Theme Session J
Is there more to eels than SLIME?
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An experimental field study on the migratory behaviours of glass eel (*Anguilla anguilla*) at the interface of fresh and salt waters, with implications to the management and improvement of glass eel migration.

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Abstract

Glass eel *Anguilla anguilla* (L.) migrate using ocean currents and Selective Tidal Stream Transport. Conventional fish ladders installed at the marine/fresh water interface, however, require the fish to actively swim upstream. 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 new siphon were tested concurrently at two sluice complexes in The Netherlands (Tholen, Nieuw Statenzijl), in spring 2005. In all but one case, the siphon caught more glass eel than the trap, and more sticklebacks and other species. These results indicate that the natural immigration process can easily be restored, at low costs and low salt intrusion levels.

Our siphons were more successful than conventional traps. Follow up studies must focus on optimisation, and the effect of a passage on the hinterland stock.

Introduction

The stock of the European eel *Anguilla anguilla* (L.) is in severe decline: current recruitment is less than 5% of the pre-1980 levels, and fishing yield is gradually diminishing 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 to permit the escapement to the sea of at least 40% of the biomass of silver eel relative to the 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. In this paper, we address just one of the potential causes: barriers to the immigration for young recruits, specifically at the interface between marine and freshwater.

Glass eel 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 rapidly colonise a watershed, as it requires little energy to float with the flood stream, up to the upper limit of the tidal movements – usually far beyond the marine/freshwater-interface. To progress further upstream, 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 eel 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 Waddensea (Netherlands) in 1932, glass eel were transported by the incoming tide, presumably as far up as Deventer (52°15’N 6°’10’E; Dekker 2004). In the current situation, 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, closing the doors just in time. Consequently, the glass eel 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. While remaining in a tidal area, their Selective Tidal Stream Transport now fails. Mark-recapture experiments (Dekker and van Willigen 1997) indicated that individuals stay in front of the sluices for several weeks, that is: the switch towards active swimming behaviour seems to be made only reluctantly made. This delayed immigration accumulates the glass eel in front of the sluices. Their abundance peaks about one 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 the glass eels persists for some time, even within the fresh water 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 passes have been installed in many rivers, and are successful also for eel. However, their operation depends completely on the active swimming behaviour of the fish. For the marine/freshwater-interface, we doubt their relevance, since the glass eel keep relying on Selective Tidal Stream Transport. The fish ladders allow older (and often pigmented) eels to migrate, but do not restore the natural immigration process of the fresh recruits.

As an alternative to common fish ladders, 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, enables glass eel to pass the sluices by means of Selective Tidal Stream Transport, while keeping the inflow of brackish water to a minimum. In this article, we report on this contraption, and compare it to a more conventional trap based on active migration.

Material and methods

At two places in the Netherlands (Nieuw Statenzijl and Tholen), two different traps were installed in spring 2005: one attracting upstream migrants, the other allowing for Selective Tidal Stream Transport. These two places were chosen on practical grounds: near to where volunteers could be found. (Figure 1)

Nieuwe Statenzijl

The sluice complex at Nieuw Statenzijl (53º14'N 7º13'E) consists of a navigational lock and a discharge sluice. Experiments took place at the upstream doors of the navigational lock. During the experiments, hardly any ship traffic occurred. The sluice was operated regularly, at low tide. During high tide, some brackish water may have leaked through crevices in the sluices and locks. Whether this allowed some glass eel to immigrate is unknown.

Tholen

The Bergse Diepsluis complex in Tholen (51º40'N 4º10'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.

Siphon

A siphon was built over the locks, consisting of 110 mm PVC pipe (see Figure 2). At the top, a hand-operated vacuum pump was installed, an electronic water velocity meter 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 at 1-2 meter from the bottom and 1-2 meter from the front of the gates. On an average high tide, 226 m^3 (Tholen) to 284 m^3 (Nieuwe Statenzijl) of sea water flushed through the siphon over the sluices, at an average velocity of approx. 1.56 and 1.44 m/s respectively. Since high and low tide are nearly symmetrical in Tholen and Nieuw Statenzijl, an equal volume will have been expelled through the siphon at low tide.

Some deliberate variation occurred 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 relative to the lock gates (left, right, tight or distanced), but the low number of experiments did not allow formal testing.

Eel trap

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

Some deliberate variation occurred in the position relative to the lock gates (left, right, tight or distanced), and in the flow rate of the attracting water, but the low number of experiments did not allow formal testing.

Both siphon and trap were operated in runs of 4 consecutive nights in April and May 2005, selecting days with high tide around midnight. Shortly after both inside and outside came to equal water levels due to the ebb tide, both nets were raised and catches identified, counted and their length measured. In the early experiments, all 4 nights were observed, but later on, only the last two nights of each 4-day run. For the glass eel, pigmentation stages were determined, according to Elie et al. (1982). The number of glass eel 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 Nieuw Statenzijl, more than 100 pigmentation stages were analysed for both trap and siphon.

Scuba observations

Scuba observations were made in 4 nights in front of the Tholen complex. This complex is the only one in The Netherlands where the visibility is such that scuba observations are possible on glass eel immigration. The purpose of these dives was to obtain an impression of the natural behaviours of glass eel in front of lock gates (1/4/05; 28/4/05; 20/5/05) and their behaviours relative to the siphon and the eel trap (5/5/06).

Results

Experiments were made between April 4 and May 20, 2005. 10 nights were observed in Nieuw Statenzijl (resulting in 10 high tide observations and 3 at low tide) and 10 in Tholen (resulting in 10 observations at high tide and 2 at low tide).

Catches

Catches in Nieuw Statenzijl were dominated by glass eel (N=7189), sticklebacks *Gasterosteus aculeatus* (1864) and young Chinese mittencrabs *Eriocheir sinensis* (2606). 72 fully pigmented eels were caught. Other species included common goby *Potamoschistus minutus* (13), ruffe *Gymnocephalus cernuus* (13), pipe fish *Syngnathus acus* (8), flounder larvae *Platychthus flesus* (4), smelt *Osmerus eperlanus* (2), perch *Perca fliviatilis* (1), roach *Rutilis rutilis* (1), and unidentified small Crustaceans (140 litre). In Tholen, 301 glass eel were caught, 1 stickleback, 1 pigmented eel, 1 common crab *Carcinus maenas* and 0.8 litre of *Beroe cucumis*. Glass eel and stickleback catches are detailed in Table 1.

In all cases but one (May 3, Nieuw Statenzijl), glass eel catches in the siphon exceeded those in the trap by a factor 6 on both locations. This ratio of siphon to trap catches varied, but showed no clear trend over the season. For sticklebacks in Nieuw Statenzijl, the siphon caught 4 times more than the trap. On May 3, the trap in Nieuw Statenzijl caught 2128 glass eels (30 times more than the siphon) and 110 sticklebacks (again 30 times more). The cause of this single aberrant result is not clear.

Development stage

Pigmentation stages (Figure 4) were generally dominated by stages VIA1-3. On the 20th of April, the glass eel in the trap in Nieuw Statenzijl showed a more advanced pigmentation stage than those from the siphon. On 3&4 May, however, the trap catches were dominated by stage VIA2, that is: both early and late stages were less abundant than those from the siphon. Note that this was the night of the aberrantly large trap catch (N=2128, while only 744 were caught in all other nights combined).

Scuba observations

At low tide, the glass eel concentrated in the top half meter of the water column, directly in front (<0.5 m) of the sluice gates, apparently the result of freshwater currents attracting the glass eel as many glass eel were observed swimming against a freshwater flow emerging from the gates. However, no glass eel were observed to enter the inland waters through openings and cracks of the sluice gates, because the water velocities in these openings were too strong. At high tide, the glass eel concentrated directly in front (<1 m) of the sluice gates, spread out over the vertical of the water column. Large numbers of glass eel were observed to reach inland waters through small openings in the sluice gates. When water levels on both sides of the gates were similar, water velocities in these cracks decreased. However, the time period during which the freshwater currents through these cracks was low, was very short (<1 min), and no glass eel were observed to reach inland waters then. (see Figure 5) The influx of glass eel seemed largely determined by the chance of an individual glass eel to end up within the influence of an opening. I.e., swimming behaviours 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 the immigration of fish through barriers at the marine/fresh water interface, for a range of fish species and for glass eel and sticklebacks in particular. Moreover, a 110 mm diameter siphon over the barrier was an effective mitigation measure, allowing fresh arrivals to pass rapidly over the barrier into inland waters, using their normal migration mechanism. The amount of sea water flowing in (226-284 m^3 per tide) is small in comparison to sluice and pump capacities and discharge volumes (4·106 m^3).

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 minutes) during the rising tide. The first alternative requires the immigrating glass eel to shift to active swimming prematurely, against an overwhelming outflow of fresh water. The second and third alternative, although perhaps successful, definitely come with a much higher inflow of brackish water. We therefore conclude that installation of a siphon over barriers is a much better alternative.

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 the transformation, resulting in a delay or absence of the active swimming. In contrast, if the transformation is internal, an unnatural long stay in marine waters will not disrupt the transition to active swimming, but might induce extra physiological strain. In natural, open rivers, glass eel will always reach a fresh environment, using Selective Tidal Stream Transport, while the physiological transition to fresh water is easily taken (Wilson et al 2004). Briand et al (2006) found higher mortality rates in estuarine caught glass eel then in active swimming glass eel in the trap on a barrier at the marine/fresh interface, which might be attributed to increased physiological stress in the brackish environment. If so, application of a siphon over a barrier would enable 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 these cases, however, the glass eel had no alternative then to wait or swim actively. In Den Oever (the Netherlands), a trap was located next to the sluices, allowing the glass eel to immigrate by relatively infrequent (and unintended) salt water intrusions into the lake (Dekker and van Willigen 2000). In this case, a conventional trap was 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, since the upstream water level is far above (approx. 30 m) the high tide level; but more complex siphon and pumping contraptions might be developed.

The main objective of the current 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 think the test is clearly in favour of our new contraption, our results do not show that the contraption is indeed successful in mitigating the effect of a barrier on the marine/fresh water interface. Nieuw Statenzijl drains 90,000 ha surface area, 10% of which will be open water surface. The combined catch of siphon and trap came to ca. 700/night, during a season of less than 100 nights. At a low stocking density of 100 individuals/ha/a (ICES 2006), our catch would suffice for less than 700 ha only. Although our contraption is successful in principle, the quantities caught are by far too low for stocking the hinterland adequately. However, no glass eel were found left behind at the sea-side of the sluices towards the end of the season, that is: no major quantities failed to pass the barrier. The low catch observed is more likely to be a reflection of low recruitment. Current recruitment is in the order of magnitude of 1 % of the pre-1980s level (ICES 2006). Full recovery of that historical recruitment level would require some 70,000 glass eels per night to pass the barrier, that is: approximately 3 glass eels per second, a capacity that can be easily accommodated by our siphons. Consequently, we conclude that installation of siphons at tidal barriers, where flood levels rise above the inland water level, is a simple and effective way to restore fish migration, contributing to the comprehensive protection and migration of the eel.

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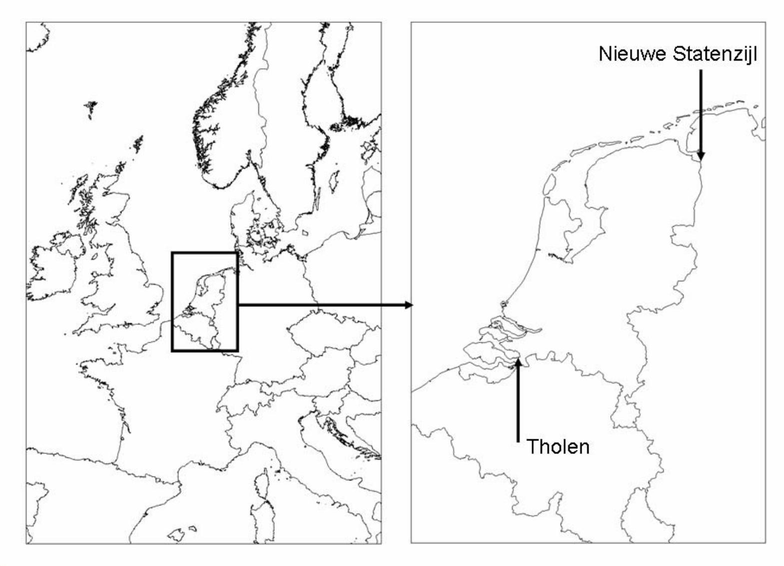
Figures



Figuur 1. Experimental locations: Nieuw Statenzijl and Tholen.

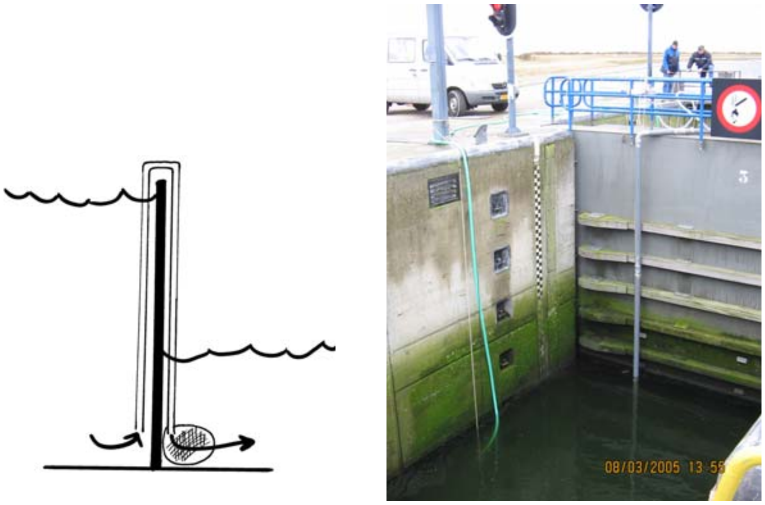


Figure 2. Siphon at high tide. Arrows indicate the direction of the water flow through the siphon.

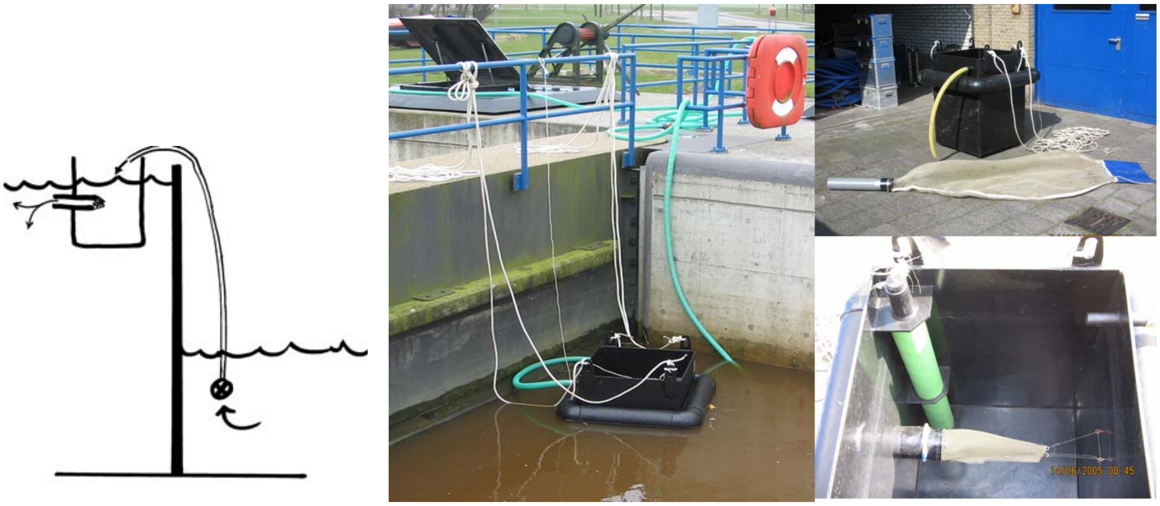


Figure 3. Eel trap at high tide. Arrows indicate the direction of the water flow through the trap.

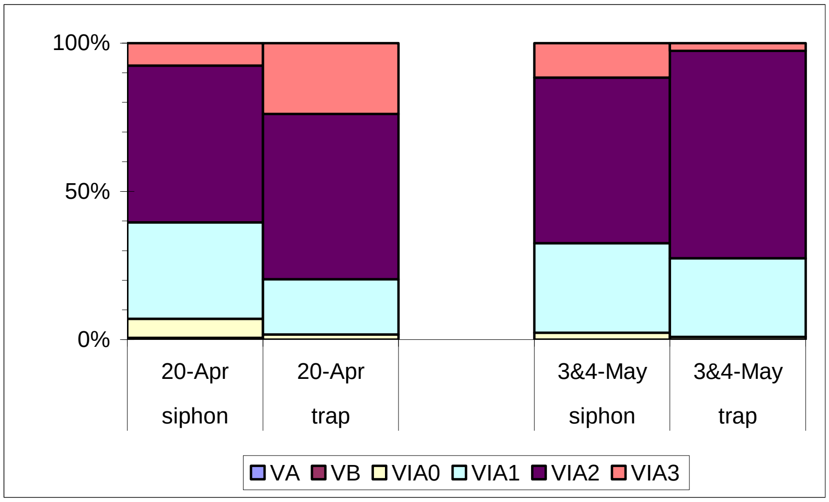


Figure 4. Glass eel catch composition by pigmentation stage, for Nieuw Statenzijl.

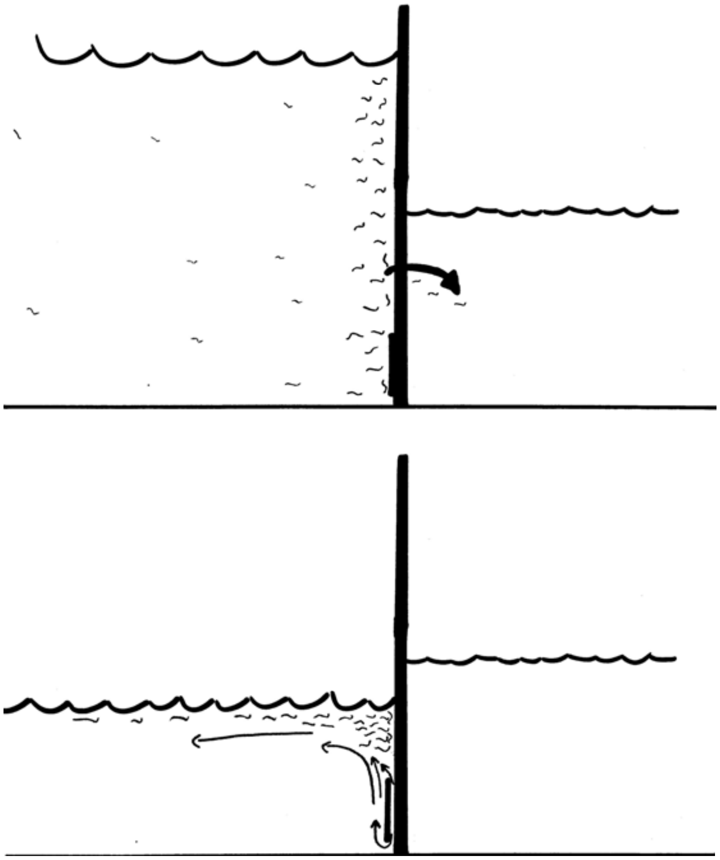


Figure 5. Cartoon summary of the high tide (top) and low tide (bottom) situation at the navigational lock at Tholen. Left: Salt water in the Eastern Scheldt; Right: fresh water in the lock chamber. Arrows indicate the direction of the water flow.

Tables

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

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

* Observations made at the end of a low tide, while all others are at the end of a high tide.

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