoration of the longitudinal connectivity of the river Sieg. Ingenieubüro Floecksmühle. March, 2006. pp 15.

Durif C (2004) Thesis abstract: The downstream migration of the European eel *Anguilla anguilla*: Characterisation of migrating silver eels, migration phenomenon, and obstacle avoidance. Cybium 28: 26.

Durif C, Elie P, Gosset C, Rives J, and Travade F (2003) Behavioral study of downstream migrating eels by radio-telemetry at a small hydroelectric power plant. In Dixon DA (ed) Biology, Management, and Protection of Catadromous Eels. Bethesda, MD: American Fisheries Society, Symposium 33, pp. 343–356.

Durif C, Dufour S, and Elie P (2005) The silvering process of *Anguilla anguilla*: A new classification from the yellow resident to the silver migrating stage. Journal of Fish Biology 66: 1025–1043.

Durif CMF and Elie P (2008) Prediction of downstream migration of silver eels in a large river catchment based on commercial fishery data. Fisheries Management and Ecology 15: 127–137.

Durif CMF, Travade F, Rives J, Elie P and Gosset C (2008) Relationship between locomotor activity, environmental factors, and timing of the spawing migration in the European eel, *Anguilla anguilla*. Aquatic Living Resources 21: 163–217.

DWA, 2005. DWA Topics: Fish protection technologies and downstream fishways. Dimensioning, Design, Effectiveness Inspecion. July 2005. Deutsche Vereinigun fur Wasserwirtschaft, Abwasser und Abfall e.V. pp 226.

EC (2000) Water Framework Directive, 2000/60/EC.

EC (2005) Proposal for the recovery of the European eel stock, COM(2005) 472.

EC (2006) Proposal for a Council Regulations establishing measures for the recovery of the stock of the European eel. 9247/06. May 11, 2006.

EC (2007) Proposal for a Council Regulation establishing measures for the recovery of the stock of European eel. 13139/05 PECHE 203 – COM(2005) 472 final. June 5, 2007.

Euston ET, Royer DD, and Simons CL (1997) Relationship of emigration of silver American eels (*Anguilla rostrata*) to environmental variables at a low head hydro station. Proceedings of the International Conference on Hydropower 1997: 549–558.

Feunteun E, Acou A, Lafaille P, and Legault A (2000) The European Eel: Prediction of spawner escapement from continental population parameters. Canadian Journal of Fisheries and Aquatic Sciences 57: 1627–1635.

Gerhardt (1893) Über Aalleitern und Aalpässe. Zeitschrift für Fischerei 1 S. 194–199.
Gosset C and Travade F (1999) Etude de dispositifs d'aide a la migration de dévalaison des salmonidae: Barrières comportementales. Cybium 23(suppl 1): 45–66.
Gosset C, Travade F, Durif C, Rives J, Elie P (2005) Tests of two types of bypass for downstream migration of eels at a small hydroelectric power plant. River Research and Applications 21: 1095–1105.
Hadderingh RH (1982) Experimental reduction of fish impingement by artificial illumination at Bergum power station. Int. Revue ges. Hydrobiol. 67: 887–900.
Hadderingh RH, Van der Stope JW and Habraken JWPM (1992) Deflecting eels from water inlets of power stations with light. Irish Fisheries Investigations Series A (Freshwater) 36, 80–89.
Hadderingh RH and Bakker HD (1998) Fish mortality due to passage through hydroelectric power stations on the Meuse and Vecht rivers. In Jungwirth M, Schmutz S and Weiss S (eds) Fish Migration and Fish Bypasses. Oxford: Fishing News Books, pp. 315–328.
Hadderingh RH and Bruijs MCM (2002) Hydroelectric power stations and fish migration. Tribune de l'eau 55(619–620/5–6): 79–87.
Hadderingh RH, Beijer RFLJ De, Van Aerssen GHFM and Van Der Velde G (1999) Reaction of silver eels on underwater light sources and water currents: An experimental study. Regulated Rivers: Research and Management 15: 356–371.
Hain JHW (1975) The behaviour of migratory eels, Anguilla anguilla, in response to current, salinity and lunar period. Helgolander Wissenschaftliche Meeresuntersuchungen. 27: 211–233.
Hansen LP and Jonsson B (1985) Downstream migration of hatchery-reared smolts of Altantic salmon (*Salmo salar*) in the river Imsa, Norway. Aquaculture 45: 237–248.
Haraldstad O, Vøllestad LA and Jonsson B (1985) Descent of European silver eels, *Anguilla anguilla*, in a Norwegian watercourse. Journal of Fish Biology 26: 37–41.
Haro A, Castro-Santos T and Boubée J (2000) Behavior, and passage of silver-phase Ameican eels, *Anguilla rostrata* (LeSueur) at a small hydroelectric facility. Dana 12:33–42.
Haro A, Castro-Santos T, Whalen K, Wippelhauser G and McLaughlin L (2003) Simulated effects of hydroelectric project regulation on mortality of American eels. In: D.A. Dixon (ed.) Biology, Management, and Protection of Catadromous Eels. Bethesda, MD: American Fisheries Society, pp. 357–365.
Hölke H (1964) Aalfang mit Hilfe von elektrischen Licht in der Fluss-Fischerei. Deutsche Fischerei Zeitung 11: 82–88.
Holzner M (2000) Neue Versuche zur Schaden minimierung bei der Aalabwanderung. SVK Fischereitagung, Künzell, March 1–2, 2000, pp. 8.
Hvidsten NA (1985) Yield of silver eel and factors effecting downstream migration in the stream Imsa, Norway. Institute of Freshwater Research Drottningholm Report 62: 75–85.
Jansen HM, Winter HV, Bruijs MCM and Polman HJG (2007) Just go with the flow? Route selection and mortality during downstream migration of silver eels in relation to river discharge. ICES Journal of Marine Science 64: 1437–1443.
Jens G (1952–1953) Über den lunaren Rhythmus der Blankaalwanderung. Arch. für Fischereiwissenschaft. 4: 94–110.
Jonsson N (1991) Influence of water flow, water temperature and light on fish migration in rivers. Nordic Journal of Freshwater Research 66: 20–35.
Korringa P (1947) Relations between the moon and periodicity in the breeding of marine animals. Ecological Monographs 17: 347–381.
Kroes MJ, Gough P, Schollema PP and Wanningen H (2006) From sea to source; Practical guidance for restoration of fish migration in European rivers.
Larinier M (1998) Upstream and downstream fish passage experience in France. In: Jungwirth, M., Schmutz, S. & Weiss, S. (eds.) Fish migration and fish bypasses. Fishing News Books, Oxford. 127–145.
Larinier M and Travade F (1998) Petits aménagements hydroélectriques et libre circulation des poissons migrateurs. Houille Blanche 8: 46–51.
Larinier M and Travade F (2002) Downstream migration: Problems and facilities. Bulletin Français de la Pêche et de la Pisciculture 634: 181–207.

Larinier M, Porcher JP, Travade F and Gosset C (1996) Passes à Poissons. Expertise, conception des ouvrages de franchissement. Conseil Supérieur de la Pêche, Paris, pp. 336.

Lobon-Cervia J and Carrascal M (1992) Seasonal timing of silver eels in a Cantabrian stream. Archiv fur Hydrobiologie 125: 121–126.

Lowe RH (1952) The influence of light and other factors on the seaward migration of the silver eel, *Anguilla anguilla*. Journal of Animal Ecology 21(2): 275–309.

Oberwahrenbrock K (1999) Aalschutzinitiative Rheinland-Pfalz/RWE-Energie AG., Projektfortshrittsbericht 1, Stand der Arbeiten an den Projektzielen a, b und c zum Januar 1999. pp 78.

Okamura A, Yamanda Y, Mikawa N, Tanaka S and Oka HP (2002) Exotic silver eels *Anguilla anguilla* in Japanese waters: seaward migration and environmental factors. Aquatic Living Resources 15, 335–341.

Poole WR, Reynolds JD, Moriarty C (1990) Observations on the silver eel migrations of the Burrishoole river system, Ireland, 1959 to 1988. Internationale Revue Der Gesamten Hydrobiologie 75: 807–815.

Raben Von K (1955) Kaplanturbinen und Fische. Wasserwirtschaft 45: 196–200.

Raben Von K (1957) Über Turbinen und ihre schädliche Wirkung auf Fische. Zeitschrift für Fischerei und deren Hilfwissenschaften, Band VI N.F. Heft 1–8: 171–182.

Richkus WA and Dixon DA (2003) Review of research and technologies on passage and protection of downstream migrating catadromous eels at hydroelectric facilities. In Dixon DA (ed) Biology, Management, and Protection of Catadromous Eels. Bethedsa, MD: American Fisheries Society, Symposium 33, pp. 377–388.

Schwevers U (1998) Die Biologie der Fischwanderung, Bibliothek Natur and Wissenschaft Band 11, VNW Verlag Natur and Wissenschaft Solingen, pp. 84. Tesch F-W (1977) The Eel. London: Chapman & Hall.

Tesch FW (2003) The Eel. Fifth edition. Oxford: Blackwell.

Thorpe JE, Ross LG, Struthers G and Watts W (1981) Tracking Atlantic salmon (*Salmo salar* L.) through Loch Voil, Scotland. Journal of Fish Biology 19: 519–537.

Todd PR (1981) Timing and periodicity of migrating New Zealand freshwater eels (*Anguilla* spp.). New Zealand Journal of Marine and Freshwater Research 15: 225–235.

Travade F and Larinier M (1992) La migration de dévalaison: Problèmes et dispositifs. Bulletin Francais de la Pêche et de la Pisciculture 326/327: 165–176.

Van Drimmelen DE (1951) Vangst van schieraal met behulp van licht. Visserij Nieuws 3: 137–140

Vøllestad LA, Jonsson B, Hvidsten NA, Næsje TF, Haraldstad O and Ruud-Hansen J (1986) Environmental factors regulating the seaward migration of European silver eels. Canadian Journal of Fisheries and Aquatic Sciences 43: 1909–1916.

Vøllestad LA, Jonsson B, Hvidsten NA and Naesje TF (1994) Experimental test of environmental factors influencing the seaward migration of European silver eels. Journal of Fish Biology 45: 641–651.

Watene EM, Boubée JAT and Haro A (2003) Downstream movement of mature eels in a hydroelectric reservoir in New Zealand. In Dixon DA (ed) Biology, Management, and Protection of Catadromous Eels. Bethesda, MD: American Fisheries Society, Symposium Series 3, pp. 295–305.

Westin L (2003) Migration failure in stocked eels *Anguilla anguilla*. Marine Ecology Progress Series 254: 307–311.

Winter HV, Jansen HM and Bruijs MCM (2006) Assessing the impact of hydropower and fisheries on downstream migrating silver eel, *Anguilla anguilla*, by telemetry in the River Meuse. Ecology of Freshwater Fish 15: 221–228.