Experimental field study on the migratory behaviour of glass eels (*Anguilla anguilla*) at the interface of fresh and salt water

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European eels (*Anguilla anguilla*) in the glass eel phase migrate using ocean currents and selective tidal stream transport. Conventional fish ladders installed at the interface of marine and fresh water, however, require the fish to swim upstream actively. We question the efficiency of these fish ladders for glass eel immigration, and propose a simple siphon over migration barriers, restoring the original selective tidal stream transport. A conventional trap and our siphon were tested concurrently at two sluice complexes in The Netherlands (Tholen, Nieuwe Statenzijl) in spring 2005. In all but one case, the siphon caught more glass eels than the trap, as well as more sticklebacks and other species. Clearly, the natural immigration process can be restored fairly easily and at low cost and with low intrusion levels of salt. Follow-up studies should focus on optimization, and the effect of a passage on the hinterland stock.

Keywords: fish ladder, glass eel, migration, selective tidal stream transport, siphon.

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Introduction

The stock of the European eel *Anguilla anguilla* is in severe decline: current recruitment is less than 5% of pre-1980 levels, and yield has been dropping gradually since the mid-1960s (Dekker, 2004). ICES (1999) considers that the stock is outside safe biological limits and that current fisheries are not sustainable. Therefore, ICES (1999, 2006) advised that an international stock protection and recovery plan should be developed, and that fisheries and other anthropogenic impacts be restricted to as close to zero as possible until such a plan has been implemented. The European Commission initiated the development of a Community Action Plan for the management of the European eel (COM 2003, 573; detailed in COM 2005, 472), with the objective of permitting the escapement to the sea of at least 40% of the biomass of silver eels relative to potential escapement in the absence of human activities affecting the fishing area or the stock.

The causes of the decline in stock and recruitment are not well known. Overfishing, habitat loss and migration barriers, increased natural predation, parasitism, ocean climate variation, and pollution might have had an impact. Precautionary protective measures are required. Here, we address just one of the potential causes: barriers to immigration of young recruits, specifically at the interface between marine and fresh water.

Glass eels entering coastal waters use selective tidal stream transport to migrate to the coast and into river systems (Creutzberg, 1958). This is an effective mechanism to colonize a watershed rapidly, because it requires little energy to float with the flood stream up to the upper limit of tidal movements, usually far beyond the marine/fresh-water interface. To progress farther upstream, though, active migration into the river is required, swimming against the river flow. During the short glass eel phase, this active migration is very directional, but yellow eels show more random dispersion (Ibbotson *et al.*, 2002).

The construction of dams, sluices, and tidal gates in estuaries has obstructed this natural immigration process. Before the construction of the dike between Lake IJsselmeer and the Wadden Sea (the Netherlands) in 1932, glass eels were transported by the incoming tide, presumably as far up as Deventer (52°15′N 6°10′E; Dekker, 2004). Currently, the sluices in the dike (52°56′N 5°03′E) discharge excess fresh water into the Wadden Sea, but prevent the inflow of brackish water by closing the tidal gate doors as the tide turns. Consequently, the glass eels coming in on the flood tide find the doors shut, more than 100 km from the place they could historically have reached using selective tidal stream transport. Although remaining in a tidal area, their selective tidal stream transport behaviour clearly fails. Mark-recapture experiments (Dekker and van Willigen, 1997) have shown that individual glass eels stay in front of the sluices for several weeks, despite periods of slow outward flow through the sluices. In other words, the switch to active swimming behaviour seems to be made by the glass eels reluctantly. Such delayed immigration accumulates glass eels in front of the sluices. Their abundance peaks about 1 month later than in other, unobstructed places at the same latitude (ICES, 2005). The correlation between stock surveys within Lake IJsselmeer and the tide in front of the sluices indicates that the tidal rhythm of glass eels persists for some time, even within the freshwater lake (Dekker and van Willigen, 2000).

Fish migration barriers can be equipped with mitigating constructions. Fish ladders provide a small bypass to the main stream of an obstructed river, allowing the fish to swim upstream against a moderate outflow. Fish ladders have been installed in many rivers, and are successful also for eels. However, their operation depends completely on the fish swimming actively. For the marine/fresh-water interface, however, we doubt their appropriateness for eels, because glass eels keep relying on selective tidal stream transport. The fish ladders allow older (often pigmented) eels to migrate, but they do not restore the natural immigration process of fresh recruits, using selective tidal stream transport at the marine/fresh-water interface.

Legault (1990) used void operations of a ship lock to transport glass eels from the Loire to the Briere marshes. The same procedure applied in Den Oever was unsuccessful (Dekker and van Willigen, 2000), probably because Legault's site in the Loire was above the zone where glass eels change to active swimming.

As an alternative to common fish ladders or void operations of ship locks, we developed a contraption that allows a small tidal movement in and out of the sluices. Either a small hole in the sluice door, or a siphon over the door, allows glass eels to pass the sluices by selective tidal stream transport, while keeping the inflow of brackish water to a minimum. Here, we report on this contraption, and compare it with a more conventional trap based on active migration.

Material and methods

At each of two sites in the Netherlands (Nieuwe Statenzijl and Tholen), two different traps were installed in spring 2005: one attracting upstream migrants (an eel trap), the other allowing for selective tidal stream transport (a siphon). The two sites were chosen on practical grounds: they were near a source of volunteers (Figure 1).

The sluice complex at Nieuwe Statenzijl (53°14′N 7°13′E) consists of a navigational lock and a discharge sluice. Experiments took place at the upstream doors of the navigational lock. During the experiments, there was hardly any ship traffic, although the sluice was operated regularly, at low tide. At high tide, some brackish water may have leaked through crevices in the sluices and locks, but whether that allowed some glass eels to immigrate is unknown.

The Bergse Diepsluis complex at Tholen (51°40′N 4°10′E) consists of a navigational lock only; experiments took place at the downstream doors, while the upstream doors were kept open. At low tide, some fresh water leaked through the crevices in the doors of the locks.

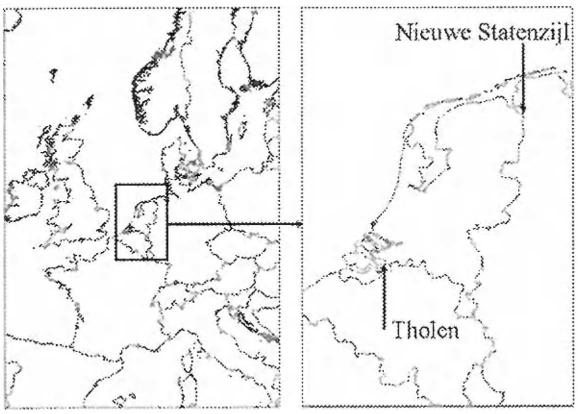

Figure 1. Locations of the experimental sites at Nieuwe Statenzijl and Tholen.

The siphon and the eel trap

A siphon was built over the locks, consisting of 110 mm PVC pipe (Figure 2). At the top, a hand-operated vacuum pump was installed, along with an electronic water-velocity metre and a flow-control valve. A net (length 2 m, diameter 1 m, mesh 1 × 1 mm) was connected to the upstream end of the siphon. The downstream end was located 1–2 m from the bottom and 1–2 m from the front of the gates. On an average high tide, 226 m^3 (Tholen)–284 m^3 (Nieuwe Statenzijl) of seawater flushed through the siphon over the sluices, at an average velocity of ~1.56 and 1.44 m s^{-1}, respectively. As high and low tide are nearly symmetrical in Tholen and Nieuwe Statenzijl, an equal volume will have been expelled through the siphon at low tide.

There was deliberate variation in the placing of the downstream end, varying the depth (fixed relative to the bottom, or to the water surface), the opening (one large or several small), and the position of the entrance relative to the lock gates (left, right, tight, or distanced), but the low number of experiments did not allow formal testing.

The eel trap consisted of a 1.5 × 1 × 1 m plastic container floating in front of the lock gates (Figure 3). A 110 mm PVC pipe equipped with a funnel of 1 × 1 mm mesh allowed glass eels to enter the box 30 cm below the surface of the water. Approximately 20 cm of the box protruded out of the water. The box was 1–2 m from the lock gates. Water was pumped over the lock and into the eel trap, creating a moderate flow of fresh water of ~ 7 cm s^{-1}, equivalent to ~15 m^3 per average tide.

Again there was deliberate variation in the position of the trap relative to the lock gates (left, right, tight, or distanced), and in the flow rate of the attracting water, but again the low number of experiments precluded formal testing.

Both siphon and trap were operated in runs of four consecutive nights in April and May 2005, days being selected when high tide was around midnight. Shortly after inside and outside lock water levels equalized through the ebb tide, both nets were raised and the catches identified, counted, and their length measured. In the early experiments, all four nights were observed, but later, only the last two nights of each 4-d run were observed. For glass eels, pigmentation stages were determined according to Elie *et al.* (1982). The number of glass eels caught was too low to determine pigmentation stages reliably on most nights, and unfortunately, practical problems with storage and analysis spoiled some of the remaining material. On two nights in Nieuwe Statenzijl, more than 100 pigmentation stages were analysed in both trap and siphon.

Scuba observations

Scuba observations were made on four nights in front of the Tholen complex. This complex is the only one in the Netherlands where visibility is such that scuba observation of glass eel immigration is possible. The purpose of the dives was to obtain an impression of the natural behaviour of glass eels in front of lock gates (1 April 2005; 28 April 2005; and 20 May 2005), as well as their behaviour relative to the siphon and the eel trap (5 May 2006).

Results

Experiments were made between 4 April and 20 May 2005. At both Nieuwe Statenzijl and Tholen, observations were made on

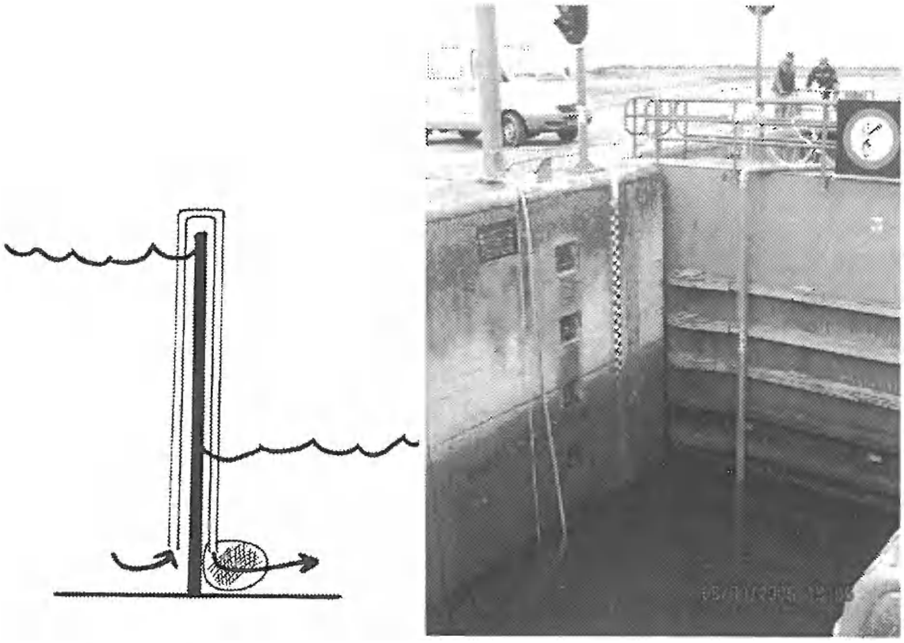

Figure 2. The siphon at high tide. Arrows indicate the direction of water flow through the siphon (left, salt water; right, fresh water).

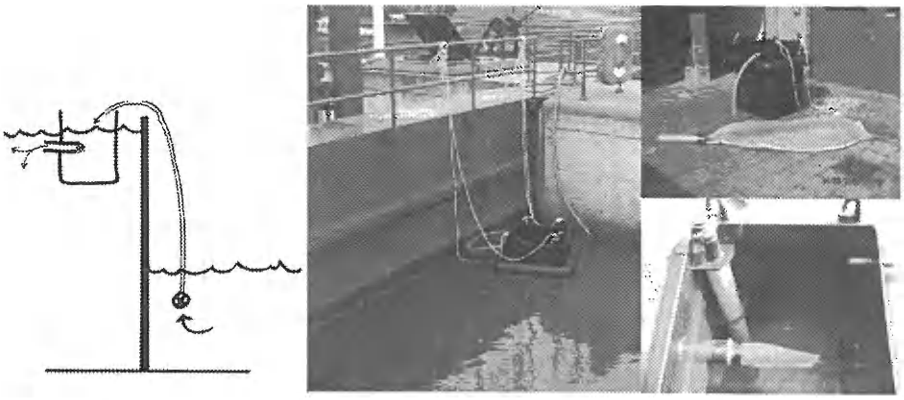

Figure 3. The eel trap at high tide. Arrows indicate the direction of water flow through the trap (left, salt water; right, fresh water).

10 nights, resulting in 10 observations at high tide and 3 at low tide at Nieuwe Statenzijl, and 10 observations at high tide and 2 at low tide at Tholen.

Catches

Catches at Nieuwe Statenzijl were dominated by glass eels ($n = 7189$), sticklebacks *Gasterosteus aculeatus* (1864), and Chinese mittencrabs *Eriocheir sinensis* (2606). In all, 72 fully pigmented eels were caught. Other species trapped included common goby *Potamoschistus minutus* (13), ruffe *Gymnocephalus cernuus* (13), pipefish *Syngnathus acus* (8), larvae of the flounder *Platychthus flesus* (4), smelt *Osmerus eperlanus* (2), perch *Perca fliviatilis* (1), roach *Rutilis rutilis* (1), and unidentified small crustaceans (140 l). At Tholen, 301 glass eels were caught, 1 stickleback, 1 pigmented eel, 1 common crab *Carcinus maenas*, and 0.8 l of *Beroe cucumis*. Catches of glass eels and sticklebacks are detailed in Table 1.

In all cases but one (3 May, Nieuwe Statenzijl), glass eel catches in the siphon exceeded those in the trap by a factor of 6, at both locations. This ratio of siphon to trap catches varied, but showed no clear trend over the season. For sticklebacks at Nieuwe Statenzijl, the siphon caught four times more than the trap. On 3 May, the trap at Nieuwe Statenzijl caught 2128 glass eels (30 times more than the siphon) and 110 sticklebacks (again 30 times more). The cause of this single exceptional result is not clear: the siphon was working well (72 glass eels caught), the lengths of the glass eels caught that night were not unusual, nor were water temperatures or tidal conditions. In other words, we did not gain the impression that a "wave" of possibly further developed (discussed later) glass eels, triggered by unusual water

Table 1. Overview of the catch of glass eel and sticklebacks (total numbers) at Nieuwe Statenzijl and Tholen.

Date	Nieuwe Statenzijl				Date	Tholen			
	Glass eel		Stickleback			Glass eel		Stickleback	
	Siphon	Eel trap	Siphon	Eel trap		Siphon	Eel trap	Siphon	Eel trap
April 4	208	2	83	0	April 4	6	1	0	0
April 5[a]	6	0	0	0	April 5[a]	0	0	0	0
April 5	506	24	347	7	April 6	11	1	0	0
April 6[a]	5	0	1	0	April 6[a]	1	0	0	0
April 6	416	10	296	1	April 7	11	0	0	0
April 7[a]	5	0	2	0	April 8	54	3	0	0
April 7	289	5	104	0	April 17	31	0	0	0
April 20	504	262	396	2	April 18	7	0	0	0
April 21	1452	206	198	313	May 2	48	7	0	0
May 3	72	2128	4	110	May 3	76	20	1	0
May 4	376	186	0	0	May 17	9	0	0	0
May 18	311	7	0	0	May 18	11	4	0	0
May 19	168	42	0	0					
Total	4317	2872	1431	433	Total	265	36	1	0

[a]Observations made at the end of a low tide; all others are at the end of a high tide.

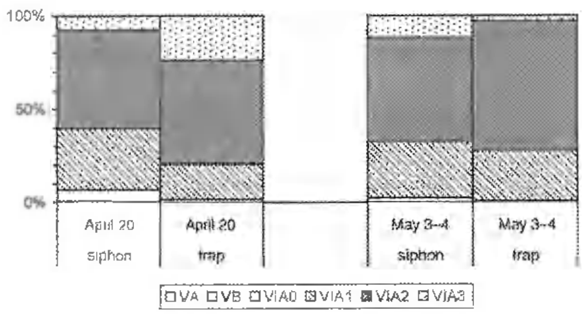

Figure 4. Glass eel catch composition by pigmentation stage at Nieuwe Statenzijl.

conditions, tried to gain access to inland waters by upstream migration.

Development stages

Pigmentation stages (Figure 4) were generally dominated by stages VIA1–3. On 20 April, the glass eels in the trap at Nieuwe Statenzijl showed more advanced pigmentation than those from the siphon. On 3 and 4 May, however, the trap catches were dominated by stage VIA2, i.e. both early and late stages were less abundant than those from the siphon. Note that this was the night of the exceptionally large trap catch ($n = 2128$, whereas just 744 glass eels were caught on all other nights combined).

Scuba observations

At low tide, the glass eels concentrated in the top half metre of the water column, directly in front (<0.5 m) of the sluice gates, apparently the result of fresh-water currents attracting the glass eels, because many glass eels were seen swimming against the fresh-water flow emerging from the gates. However, no glass eels were seen to enter the inland waters through openings or cracks in the sluice gates, because the water velocities in these openings were too strong. At high tide, the glass eels concentrated directly in front (<1 m) of the sluice gates, spread throughout the water column. Then, large numbers of glass eels managed to gain access to inland waters through small openings in the sluice gates. When water levels on both sides of the gates were similar, water velocities in the cracks decreased. However, the time during which the fresh-water currents through the cracks were low was very short (<1 min), and no glass eels were observed reaching inland waters then (Figure 5). The influx of glass eels seemed largely influenced by the chance of an individual ending up within the influence of an opening, i.e. swimming behaviour seemed more important than the flow and suction power of openings.

Discussion

Our results clearly indicate that selective tidal stream transport is the main process driving immigration of fish through barriers at the marine/fresh-water interface, for a range of fish species, and for glass eels and sticklebacks in particular. Moreover, a 110-mm-diameter siphon over the barrier was an efficient mitigation measure, allowing new arrivals to pass rapidly over the barrier into inland waters, using their normal migration mechanism. The amount of seawater flowing in (226–284 m^3 per tide) is small in comparison with sluice and pump capacities and discharge volumes (4×10^6 m^3 per tide).

Alternative strategies to facilitate fish immigration at the marine/fresh-water interfaces currently used by water managers in the Netherlands include opening the sluices at low tide, void ship lock turning at various moments in the tidal cycle, and leaving sluices open for a short period (5–15 min) during the rising tide. The first alternative requires the immigrating glass eels to shift to active swimming prematurely, against an overwhelming outflow of fresh water. The second and third alternatives, although marginally successful, definitely come with a much greater inflow of brackish water. We therefore conclude that installation of a siphon over the barriers is a better alternative.

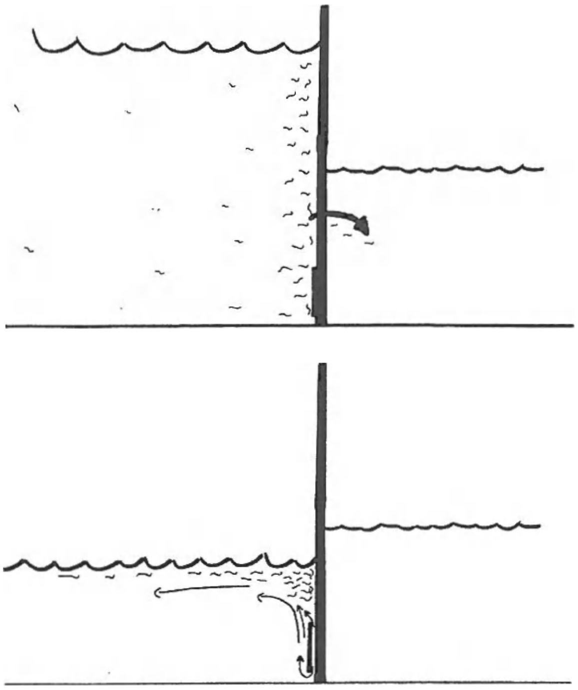

Figure 5. A perspective of the situation at the navigational lock at Tholen at (top) high tide, and (bottom) low tide. Left, salt water in the Eastern Scheldt; right, fresh water in the lock chamber. Arrows indicate the direction of water flow.

The transition from selective tidal stream transport to active swimming has been related to a change in external factors (salinity or temperature; Creutzberg, 1961), but has also been described as an internally determined delay, allowing morphological and physiological adaptation (Deelder, 1958; McCleave and Wippelhauser, 1987). If this transformation process is exclusively determined by external factors, the sharp transition from marine to fresh water at barriers will not stimulate it, resulting in a delay or absence of active swimming. In contrast, if the transformation is internal, an unnaturally long stay in seawater will not disrupt the transition to active swimming, but might induce extra physiological strain (Edeline *et al.*, 2004). In natural, open rivers, glass eels will always reach a fresh environment, using selective tidal stream transport, whereas the physiological transition to fresh water is easily taken (Wilson *et al.*, 2004). Briand *et al.* (2005) found greater rates of mortality in estuary-caught glass eels than in actively swimming glass eels in the trap on a barrier at the marine/fresh-water interface, which might be attributed to increased physiological stress in the brackish environment. If so, application of a siphon over a barrier would allow faster immigration, at a lower mortality than a conventional eel trap. Installation of a siphon, and follow-up monitoring of the hinterland stock, will be required to test this speculation.

Conventional eel traps are found on barriers at the marine/fresh-water interface in several places in Europe, including on the Rivers Viskan (Sweden) and Erne (Ireland) (Dekker, 2002), and catches have been considerable. In those cases, however, the glass eels had no alternative than to wait or to swim actively. At Den Oever (the Netherlands), a trap is located next to the sluices, allowing the glass eels to immigrate by relatively infrequent (and unintended) seawater intrusions into the lake (Dekker and van Willigen, 2000). In that case, a conventional trap is unsuccessful (Heermans and van Willigen, 1974). We speculate that restoration of the natural selective tidal stream transport through a siphon would have done as least as well as the trap in all these cases. Obviously, a simple siphon would not have restored selective tidal stream transport in the Erne, because the upstream water level is far above (~30 m) the high tide level, but more complex siphon and pumping contraptions might be developed.

The main objective of our study was to test our new contraption, based on selective tidal stream transport, against a conventional eel trap based on active upstream migration. Although we believe that the results of the experiment do favour the new contraption, they do not show that the contraption is successful in mitigating the effect of a barrier at the marine/fresh-water interface. Nieuwe Statenzijl drains 90000 ha surface area, 10% of which is open water surface. The combined catch of siphon and trap came to ca. 700 per night, during a season of fewer than 100 nights. At a low stocking density of 100 individuals ha^{-1} $year^{-1}$ (ICES, 2006), our catch would suffice for less than 700 ha only. Although our contraption was successful in principle, the quantities caught were far too low to stock the hinterland adequately. However, no glass eels were left on the marine side of the sluices towards the end of the season; we therefore hypothesize that no significant quantities failed to pass the barrier. The low catch observed is more likely to be a reflection of low recruitment. Current recruitment is just 1% of its level pre-1980s (ICES, 2006). Full recovery to that historical recruitment level would require some 70000 glass eels per night to pass the barrier, i.e. ~3 glass eels per second, a capacity that can be accommodated easily by our siphon. Consequently, we believe that installation of siphons at tidal barriers, where flood levels rise above the inland water level, is a simple and efficient way to restore fish migration, contributing to the comprehensive protection and migration of the European eel. Further optimization of the siphon and the eel trap is possible, including the use of fresh-water currents and artificial light from the surface to attract glass eels closer to the intake of the siphon, siphon constructions with multiple small intakes instead of a single large one, and positioning of the intake. If seawater intrusion as a consequence of the volume of water required to pass a significant portion of the population is deemed to be a problem, some type of pump-back system could also be employed to maximize the flow and passage of glass eels, while minimizing intrusion of salt water.

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