REPORT ON TRIAL TIDAL EXCLUSION IN COPPERHOUSE POOL

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11 AUGUST 2011

1. EXECUTIVE SUMMARY

1.1 Recommendation

Our recommendation is that further single exclusions could be carried out without detailed monitoring of fish, aquatic invertebrates and algae, provided that the following mitigation measures are carried out:

1. Tidal exclusions should be at least 3 days apart.
   REASON: This mitigation is to ensure that feeding and reproduction of invertebrates is not affected. The interval of three days also gives time for other species such as seaweeds to make a complete recovery.
2. The tidal exclusion should be postponed if the predicted air temperature for Hayle is above 20°C (forecast taken no later than 24 hours before the gate being closed).
3. Tidal exclusion should be postponed if heavy rain occurs during the 24 hour period before a tidal exclusion, or if heavy rain is forecast during the day of the tidal exclusion.
   REASON 1: The salinity in the low water channel in the upper part of Copperhouse Pool fell to 1.8 psu during the trial exclusion on 4 August. This is approximately 5% of seawater (34-35 psu). No mortalities of brown shrimp were observed at 1.8 psu, broadly in agreement with the laboratory toxicity tests we carried out prior to the trial exclusion, which showed that they can tolerate 2 psu salinity, but not 1 psu. We think salinities may approach 2 psu during normal weather, but could fall to 1 psu or below after or during heavy rain.
   REASON 2: Some fish near to the freshwater input to the low water pool experienced salinities down to 3.5 psu (approximately 10% seawater) during the tidal exclusion on 4 August. We had anticipated that salinity might decline to 4 -5 psu during the trial exclusion during dry weather or drizzle, due to the influence of freshwater inputs over an additional 12 hours. The occurrence of a short period of heavy rain during the night of 3-4 August increased the effects of freshwater input. Sandbags were used to mitigate the impacts of freshwater inputs but are not advisable for future exclusions (see point 3 below). There were no fish mortalities, but a tidal exclusion during or after a period of heavy rain could lower salinities to perhaps 3 psu and would be more problematic.

4. We recommend that sandbags across the exit from the low water pool are not used in any further tidal exclusion.
   REASON: The blockage of the exit/entry route to the low water pool caused confusion in fish, particularly sea bass. Their aggregation near to the bags and increased jumping out of the water led to some fish becoming temporarily stranded among seaweeds nearby. We were able to rescue all fish rapidly, and return them to the water. They rapidly moved away and no prolonged stress was evident. However, a rapid decision was taken to remove a layer of sandbags. This allowed free movement of fish in and out of the pool; sea bass and mullet were observed moving in both directions.
5. If the weather on the day of the exclusion turns out to be above 20 ^{o}C or there is unexpected and prolonged heavy rain then we recommend that we are asked to attend as quickly as possible.

1.2 Frequency of Tidal Exclusions

It should be possible to exclude a single daytime high tide at intervals of 3-4 days (e.g. Monday and Thursday, or Monday and Friday) provided that weather conditions are suitable. It is likely that two exclusions in a week with cool, damp weather would be less damaging than a single exclusion on a warm, windy day. Our data suggest that a tidal exclusion on a damp, cool day is probably less damaging to seaweeds than a normal low water during hot, sunny and windy weather.

The best conditions for future tidal exclusions would be cool (maximum daytime <18° C), cloudy and humid, with a gentle breeze or no wind. There should have been little rain prior to the exclusion, but light drizzle on the day would help keep seaweeds hydrated.

The worst conditions would be either hot, dry and windy (which would cause seaweeds to become unusually dehydrated and also cause unacceptably high water temperatures) or high freshwater flows due to rainfall prior to the study or moderate to heavy rain on the day of the exclusion.

1.4 Assessment of Individual Species

The following species are very unlikely to be affected by occasional tidal exclusions, even in the absence of mitigation:

- Cord grass (*Spartina anglica*)
- Glasswort (*Salicornia* spp.)
- *Ulva* species (formerly in *Enteromorpha*). Based on results from the trial exclusion.
- Rough periwinkle (*Littorina saxatilis*)
- Shore crab (*Carcinus maenas*)

- *Corophium volutator* (an amphipod crustacean)
- Sea slater (*Ligia oceanic*)
- Ragworm (*Nereis diversicolor*)
- Enchytraeid oligochaete worms
- Marine bristle tail (*Petrobius maritimus*)

The list of species that are very unlikely to be affected by occasional tidal exclusions includes nearly all the most important wader prey found in Copperhouse Pool. This suggests that overwintering and migrant birds will not experience any reduction in prey densities.

Moderately sensitive groups that could be affected by a single tidal exclusion (without mitigation) are:

- Fish in the low water pool
- Gobies in the low water channel
- Lugworm (*Arenicola marina*). Based on results from trial tidal exclusion.

The most sensitive species may show some minor sublethal effects due to occasional tidal exclusions (even with the proposed mitigation), but we do not predict any mortality:

- Brown shrimp (*Crangon crangon*) in the low water channel.
- Bladder wrack (*Fucus vesiculosus*).
- Spiral wrack (*Fucus spiralis*).
- Knotted wrack (*Ascophylum nodosum*).
- *Rhizoclonium riparium* (a filamentous green seaweed).

1.4 Monitoring Programme

Table 1 provides a summary of the monitoring carried out on 3-5 August.

Most of the monitoring was carried out on the lower third of Copperhouse Pool. Occasional visits to the upper part of the low water channel allowed assessment of the salinity and the behaviour of brown shrimp.

Table 1 Summary of Monitoring on 3-5 August

Meteorological data
Air temperature, humidity, wind speed, cloud cover
Water quality in low water pool
DO, pH, NH_3, salinity & temperature
Metals (dissolved arsenic, chromium, copper & zinc; plus total zinc)
Fish behaviour in low water pool
Visual observations
Video recording
Still photography as required
Low Water Channel
Salinity & temperature in low water channel
Invertebrates
Crangon crangon checks for mortality in LW channel
Corophium volutator behaviour
Nereis diversicolor visual survey for surface activity
Arenicola marina cast counts
Seaweeds & higher plants
Pocket PEA – *Fucus vesiculosus*
Pocket PEA – *Fucus spiralis*
Pocket PEA – *Ascophylum nodosum*
Pocket PEA – *Ulva torta*
Visual observations all species
Water content of *Fucus spiralis* by oven drying
Water content of *Fucus vesiculosus* by oven drying

1.5 Summary of Main Findings and Mitigation

Table 2 summarises the main findings from the study, including any observed impacts and relevant mitigation measures.

The analysis of 34 water samples for dissolved metals (arsenic, chromium, copper and zinc) and total zinc showed that the tidal exclusion had no deleterious effect on metal concentrations in the low water pool. The lowest metal concentrations were generally recorded on the day of the tidal exclusion (4 August 2011). This rather surprising result is due to the fact that the flood tide from the harbour has high concentrations of chromium, copper and zinc. Although some of these metals may be mobilised from historically contaminated sediments in the harbour, we think the majority of the chromium is due to current disposal practices. Chromium is of particular concern, as the highest concentration measured was 56 times the Environmental Quality Standard. Concentrations of chromium in the harbour water are high enough to cause toxicity to the most sensitive species, such as polychaete worms. The source of chromium needs to be investigated urgently.

Table 2. Summary of Main Findings of Trial Exclusion & Proposed Mitigation

	IMPACTS	MITIGATION
SEAWEEDS		
Fucus spiralis Spiral wrack	No impacts because of cool damp weather	Temperature restriction & spacing of tidal exclusion events at least 3 days apart
Fucus vesiculosus Bladder wrack	No impacts because of cool damp weather.	Temperature restriction & spacing of tidal exclusion events at least 3 days apart
Ascophylum nodosum Knotted wrack	No impacts because of cool damp weather	Temperature restriction & spacing of tidal exclusion events at least 3 days apart
Ulva torta A filamentous green seaweed	None	None required, apart from spacing of tidal exclusion events at least 3 days apart
INVERTEBRATES		
Arenicola marina Lugworm	Reduced feeding activity, especially near low water pool	No use of sandbags in future tidal exclusions. Spacing of tidal exclusion events at least 3 days apart
Nereis diversicolor Ragworm	None	None required, apart from spacing of tidal exclusion events at least 3 days apart
Crangon crangon Brown shrimp	None, but salinities approached critical values.	Heavy rainfall restriction
Corophium volutator An amphipod crustacean	None	None required, apart from spacing of tidal exclusion events at least 3 days apart
FISH		
Fish in low water pool	Fish confused by blockage of exit/entry from low water pool Salinity in low water pool decreased to 3.5 psu near freshwater input Surface activity increased on the day after tidal exclusion	No use of sandbags in future tidal exclusions. Heavy rainfall restriction Spacing of tidal exclusion events at least 3 days apart
Gobies in low water channel	None, but salinities approached critical values	Heavy rainfall restriction

2. OVERVIEW OF METHODS

2.1 Dates of study and tides

The study took place between 3-5 August, a period of Spring tides. The times (BST) for predicted low water (LW) and high water (Hw) at St Ives during the monitoring and tidal heights are given in Table 1. At Copperhouse Pool, the high tide time is delayed compared to St Ives by approximately one hour. The raised and narrow entrance to Copperhouse Pool adds an extra delay and the low water pool continues to empty for approximately 3 to 3.5 hours after the predicted low tide for St Ives.

Table 3. Predicted Tidal Conditions at St Ives for 3-5 August

	Time of LW (height, m)	Time of HW (height, m)	Time of LW (height, m)	Time of HW (height, m)
3 August	02:29 (0.6)	08:20 (6.7)	14:45 (0.7)	20:40 (6.8)
4 August	03:14 (0.8)	09:05 (6.5)	15:30 (0.9)	21:26 (6.6)
5 August	03:58 (1.1)	09:52 (6.2)	16:17 (1.2)	22:17 (6.2)

On each day we carried out the same monitoring programme to assess water quality, fish, invertebrates and seaweeds.

3 August Baseline data were obtained under normal tidal conditions (see below)
4 August Trial tidal exclusion - the normal daytime high tide at Copperhouse Pool was excluded by closure of the tidal gate at approximately 6 am.
5 August Assessment of recovery from the tidal exclusion

On 3 August, we were on site from 09:00 to 19:45, so we were able to assess almost a full tidal cycle of events in the pool prior to exclusion. However, to mitigate the potential effects on fish in the low water pool it had been agreed beforehand with consultees that sandbags would be placed at the exit from the pool, to raise water levels. A line of sandbags, two sandbags in height (approx 32 cm total depth) were placed across the exit into the canalised section from 15:00 to 15:30, in advance of the normal maximum emptying of the pool that would have occurred about 3 to 3.5 h after low tide (at about 18:00). The sandbags were noted to slow the exit of water from the pool, but did not prevent water flow. They were finally removed on 5 Aug at 14:05.

2.2 Sampling site locations

All sampling sites were marked with numbered canes and a handheld GPS was used to obtain the NGR of each cane. The location of sites is shown in Figures 1 & 2. Where sites had been previously used in the baseline study on 21 July (water quality monitoring in the low water pool and 2 sites for counts of lugworm casts) we retained the original site number and relocated the sites with the GPS.

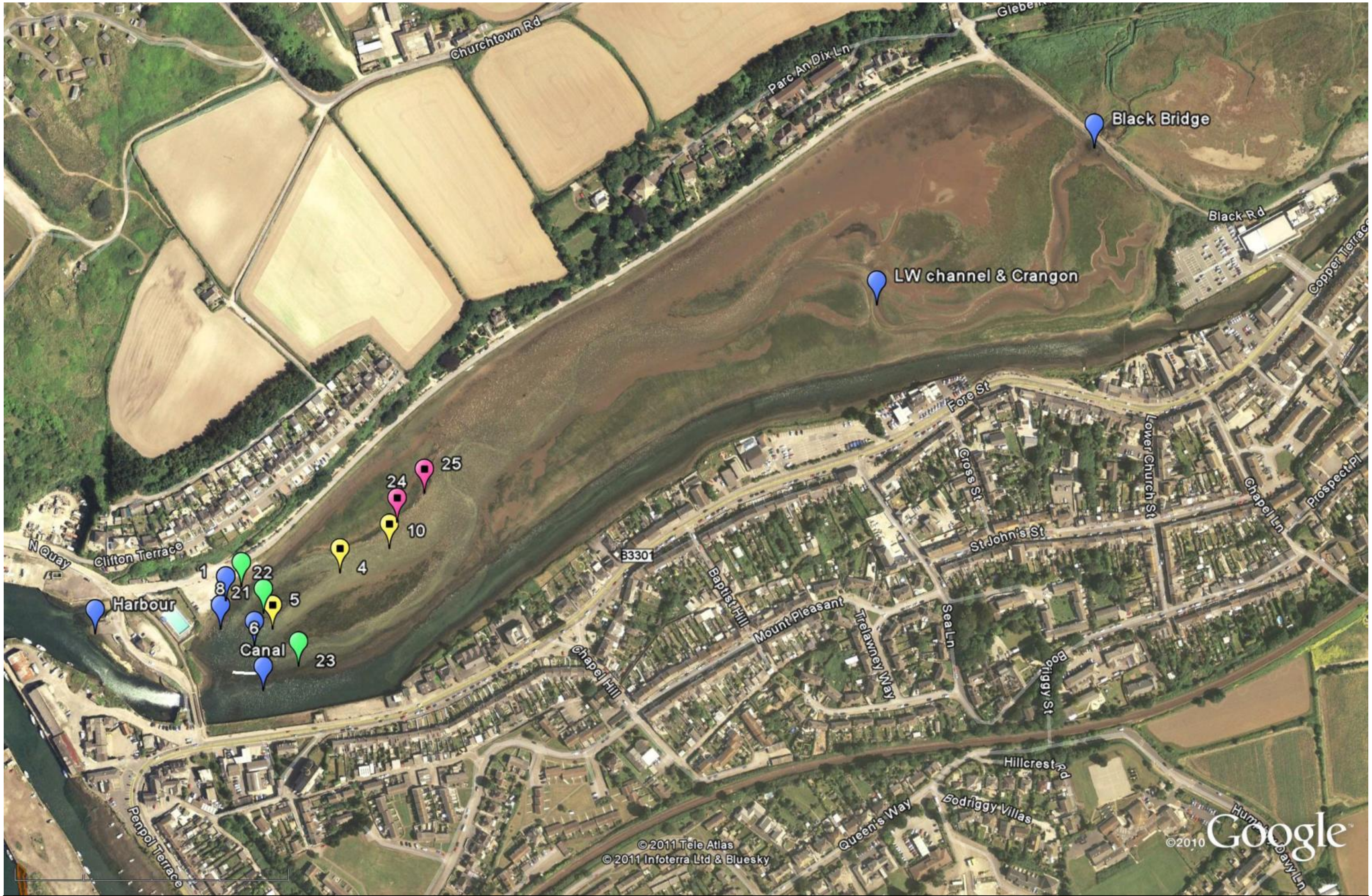


Figure 1. Sampling sites. Blue = water samples. Pink = *Corophium*. Yellow = lugworm. Green = algae.

Figure 2. Sampling sites in lower Copperhouse Pool. Blue = water samples. Pink = *Corophium*. Yellow = lugworm. Green = algae (21 = *Fucus spiralis* and *F. vesiculosus*; 22 = *Ulva torta*; 23 = *Ascophylum nodosum*). White line is the approx line of sandbags.

2.3 Fish Behaviour

We used a combination of video recording from a fixed location and visual survey around the low water pool and from the car park at Copperhouse Pool to assess fish activity on 3 August (during a normal tidal cycle), on 4 August (to determine whether there were any changes in activity patterns of fish in the low water pool) and on 5 August (to assess whether fish behaviour followed the usual pattern linked to tides).

Video records were of at least one minute at approximately hourly intervals. Video imagery was used to determine fish active at the surface over the first minute of recording and the number of 'jumps' out of water.

2.4 Water Quality

Meters were used to obtain the following data in the field:

- Salinity (Yellow Springs Model 30 Meter, calibrated on 2 August) - recorded in practical salinity units (psu); values are equivalent to parts per thousand (ppt)
- Water temperature (°C) recorded by Yellow Springs conductivity meter
- pH (Hanna H198127 meter)
- Ammonia (total, mg/l), measured by Hach field ammonia meter. Calibration was checked by spiking samples of Copperhouse Pool water and ultrapure water prior to the study. The proportion of unionised ammonia (the toxic form) in each sample, which varies with temperature and pH was calculated.
- Nitrite concentration (mg/l) was estimated by using a kit.
- Dissolved oxygen (mg/l and % saturation, monitored by Hach 30d meter with a Luminescent Dissolved Oxygen Probe

Water samples for metal analysis were obtained from 2 locations around the low water pool. A sample bottle on a telescopic pole was used to avoid disturbance of fish in the pool or the sediments. All samples were collected within the 50 cm of the surface.

Water samples were poured into 250 ml plastic bottles, which were collected in a cool box with ice packs. In total, 34 samples were sent to Chemtest for analysis of the following determinands:

- Dissolved arsenic
- Dissolved chromium
- Dissolved copper
- Dissolved zinc
- Total zinc

2.3 Meteorological Conditions

All the meteorological observations were made near Site 21 (see Figure 2 for location).

A handheld met station (WindMate 300) was used to monitor the following parameters at 1 – 2 hour intervals:

- Temperature (°C)
- Humidity (%)
- Mean wind speed (m/s) over approximately 1 minute
- Maximum wind speed (m/s) over approximately 1 minute

We also noted whether it was sunny or raining (drizzle or light rain) and estimated the percentage cloud cover.

2.4 Seaweeds – Photosynthetic performance using Pocket PEA

A Pocket PEA fluorimeter (Hansatech Instruments) was used to assess the response of the photosynthetic systems of four species of seaweed under normal conditions (3 August), during tidal exclusion (4 August) and recovery from tidal exclusion (5 August). The Pocket PEA chlorophyll fluorimeter uses focussed, high intensity light from red LEDs to induce a fast chlorophyll fluorescence response from a dark adapted sample. The Pocket PEA method requires the use of a special leafclip system. This is a multi-purpose tool which provides dark adaptation for the sample (required for the measurement of maximum photochemical efficiency), defines the measurement area on the sample and prevents ambient light leakage into the highly sensitive photodiode used by the instrument for chlorophyll fluorescence detection.

For the four species we assessed (*Fucus spiralis, Fucus vesiculosus, Ascophylum nodosum* and *Ulva torta*) we normally obtained at least 4 replicate measurements per species at approximately 2 hour intervals throughout the day. We sometimes only obtained 1-3 readings due to error messages, primarily due to drying of *Fucus* specimens causing crinkling which meant that light was not excluded during the measurement. We took the mean values of any reliable readings we obtained.

The location where we monitored filamentous green seaweeds (Site 22) supported mainly *Ulva torta*, but two other filamentous green seaweeds (*Rhizoclonium* riparium and *Blidingia* marginata) were also present in the sample we brought back for identification. Each was less than 1% of the total sample, so their presence was unlikely to have affected the results from the Pocket PEA.

The Pocket PEA produces data on several parameters; the most important of these is Fv/Fm, the proportion of variable fluorescence (Fv) to maximum fluorescence (Fm). The Fv/Fm ratio is widely used by plant physiologists as a sensitive measure of plant photosynthetic performance. Maximum values for Fv/Fm for unstressed plants are usually in the range 0.8 to 0.85, and this value falls as the plant’s photosynthetic ability declines due to any form of stress, for example desiccation.

2.5 Water Content of *Fucus spiralis* and *Fucus vesiculosus*

The water content of *Fucus spiralis* and *Fucus vesiculosus* during the normal drying cycle was assessed by taking 3 replicate samples from the uppermost parts of the plants (the lowest parts in contact with the sediment remained damp throughout the day). These were placed in weighed glass vials which were sealed with plastic lids to prevent loss of moisture. The vials were re-weighed with the *Fucus* sample then dried to constant weight at 80° C. The water present in each sample was then calculated on an Excel spreadsheet.

2.6 Visual observations of seaweeds and higher plants

At approximately two hourly intervals we visually assessed the condition of the main plant species near the low water pool. The visual observations produced some ancillary information on condition which was useful (for example we noted that *Fucus spiralis* and *Fucus vesiculosus* plants were rehydrating with rainfall on 3 August), but it was not as sensitive as the water content and the Pocket PEA techniques.

2.7 Quadrat Counts of Invertebrates

Lugworm (*Arenicola marina*)

Counts of lugworm casts were made in 3 locations (Sites 4, 5 & 10 on Figure 2). Site 5 was closest to the low water pool. In each case counts were made over an area of 1 m^2, by recording in 4 x 0.5 m^2 quadrats. The locations were marked with a central cane and 4 corner canes to ensure repeatability of site location. Counts were always made from the same starting square and in the same order for the 4 sub-areas, so that we could compare the 4 counts as well as the total count for each location over the natural tidal cycle. Counts of lugworm casts were made close to predicted low water.

Corophium volutator (an amphipod crustacean)

We located two areas with high densities of the amphipod crustacean *Corophium volutator* (Sites 24 and 25 on Figure 2). Counts were made of *Corophium volutator* on the surface in five 10 cm x 10 cm squares. This smaller area was chosen due to the large number of *Corophium* holes present. We also examined the entire 0.5 square metre quadrat, in case the smaller 10 x 10 cm squares were unrepresentative.

We had some concerns whether the Corophium population was healthy, as we had not seen much surface activity and had noted a large number of recently dead *Corophium* (or possibly exoskeletons) on 21 July and on the current survey. We therefore investigated whether the *Corophium* were alive and active below the surface. A section of sediment was opened up with a trowel on 4 & 5 August and the depth distribution of the *Corophium* was noted. Some of the *Corophium* bodies were brought back to the laboratory for microscopic examination.

2.8 Observations

Ragworm (*Nereis diversicolor*)

We failed to find any locations where ragworm (*Nereis diversicolor*) were on the surface and could be counted, but we did examine a large area (2 m x 4 m) each day. On each occasion no ragworm were seen on the surface.

Brown shrimp activity

We were concerned that salinities in the low water channel may fall to values toxic to brown shrimp. We therefore monitored salinity in the low water channel (see Figure 1) on each day and also caught brown shrimp (plus mysids and gobies) at extreme low water to assess their activity. The brown shrimp, mysids and gobies were placed in a white tray to assess their activity. We also checked for any dead brown shrimps, but none were seen.

3. RESULTS & DISCUSSION

3.1 Meteorological Conditions

The forecast for 3 to 5 August 2011 (Camborne) was generally cool and unsettled with sunny intervals and showers. There was little possibility that high temperatures would be a problem (we had specified a maximum temperature of 20 ^{o}C on the day of the exclusion). Rain was a more important issue, as by 3 August the forecast showed a period of heavy overnight rain at around 4-7 am on 4 August. Although we had specified that the trial should not go ahead if there was heavy rain on the days prior to the exclusion (which would have caused high flows and low salinities) this was for prolonged heavy rain, rather than a short event. We therefore gave approval for the trial exclusion to go ahead.

Table 4 summarises the meteorological data. Full details are provided in Table 5.

Table 4. Meteorological Conditions during daylight hours 3–5 August 2011

3 August. Initially sunny, then overcast at lunchtime followed by periods of drizzle and light rain.

	Minimum	Maximum
Pressure (mb)	1016	1017
Air temperature (°C)	17.0	19.5
Humidity (%)	57	93
Cloud cover (%)	65	100
Mean wind speed (m/s)	1.0	2.0
Maximum wind speed (m/s)	1.3	4.0

4 August. Initially some sunny spells (after some heavy overnight rain), then sunny periods with occasional light drizzle.

	Minimum	Maximum
Pressure (mb)	1012	1015
Air temperature (°C)	17.0	20.5
Humidity (%)	51	93
Cloud cover (%)	80	100
Mean wind speed (m/s)	0.2	0.8
Maximum wind speed (m/s)	0.5	1.5

5 August. Sunny periods throughout the survey, no rain.

	Minimum	Maximum
Pressure (mb)	1015	1016
Air temperature (°C)	18.5	20.5
Humidity (%)	30	47
Cloud cover (%)	15	95
Mean wind speed (m/s)	0.0	1.5
Maximum wind speed (m/s)	0.0	2.0

The humidity data were very useful for interpreting the results from the Pocket PEA meter.

The period for which the seaweeds had been uncovered by the falling tide was also important so we noted times when the patch being monitored was first uncovered. For the *Ascophylum nodosum* there was a short period on the trial exclusion day when they were inadvertently immersed by seawater, due to the rise in levels in the low water pool caused by the sandbags. When the sandbags were removed the *Ascophylum* was quickly uncovered.

Table 5. Meteorological Data.

Date	Time	Cloud cover (%)	Wind speed mean (m/s)	Wind speed max (m/s)	Rain/drizzle	Humidity (%)	Temperature C
03-Aug-11	11:25	65	1.2	2.7	Dry	60	19.5
03-Aug-11	12:32	99	1.5	3.0	Dry	57	19.5
03-Aug-11	13:58	90	2.0	4.0	Slight drizzle	66	19.5
03-Aug-11	15:13	100	1.0	1.3	Slight drizzle	75	17.0
03-Aug-11	16:05	100	2.0	2.8	Dry	75	18.5
03-Aug-11	17:23	100	1.0	1.6	Light rain	81	17.5
03-Aug-11	18:30	100	1.5	1.7	Drizzle	93	17.0
04-Aug-11	10:29	90	0.2	0.5	Dry	77	20.0
04-Aug-11	12:29	95	0.7	1.2	Very light drizzle at times	63	19.5
04-Aug-11	14:30	80	0.6	0.9	Dry	51	20.5
04-Aug-11	16:09	95	0.8	1.5	Very light drizzle at times	62	20.5
04-Aug-11	18:06	100	0.7	0.8	Very light drizzle at times	66	18.2
04-Aug-11	19:10	100	0.3	0.6	Dry	74	17.0
05-Aug-11	11:57	15	0.4	1.1	Dry	52	18.5
05-Aug-11	12:53	35	1.5	2.0	Dry	40	19.5
05-Aug-11	14:03	55	1.0	1.6	Dry	30	20.5
05-Aug-11	15:24	95	0.2	1.0	Dry	47	19.0
05-Aug-11	16:12	75	0.0	0.0	Dry	45	19.5

Table 6. Summary of Seaweed Exposure Times

3 August	
Fucus spiralis	Exposed 11:45 (3:20 after predicted HW)
Fucus vesiculosus	Exposed 12:10 (3:50 after predicted HW)
Ulva torta	Exposed 12:25 (4:05 after predicted HW)
Ascophylum nodosum	Covered 18:25 (2:15 before predicted HW)
Fucus vesiculosus	Covered 18:43 (1:57 before predicted HW)
Ulva torta	Covered 18:45 (1:55 before predicted HW)
Fucus spiralis	Covered 19:10 (1:30 before predicted HW)
4 August (morning high tide excluded)	
Ascophylum nodosum	Covered 19:05 (2:21 before predicted HW)
Ulva torta	Covered 19:25 (2:01 before predicted HW)
5 August	
Fucus spiralis	Exposed 12:39 (2:47 after predicted HW)
Fucus vesiculosus	Exposed 13:05 (3:13 after predicted HW)
Ulva torta	Exposed 13:18 (3:26 after predicted HW)

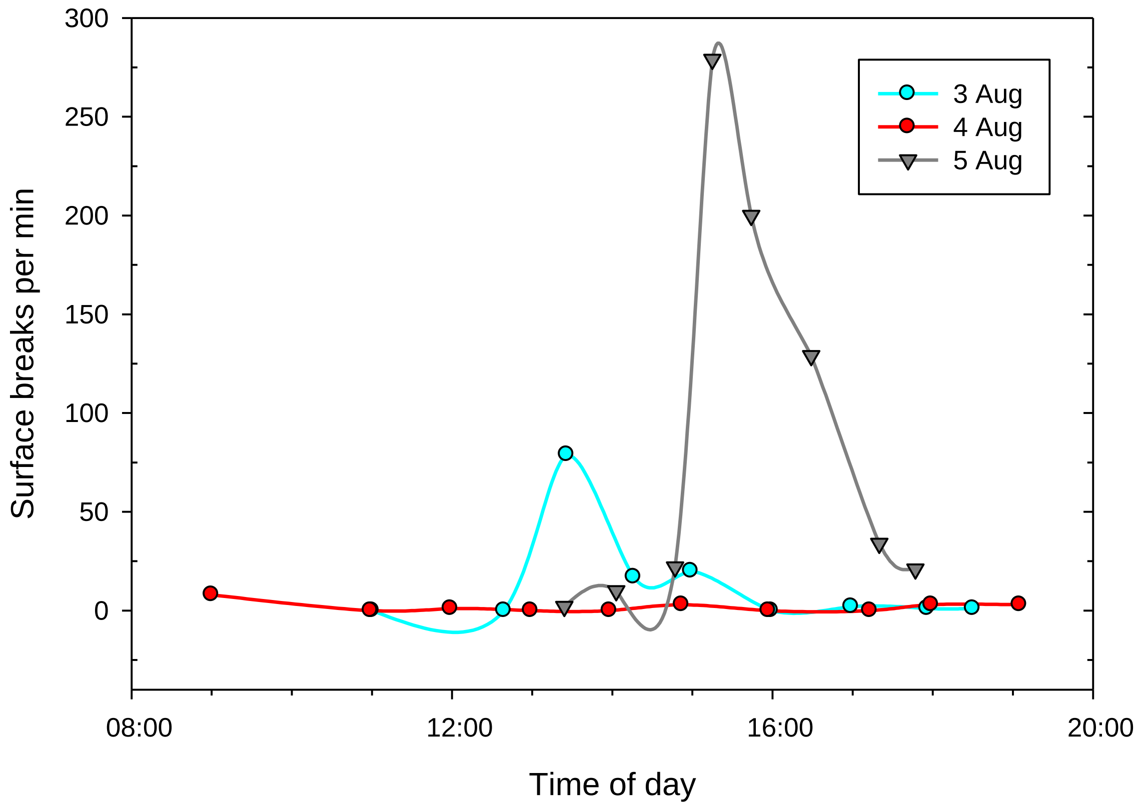
Taking the times for *Fucus vesiculosus* and *Fucus spiralis* to be uncovered and covered on 3 August (Table 6) suggests that the high tide in Copperhouse Pool lags the predicted high tide at St Ives by 55- 56 minutes. This is in agreement with the observed time when the tide turned at Copperhouse Bridge on 5 August, at 10:48, 56 minutes later than predicted for St Ives.

3.2 Fish

3.2.1 Fish activity

Video recording on 21 July had shown that fish in the low water pool show changes in activity (monitored as surface breaks) that are linked to the cycle of empting and filling of the pool. On 3-5 August we monitored the surface breaks and any jumping out of the water each day. The number of surface breaks are shown for each day in Figure 1.

Figure 1. Number of surface breaks of fish in the low water pool on 3-5 August



Prior to the tidal exclusion, on 3 August, there was the normal increase in activity of fish in the low water pool seen during the ebb tide. The number of surface breaks peaked at 79 per min before declining to low levels (Figure 1). This cycle of activity is similar to that seen on 21 July, although with a higher maximum number of breaks, compared to the peak of 39 breaks per min on 21 July. The higher peak activity may be the result of the Spring tides during 3 Aug and/or the result of a higher density of fish in the pool.

Video recording also captured images of fish jumping out of the water. In a normal tidal cycle (3 August) video records before 13:00 did not show any fish jumps, but at 13:25 when surface breaking peaked, 4 jumps per min were recorded but there were no further jumps recorded except at 18:30 after tidal inflow commenced.

During the tidal exclusion, we did not observe any significant changes in fish activity. The maximum number of fish jumps from the water was 1 per min, and usually there was none seen in the video records. Surface breaking remained at a low level throughout the day (Figure 1). This was to be expected as fish would have accumulated in the pool in the early hours of the morning during the normal ebb tide and then settled down. The lack of inundation of Copperhouse, and an ebb tide there was no evidence of changing activity patterns.

The maximum number of surface breaks during the tidal exclusion was recorded at 9:00, when 8 surface breaks per min were recorded. Most of these occurred close to the sandbags, but there were no signs of any fish distress. However, by 10:00 it was clear that a problem had emerged around the sandbags. The blockage of the exit/entry route to the low water pool caused confusion in some fish, particularly sea bass. Their aggregation near to the bags and increased jumping out of the water led to some fish becoming temporarily stranded among seaweeds nearby. We were able to rescue all fish rapidly, and return them to the water. They rapidly moved away and no prolonged stress was evident. However, a rapid decision was taken to remove one of the two layers of sandbags. This allowed free movement of fish in and out of the pool; sea bass and mullet were observed moving in both directions.

For the rest of the tidal exclusion the area around the sandbags was inspected at regular intervals and checks were made around the margins of the pool for any stranded fish. There was no sign of any long term distress of fish within the pool throughout the rest of the tidal exclusion. For example, no surface gulping was seen, no fish were seen lying on the surface of the pool, and no fish were stranded in the margins. The 0^+ and 1^+ fish continued to make use of the margins of the pool as usual.

On 5 August, the day following tidal exclusion, the normal pattern of change in activity was restored. The maximum number of surface breaks occurred approximately 2 h after the peak on 2 August, which is in keeping with the change in the predicted time of low water time which was approximately 2.5 h later on 5 August that on 3 August (Table 3). However, the maximum number of surface breaks was much higher than previously recorded (either on 3 August or 21 July), reaching 279 per min at 15:15. The higher rate of surface breaking was also more persistent (200 per min at 15:44, 129 per min at 16:29) than on 3 August, although within 2.5 h of the peak when recording stopped there was a decline of 92.5% in surface breaks per min.

3.2.2 Water quality and effects on fish in the low water pool

Water quality (salinity, dissolved oxygen, pH and ammonia, and metal concentrations) were monitored regularly monitored at 2 locations (Sites 6 & 8). There was also less frequent monitoring at an additional location (Site 1) higher up the shore (see Figure 2). National Grid References (NGRs) of for each site are given in Table 8.

Table 8. NGRs and descriptions of water quality monitoring sites (see also Figure 2)

Site	NGR	Site description
1	1 SW 55847 37745	Upper shore location, close to low water pool on side parallel to King George V Memorial Walk
6	SW 55871 37705	In deep section of pool on southern side, close to where main freshwater input enters the pool
8	SW 55842 37721	On King George V Memorial Walk side of the low water pool, further towards causeway than sites 1 & 9

Salinity

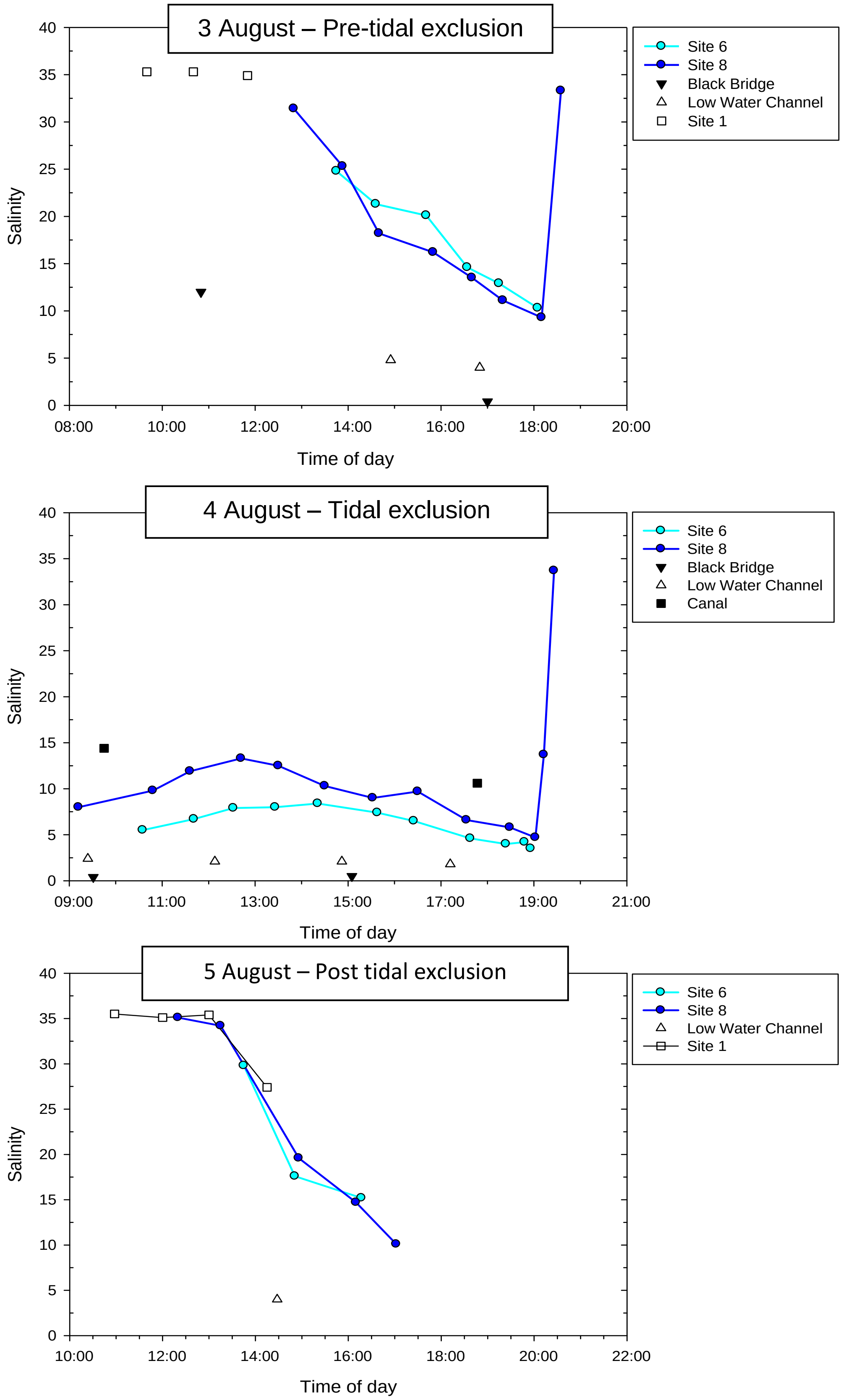
Figure 2 shows the salinities recorded in the low water pool on 3 August, the day before tidal exclusion, the 4 August, the day of tidal exclusion and the 5 August, after tidal exclusion.

During a normal tidal cycle the salinity in Copperhouse Pool reached salinities similar to that in the Harbour, recorded as 34.8 psu on 3 August at 9:20 and 34.4 psu on 5 August at 10:42. During the ebb tide the salinity of the low water pool decreases because of the continued passage of freshwater along channels that enter the pool. On 3 August, the salinity decreased to a minimum value of 9.3 psu, at Site 8. This was similar to the minimum salinity reached at Site 8 on 21 July (10.3 psu). At Site 6, adjacent to the main freshwater input, salinity reached a minimum value of 10.3 at 18:05 on 3 August, which was somewhat higher than the minimum value recorded on 21 July (7.2) just before seawater entered the pool on the flood tide.

During the tidal exclusion, consistently lower salinities were recorded at Site 6, adjacent to the freshwater inflow, than at Site 8 at the opposite side of the pool, with a salinity differences of up to 5.4 psu (at 12:20 – 12: 42). The lowest salinity recorded at Site 6 was 3.5 psu at 18:56, just after the tidal inflow which started at 18:50. The lowest salinity recorded at Site 8 was 4.7 psu at 19:02.

Prior to the tidal exclusion, we predicted that exclusion would lead to a lower salinity in the low water pool due to the continued entry of freshwater via the channels entering the pool, and that salinity may approach the level in the low water channel. To attempt to reduce this effect, and mitigate potential effects on fish in the pool, sandbags were placed at the exit from the pool. Although the sandbags did cause other significant problems for fish in the pool, as

Figure 2. Salinity of Copperhouse Pool during normal tidal cycle on 3 August, during a daytime tidal exclusion (4 August) and normal tidal cycle on 5 August.



outlined above, this procedure did mitigate the decline in salinity after the overnight rain. Low water channel salinities of 2.4 and 2.1 were recorded at 9:24 and 14:52 respectively (see Figure 4), compared to a value of 3.9 on 21 July.

The sandbags were put in place from 15:00 to 15:00 on 3 August. The upper layer of sandbags in the middle section was removed at approximately 10:00 on 4 August to allow the free passage of fish into and out of the low water pool. After removal of these sandbags there was rapid discharge of water from the pool through the exit channel. A slight rise in salinity was recorded between 10:35 and approximately 13:30, at both sampling sites (3.5 psu increase at Site 8; 2.9 psu increase at Site 6; Figure 4). This suggests that the rapid water discharge preferentially allowed lower salinity surface water to exit from the low water pool.

Temperature

Water temperatures rose during the normal tidal cycle but with a lower maximum temperature than on 21 July, when water temperature reached 24.4 ^{o}C. The maximum temperature was 20.5 ^{o}C at Site 8 on 3 August. During the tidal exclusion, a slightly higher maximum was recorded than on the previous day (Table 9), but not to a level that would have caused any problems for fish in the pool. The temperatures would be ideal for mullet and sea bass, which prefer warm waters and for which optimal temperatures of 22-25 ^{o}C are reported. The entry of water from the harbour at 18:50 resulted in a rapid decline in water temperature. The following day (5 August) water temperature reached 22.3 ^{o}C at Site 8.

Table 9. Maximum water temperatures recorded in Copperhouse Pool on 3-5 August

	Maximum Water Temperature ^{o}C	Time	Location
3 August 2011	20.5	13:53	Site 8
4 August 2011	20.9	16:25; 16:30	Site 6; Site 8
5 August 2011	22.3	14:15	Site 8

Dissolved Oxygen (DO)

Dissolved oxygen concentrations in the low water pool will be influenced by:

- Weather conditions, e.g. sunlight stimulation of photosynthesis by seaweeds and phytoplankton.
- Fluctuations in water temperature; oxygen solubility in water is reduced by an increase in temperature

- Biological Oxygen Demand (BOD) due to microbial degradation of organic matter which uses up oxygen.
- Chemical Oxygen Demand (COD) due to oxidation of chemical compounds, e.g. metal sulphides to metal sulphates.
- Fish (and invertebrate) biomass and their oxygen consumption which increases with body temperature that closely follows water temperature (about 2-3 fold increase in oxygen requirement for a 10 ^{o}C rise in water temperature)

For fish in the low water pool, what matters is the oxygen tension in the water or the concentration of dissolved oxygen (mg/l). Table 10 shows that the changes in dissolved oxygen concentrations at each monitored site, throughout the day.

Table 10. Dissolved oxygen (DO) concentrations at Sites 6 & 8 in the low water pool

	Site 8				**Site 6**			
	Time	**DO (mg/l)**	**DO (% Sat^{n})**	**^{o}C**	**Time**	**DO (mg/l)**	**DO (% Sat^{n})**	**^{o}C**
Pre-exclusion 3-August								
	12:50	10.00	108.2	19.0				
	13:53	9.56	105.7	20.5	13:45	9.19	102.1	20.2
	14:40	9.28	101.9	20.2	14.36	9.02	99.4	20.3
	15:50	9.13	99.9	20.0	15:41	8.78	97.1	20.1
	16:40	9.17	100.1	19.9	16:34	9.08	99.5	20.1
Sandbags across exit - 17:10	17:20	9.14	98.8	19.3	17:15	9.02	97.9	19.5
	18:10	9.22	98.6	18.9	18:05	9.06	96.9	19.1
Inflow at ~ 18:15	18:35	9.71	99.0	16.2				
Tidal Exclusion 4-August								
	09:12	7.92	82.0	16.9				
Some sandbags removed 10:00	10:48	8.43	88.7	17.8	10:35	9.13	97.9	18.5
	11:36	8.50	93.8	19.1	11:41	9.29	100.6	19.3
Tidal gate opened at ≈ 12:00	12:42	8.92	96.9	19.4	12:32	8.95	99.8	19.8
	13:30	9.28	102.4	20.1	13:26	9.20	102.1	20.3
	14:30	9.52	105.4	20.6	14:21	8.94	100.8	20.7
	15:32	9.74	109.9	21.2	15:38	9.29	104.2	21.1
	16:30	9.47	105.4	20.9	16:25	9.28	104.2	20.9
	17:33	9.53	104.9	20.2	17:38	9.47	103.3	19.7
	18:29	9.63	103.9	19.4	18:24	9.46	101.5	19.0
Inflow at 18:50	19:02	9.46	101.0	18.8	18:48	9.55	101.3	18.8
	19:13	8.83	96.3	19.8	18:56	9.36	98.9	18.3
	19:26	10.17	104.5	16.7				
Recovery 5-August	12:20	10.86	117.1	18.4				
Outflow commenced 10:48	13:15	10.95	118.0	19.0				
	14:15	10.44	120.5	22.3	13:45	10.70	120.5	20.9
	14:56	10.03	112.8	19.6	14:51	9.42	107.2	21.9
	16:10	9.66	113.0	22.8	16:17	9.65	110.3	22.3
	17:02	9.91	111.1	21.3				

During the normal tidal cycle the highest dissolved oxygen concentrations and percent saturation were recorded at the beginning of the recordings at 12:50 (10 mg/l, 108.2 % saturation at Site 8) and probably reflect the sunny conditions and high levels of photosynthesis preceding this point. Dissolved oxygen concentrations remained high during the rest of the day with percent saturation of 96.9 to 105.7 in the two sampling sites. This is indicative of a good balance between oxygen production by photosynthesis and oxygen uptake due to respiration by fish, invertebrates, phytoplankton and seaweeds.

On 4 August, during the tidal exclusion, the dissolved oxygen concentration reached the lowest concentrations recorded over the 3 day study. This value was obtained early in the day (09:12) and in overcast conditions when there would have been less photosynthetic activity. The concentration of 7.92 mg/l recorded at the beginning of the day is well above the concentration that would become of concern for either fish or invertebrates in the low water pool. From this point onwards during the tidal exclusion, oxygen concentrations at both study sites increased to a peak of 9.63 mg/l at 18:29 (Site 8) and a peak of 9.55 mg/l in Site 6 at 18:48. Microbial, phytoplankton and algal photosynthesis increased oxygen saturation to above 100%.

Sites 1 in the marginal fucoid zone was occasionally monitored on 3 August and 5 August, but was uncovered on 4 August during tidal exclusion. At 11:50 on 3 August this site had the highest DO seen during the 3 day study at 11.77 mg/l, 130.5 % saturation. The high DO agrees with our observations on 21 July when oxygen saturation at 12:22 reached 125.6 % at this site. Young fish (0+ and 1+ cohort) make frequent use of these habitats, and move back and forth in the marginal shallow water.

pH

Table 11 shows that water pH was stable throughout the tidal cycle on 3-August, varying between 8.2 and 8.4. During the tidal exclusion the variation in water pH was slightly greater (8.1 to 8.5). This is probably due to a combination of the higher than anticipated freshwater input after overnight rain, perhaps coupled with the effects of respiration of fish and invertebrates in the pool. The impact of this variation in pH on ammonia ionisation is minimal (Seager et al., 1988).

Ammonia and Nitrite

Fish excrete up to 90% of their nitrogenous waste as ammonia which is normally diluted by the water to values that are not toxic to fish. However, in the absence of the normal flood tide the dilution available will be less and a high density of fish in the low water pool could cause an increase in ammonia towards toxic levels. Ammonia toxicity increases with higher temperatures, salinity and pH, mainly due to the increased proportion of unionised ammonia, (NH_3), which is 300-400 times more toxic than the ionised form (NH_4^+) (Seager et al 1988; Environment Agency, 2007). From our measurements we have calculated the proportion of unionised ammonia. The current Environmental Quality Standard (EQS) for protection of marine fish is 0.021 mg/l unionised ammonia-N (Seager et al., 1988). This EQS is an annual average value and there is no short term EQS or Probable No Effects Concentration (PNEC) for ammonia, although there is a proposed PNEC of 0.0057 mg/l based on the most sensitive test organism, a sea urchin (Environment Agency, 2007).

Table 11. Total ammonia and estimated unionised ammonia, and pH in the low water pool on 3-5 August.

	date	time	Site	pH	Temp °C	Total Ammonia (mg/l)	Unionised Ammonia (mg/l)
Normal Tidal Cycle	03-Aug	11:50	1	8.4	18.6	0.06	0.005
	03-Aug	12:50	8	8.2	19.0	0.01	0.001
	03-Aug	13:45	6	8.3	20.2	0.06	0.005
	03-Aug	13:53	8	8.3	20.5	0.13	0.010
	03-Aug	15:41	6	8.3	20.1	0.06	0.004
	03-Aug	15:50	8	8.4	20.0	0.17	0.015
	03-Aug	17:15	6	8.4	19.5	0.16	0.014
	03-Aug	17:20	8	8.4	19.3	0.04	0.004
inflow ~18:15	03-Aug	18:35	8	8.4	16.2	0.11	0.008
Tidal Exclusion	04-Aug	10:35	6	8.2	18.5	0.10	0.005
	04-Aug	10:48	8	8.1	17.8	0.11	0.005
	04-Aug	12:32	6	8.2	19.8	0.11	0.006
	04-Aug	12:42	8	8.2	19.4	0.12	0.007
	04-Aug	14:21	6	8.3	20.7	0.12	0.009
	04-Aug	14:30	8	8.3	20.6	0.13	0.010
	04-Aug	16:25	6	8.4	20.9	0.07	0.007
	04-Aug	16:30	8	8.3	20.9	0.09	0.007
	04-Aug	18:24	6	8.5	19.0	0.06	0.006
inflow 18:50	04-Aug	18:29	8	8.3	19.4	0.07	0.005
Normal Tidal cycle	05-Aug	10:58	1	8.3	16.7	0.04	0.002
	05-Aug	12:20	8	8.3	18.4	0.13	0.009
	05-Aug	13:00	1	8.3	20.3	0.09	0.007
	05-Aug	13:15	8	8.3	19.0	0.09	0.006
	05-Aug	13:45	6	8.4	20.9	0.12	0.012
	05-Aug	14:15	8	8.4	22.3	0.10	0.011

On 3 August, during the normal tidal cycle the highest concentrations of ammonia occurred between 15:50 & 17:20, when total ammonia was 0.16-0.17 mg/l and the estimated unionised ammonia was 0.014-0.015 mg/l. Unionised ammonia concentrations declined during the next hour but did not reach the undetectable levels that had been seen on 21 July (Table 11).

The maximum concentrations of ammonia during the tidal exclusion (total ammonia: 0.13 mg/l; estimated unionised ammonia: 0.01 mg/l) were below the peak levels observed on the 3

August. Therefore we can conclude that the tidal exclusion is highly unlikely to have had adverse effects on ammonia concentrations that could result in sub-lethal impacts on fish in the low water pool. Furthermore, the lowest reliable No Observable Effects Concentration (NOEC) for long-term effects of unionised ammonia on marine fish is 0.066 mg/l for growth of Dover sole (Environment Agency, 2007). This value is 4.4 times higher than the highest concentration we recorded in the low water pool, 0.015 mg/l on 3 August, during a normal tidal cycle.

Bacterial nitrification of ammonia forms nitrite which is usually rapidly oxidised to nitrate, but increased concentrations of nitrite can occur in water reuse systems, and can be of concern for fish in low salinity water. Two different genera of bacteria are involved in the oxidation of ammonia to nitrate. Ammonia is initially oxidised to nitrite by *Nitrosomonas*. The nitrite is then converted to nitrate by *Nitrobacter*. We therefore considered the possibility that high metal concentrations in the low water pool could inhibit the *Nitrobacter*, which would result in an accumulation of nitrite.

Nitrite toxicity decreases with an increasing concentration of chloride ions in seawater. Since salinity was predicted to decline during the trial tidal exclusion we included a few checks of nitrite concentration in our analyses. The recorded nitrite concentration in the low water pool on 5 August at 17:00 was 0.1 mg/l. This was similar to the concentration recorded on 4 August at 16:25-16:30 at both sampling sites in the low water pool.

The protective effect of chloride ions is so great that even at 1 psu (a chloride concentration of 554 mg/l) there is no possibility that nitrite concentrations could rise to toxic levels. At 41 mg/l chloride ions (equivalent to 0.074 psu saline) the 96 hour LC50 for nitrite for rainbow trout is 12.2 mg/l (Russo and Thurston, 1977). There are therefore no concerns regarding nitrite concentrations in the low water pool, even at very low salinities.

Metals (total & dissolved)

Table 12 shows the mean concentrations of the metals in the lower part of Copperhouse Pool on each day. The maximum concentration in relation to the relevant Environmental Quality Standard (EQS) is also shown. Generally it is the dissolved metals that are directly toxic to fish and the EQSs are usually stated as dissolved concentrations. However, for zinc the EQS is for total zinc. In all cases the EQS values are for annual mean concentrations.

Table 12. Metals in Copperhouse Pool.

		Arsenic dissolved ug/l	Chromium dissolved ug/l	Copper dissolved ug/l	Zinc dissolved ug/l	Zinc total ug/l
Mean	03-Aug	161	421	62	119	121
Mean	04-Aug	127	175	36	80	89
Mean	05-Aug	177	639	55	134	140
EQS		25	15	5	NA	40
Max/EQS	03-Aug	8.0	56.0	24.0	NA	4.25
Max/EQS	04-Aug	6.0	36.7	9.0	NA	3.50
Max/EQS	05-Aug	7.6	49.3	12.2	NA	3.75

The maximum concentrations recorded for each metal were on 3 August when Copperhouse Pool was relatively full. Mean concentrations of most metals (except copper) in the low water pool were highest on 5 August, this is due to the fact that on 5 August we only monitored the start of the ebb tide, so the low values observed towards low water were not recorded.

The mean concentrations of all metals were much lower on 4 August, the day of the tidal exclusion.

Chromium is not usually considered to be of particular concern in Copperhouse Pool, but the results from the 21 July study and the trial exclusion show that the ratios of maximum chromium concentrations to the EQS is very high and of significant concern. At present we think this is more likely to be due to an industrial discharge than either historical contamination or pollution caused by construction works, but this issue needs to be examined by the Environment Agency to determine the source of the chromium.

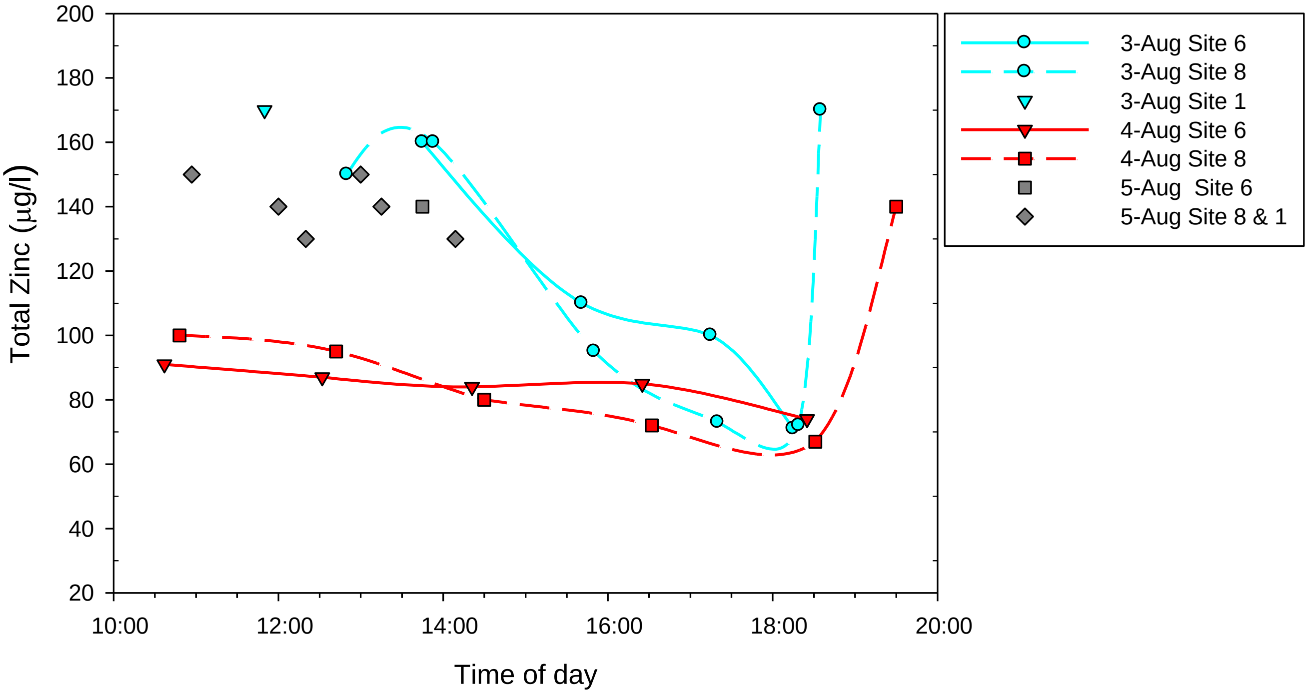
The analysis of water samples collected from the low water pool showed the dynamic changes in metal concentrations in a normal tidal cycle within the low water pool and the impacts of tidal influx of harbour water on the flood tide and freshwater on the ebb tide.

Total Zinc

Total zinc concentrations are shown in Figure 3. On the incoming tide, the total zinc concentrations in the low water pool exceeded the EQS for total zinc by up to 4.25 fold. During the ebb tide the concentration of zinc decreased in the low water pool (Figure 3). This is probably due to a combination of dilution by freshwater (which had a lower zinc content) and zinc attaching to the sediments in the pool. We avoided disturbing the sediments by using a sampling pole.

During the ebb tide on 3 and 4 August zinc concentrations decreased to just under twice the EQS. On 5 August monitoring did not continue to the extreme low water, but the downward trend in zinc concentrations was similar (Figure 3).

Figure 3. Total zinc in lower Copperhouse Pool, 3 – 5 August 2011.



Dissolved Copper

Dissolved copper concentrations were high in Hayle Harbour and the flood tide brought in high concentrations to Copperhouse Pool (Figure 4).

The mean dissolved copper concentrations were highest on 3 August and lowest on 4 August. Maximum dissolved copper concentrations exceeded the EQS by 24 fold on 3 August, but only 9 fold on 4 August (Table 12). The results show that tidal exclusion had a beneficial effect on copper concentrations in the low water pool.

Dissolved Arsenic

Figure 5 shows the changes in dissolved arsenic concentrations on each of the three survey days. Concentrations of arsenic were slightly higher when water levels in the pool were higher, but this may be due to dissolved arsenic becoming attached to suspended solids or sediments on the bed of Copperhouse Pool. Dissolved arsenic concentrations in the harbour on two occasions were 180 µg/l; in the low water channel dissolved arsenic was 140 µg/l on both occasions.

The maximum concentration of dissolved arsenic was 200 µg/l on 3 August, near the time of high tide. This was 8 times the EQS for dissolved arsenic.

Arsenic concentrations in the low water pool area were lowest on the 4 August, when the high tide had been excluded. During the tidal exclusion the maximum concentration was 140 µg/l, this rose slighjtly on the flood tide to 150 µg/l (6 times the EQS).

Figure 4. Dissolved copper in lower Copperhouse Pool, 3 – 5 August 2011.

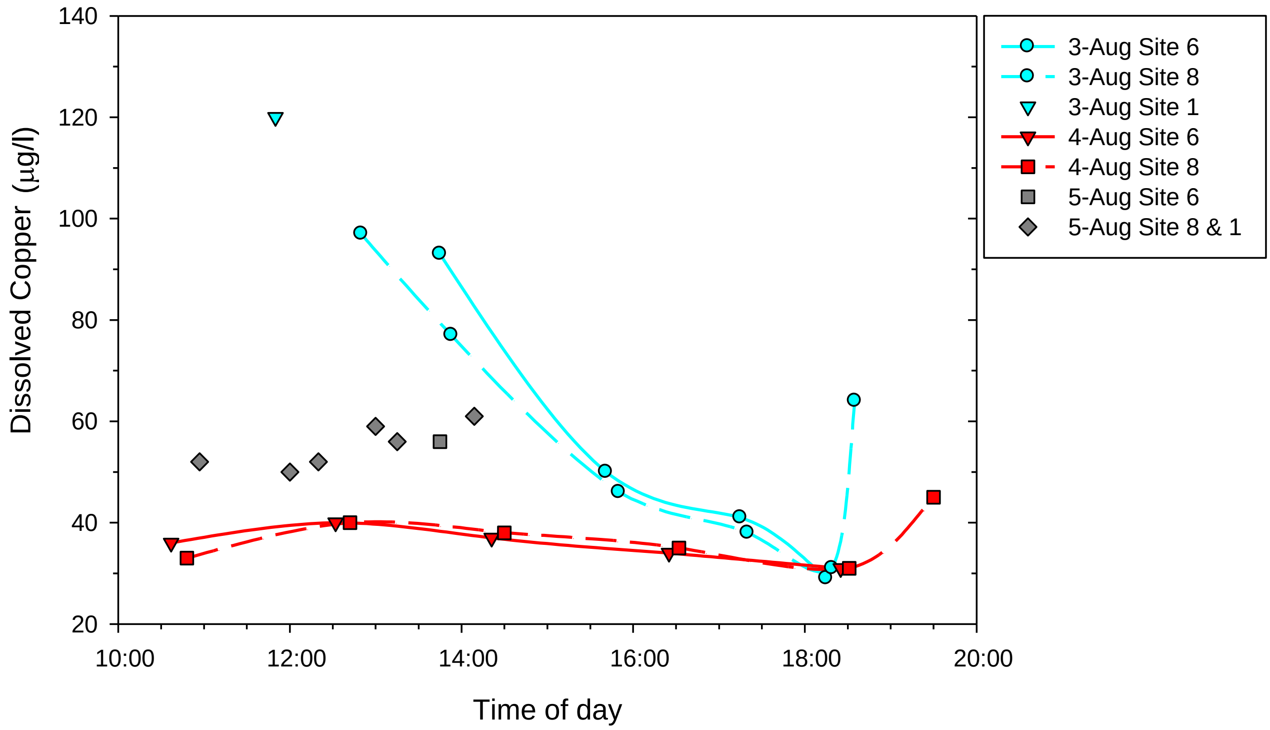
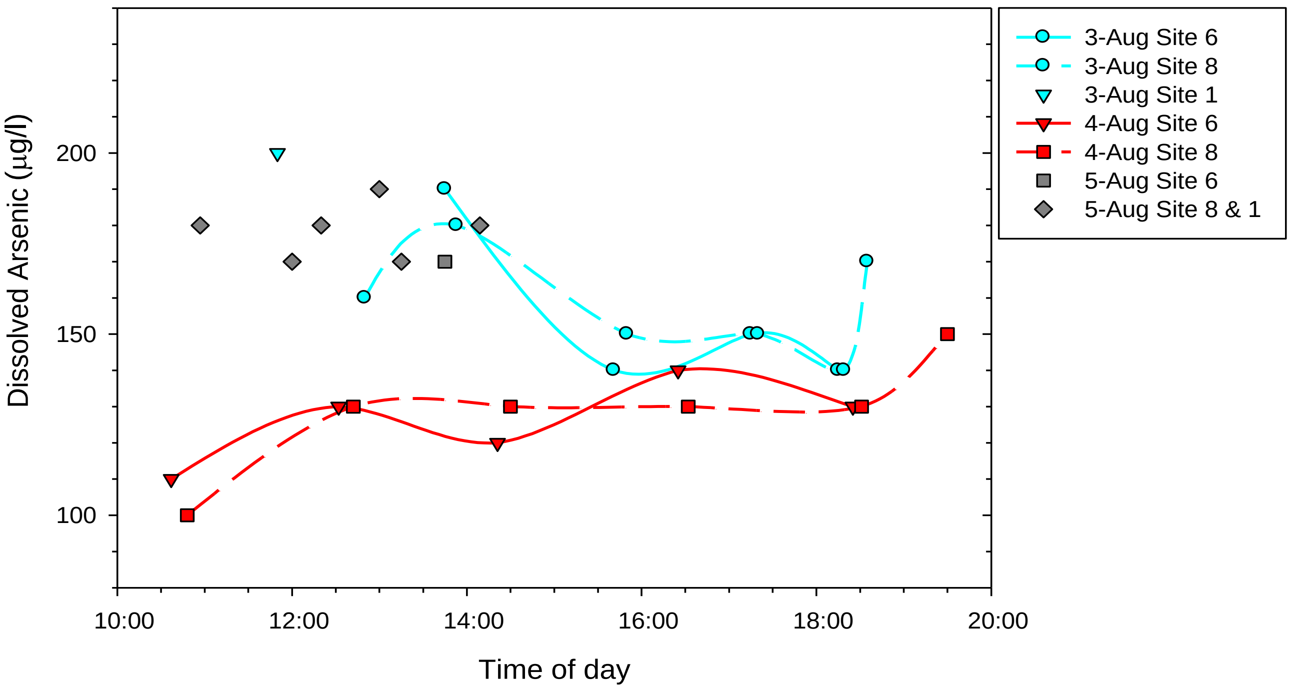


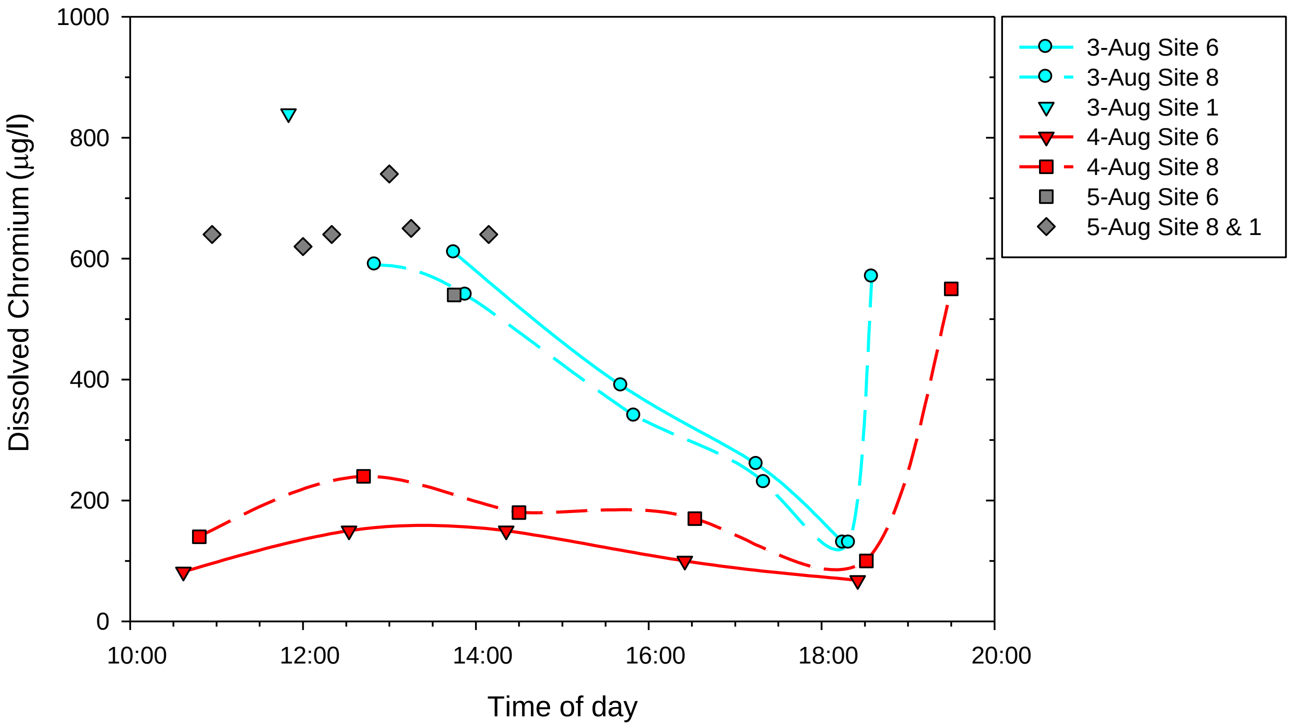
Figure 5. Dissolved arsenic in lower Copperhouse Pool, 3 – 5 August 2011.



Dissolved Chromium

The results showed high concentrations of dissolved chromium in Hayle Harbour (630 – 680 µg/l), which increased the concentration of dissolved chromium in Copperhouse Pool on each flood tide (Figure 6). Concentrations of dissolved chromium were much lower in the two samples taken from the low water channel (30 µg/l on 4 August and 92 µg/l on 5 August). The maximum concentration of dissolved chromium in Copperhouse Pool (840 µg/l at 11:40 on 3 August) was 56 times higher than the EQS.

Figure 6. Dissolved chromium in lower Copperhouse Pool, 3 – 5 August 2011.



Chromium concentrations in the low water pool decreased during the ebb tide (Figure 6), but even the lowest concentrations recorded were 8.7 times the EQS on 3 August and 4.5 times the EQS on 4 August. On 5 August sampling stopped before the lowest concentrations were reached.

The high concentrations of chromium in the harbour relative to the low water channel strongly suggest a discharge into the harbour area, but we have not been able to identify the source. It could be an industrial site, such as a metal finishing works, in the Hayle area.

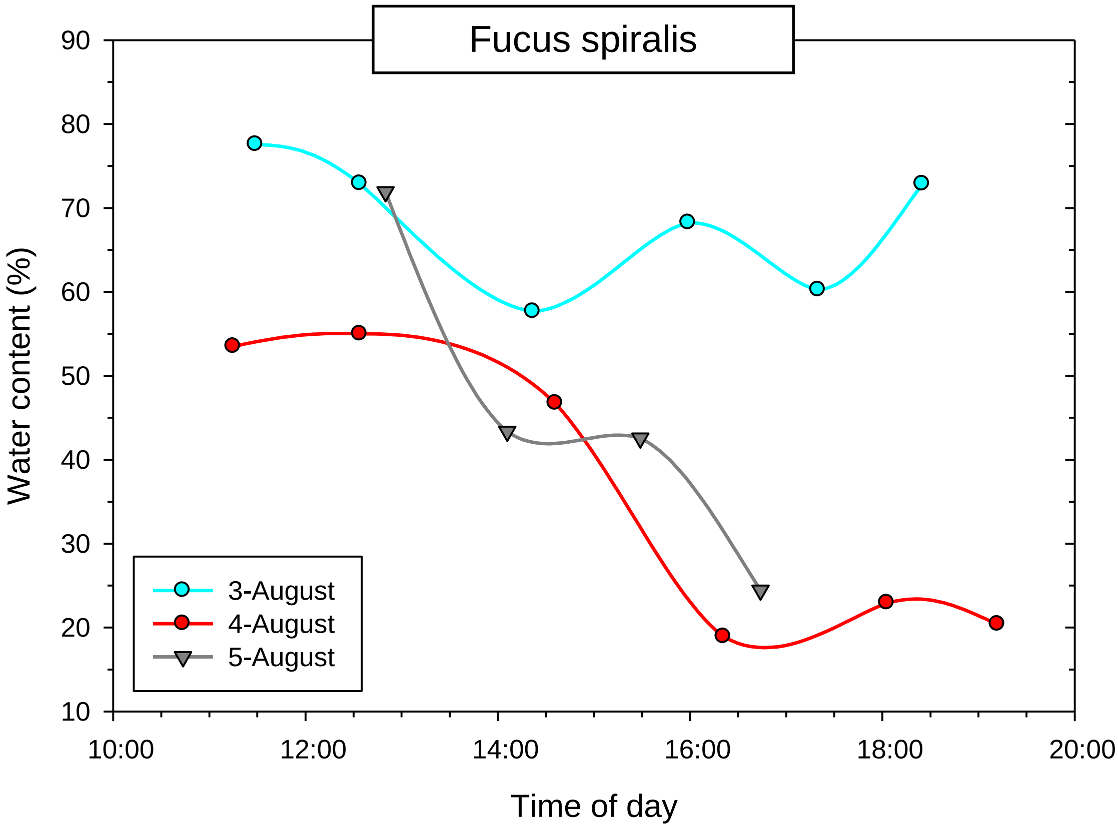
3.4 Seaweeds

3.4.1 Spiral wrack, *Fucus spiralis*

In Copperhouse Pool the brown seaweed that occupies the highest zone on the intertidal is spiral wrack (*Fucus spiralis*). From its position on the shore we estimate that it will be inundated on every high tide, even the lowest neap tides. However, if a neap tide was combined with very high pressure the water level may not be sufficient to cover the plants.

Spiral wrack specimens were monitored at Site 21 (Figure 2). Water content in plants that were submerged (sample shaken dry before being placed in vial) was 78% on 3 August and 72% on 5 August (Figure 7). On the 3 August the initial warm and sunny conditions caused water content to fall to 58% at 14:22, but there was a general increase in water content to reach 73% (i.e. almost fully hydrated) by 18:25, well before the plants were covered by the rising tide. The increase in water content during the afternoon was due to increased humidity with drizzle and light rain.

Figure 7. Water content of Spiral Wrack, *Fucus spiralis*

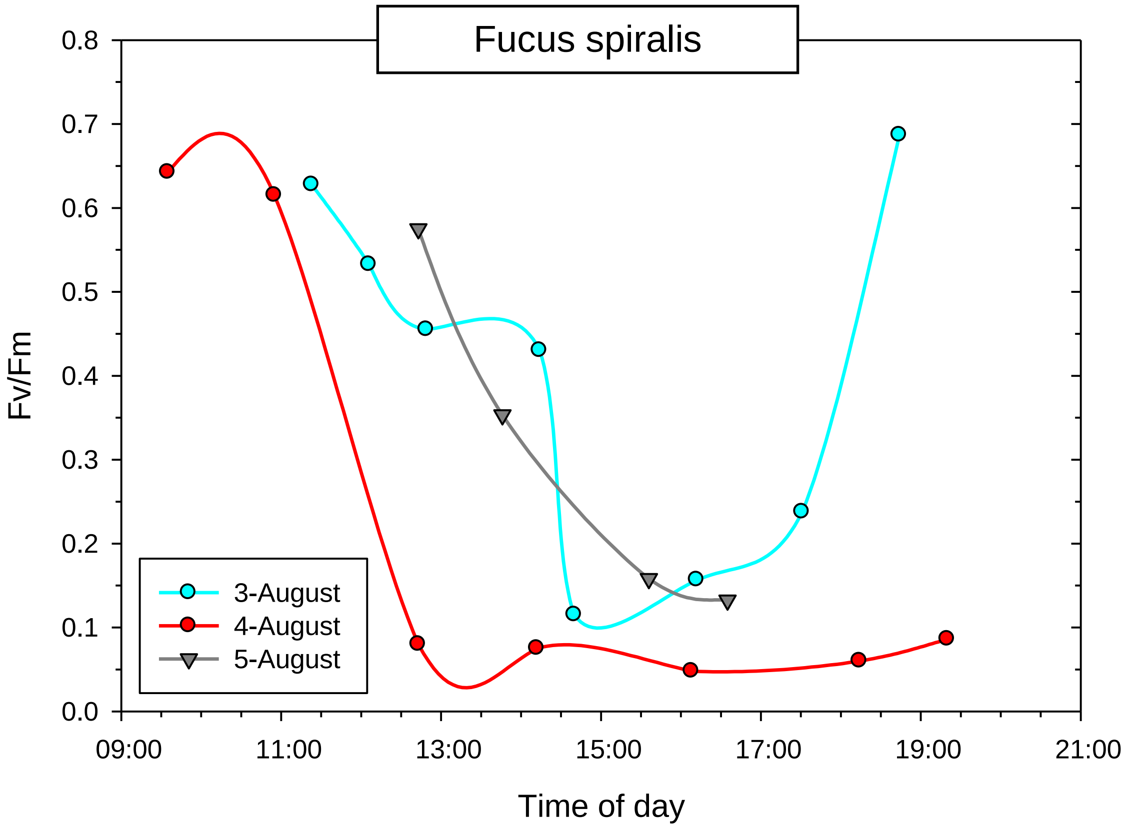


On 4 August the overnight rain did not rehydrate the plants as much as we expected. This may be due to our relatively late start on the monitoring, due to the higher priority we had to give to fish that were seen to be struggling near the sandbags. The first sample of spiral wrack we took on 4 August was at 11:15, when it was dry and quite warm (about 20°C). This probably explains the water content of 54%. There was a slight increase in water content to 55% after some drizzle, then water content fell to a low of 19% at 16:21. The final sample at 19:12 on 4 August had a water content of 20%.

The lowest water content on the day of the tidal exclusion (19%) was similar to the lowest value we recorded the next day (5 August) when 24% was recorded at 16:44 (our last sample). It seems likely that water content would have fallen even lower on 5 August if sampling had continued.

Fv/Fm values are shown in Figure 8. The two highest Fv/Fm mean values occurred when the plants had been exposed to the air for several hours, but had been re-wetted by high humidity and rain. On 3 August the maximum Fv/Fm was 0.69 at 18:44. On 4 August the maximum Fv/Fm was 0.64 at 09:35. By comparison, spiral wrack that were totally hydrated by seawater had maximum Fv/Fm values of 0.63 (11:23 on 3 August) and 0.58 at 12:43 on 5 August.

Figure 8. Fv/Fm values for Spiral Wrack, *Fucus spiralis*



It is possible that metal contamination is affecting the photosynthetic ability of spiral wrack in Copperhouse Pool, and depressing Fv/Fm values slightly. Wetting by rainfall may dilute the effects of the contaminants and result in higher Fv/Fm values. However, the plants would clearly suffer if they were placed in freshwater, as they need saline conditions to thrive.

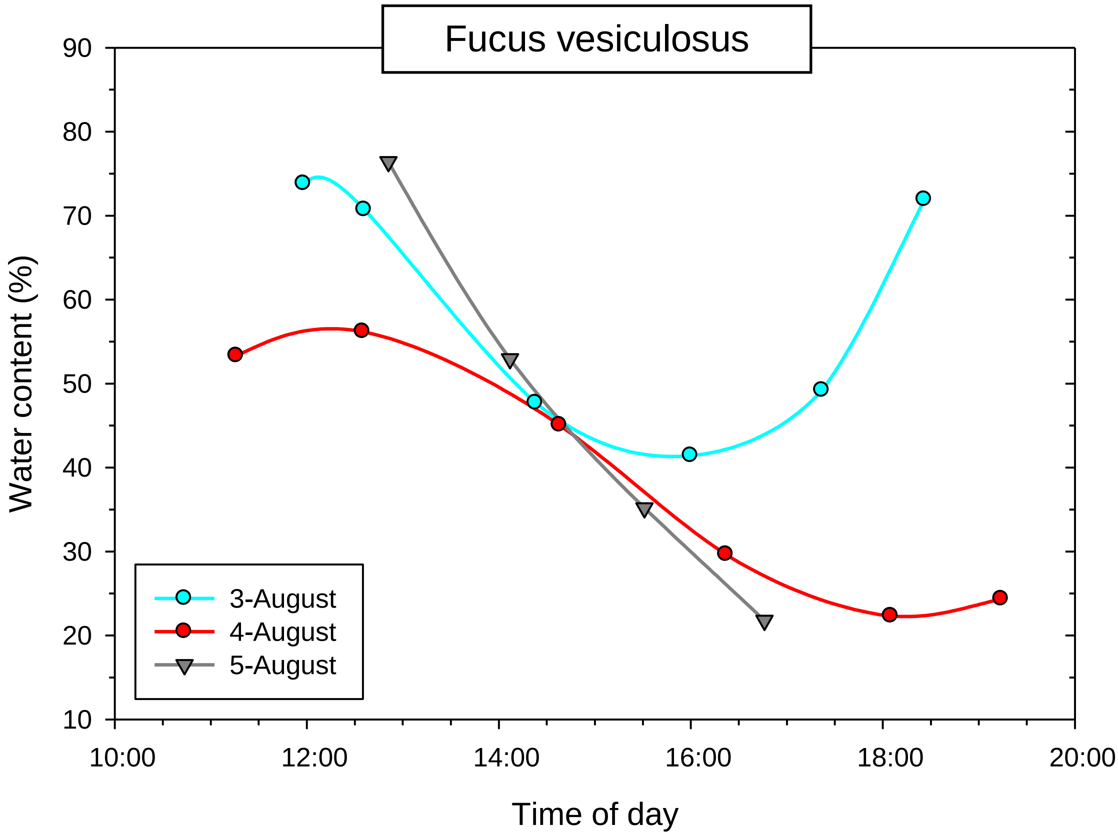
We conclude that spiral wrack is more no more affected by a tidal exclusion on a damp, humid and cool day than by a warm, dry day under normal tidal conditions.

3.4.2 Bladder wrack, *Fucus vesiculosus*

Bladder wrack were studied about 3 m down shore from the spiral wrack (Site 21, Figure 2).

Water content of bladder wrack over the 3 day study is shown in Figure 9. On the previous survey on 21 July there were much warmer and more drying conditions and water content of bladder wrack fell from 64% at the start of the study to 16% at 18:00. It then steadily increased to 36% (due to more humid air) immediately prior to being covered by the incoming tide and increased further to 48% when it had been covered by seawater for a few minutes.

Figure 9. Water content of bladder wrack, *Fucus vesiculosus*



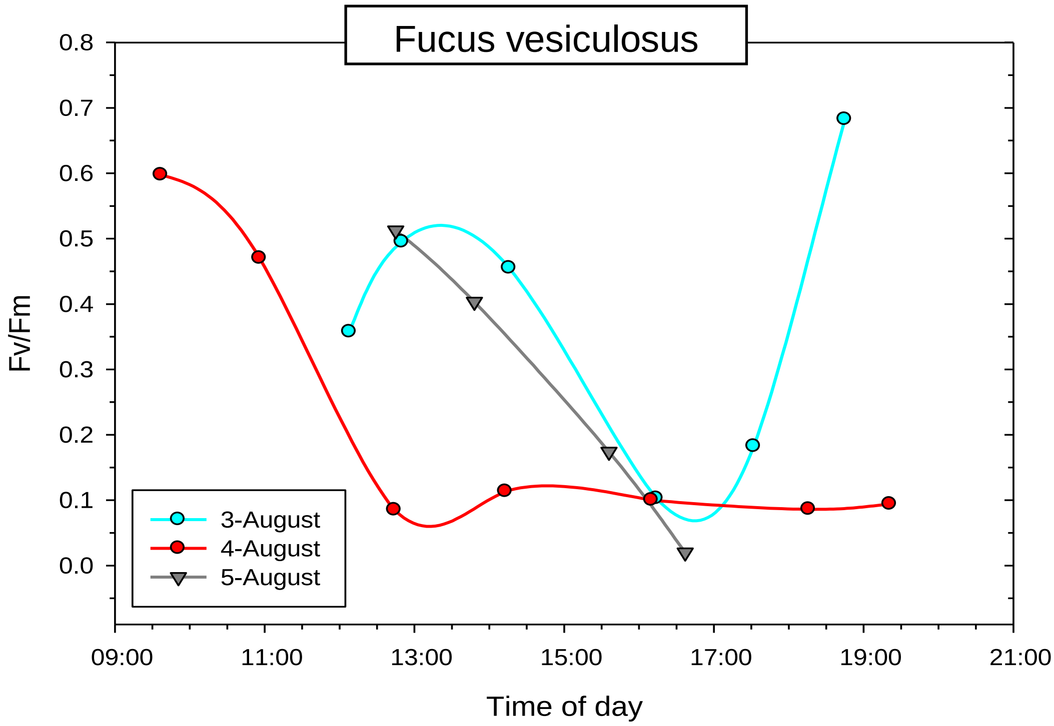
On 3 August our first sample was obtained whilst the plants were still submerged (the specimens were shaken dry before being placed in the vials). The water content at this point (74%) is therefore for a fully saturated plant. A similar value of 76% was obtained on 5 August. The water content fell to 41% at 16:00 on 3 August. After that point the water content of the plants increased rapidly due to the drizzle, rain and increased humidity, reaching 72% at 18:26, well before they were inundated by the flood tide. This final value of 72% on 3 August was very close to that obtained for the fully saturated we obtained (74 - 76%), showing that bladder wrack can rehydrate very well in damp conditions.

The lowest water content values (22%) were obtained at 18:05 on 4 August and 16:46 on 5 August. It is possible that water content would have fallen lower on the 5 August, as the 16:46 result was from the last sample we obtained.

During the tidal exclusion on 4 August water content fell to a minimum of 22%, above the 16% value obtained during a dry sunny day on 21 July. We conclude that bladder wrack is more affected by a warm, dry day under normal tidal conditions than by a tidal exclusion on a damp, humid and cool day.

The Fv/Fm data for bladder wrack obtained using the Pocket PEA meter (Figure 10) shows a similar pattern to the water content (Figure 9). This indicates that water content is likely to be the main factor affecting photosynthetic performance on bladder wrack. Perhaps the only surprising results from the Pocket PEA are the relatively low values of Fv/Fm at the start of the monitoring on 3 August. Initial values were below 0.50, even though the plants had only just been uncovered by the falling tide. The highest mean Fv/Fm value (0.68) was obtained at 18:45 on 3 August, when the plants had been uncovered for several hours. This high value is probably a combination of re-wetting by drizzle, light rain and high humidity and possibly lower dissolved metal concentrations than occur when the plants are covered by seawater. By comparison, the highest Fv/Fm values obtained when the plants were in seawater were 0.358 (3 August) and 0.513 (5 August). These low values in seawater lend weight to the hypothesis that bladder wracks in Copperhouse Pool are affected by contaminants in seawater, probably metals. This may also explain the relatively high Fv/Fm (0.60) at 9:37 on 4 August, when the plants had been exposed to the air and overnight heavy rain for several hours. On the previous survey the highest Fv/Fm value (0.65) for bladder wrack occurred after the plants had been held in seawater from the harbour overnight.

Figure 10. Fv/Fm values for Bladder Wrack, *Fucus vesiculosus*.



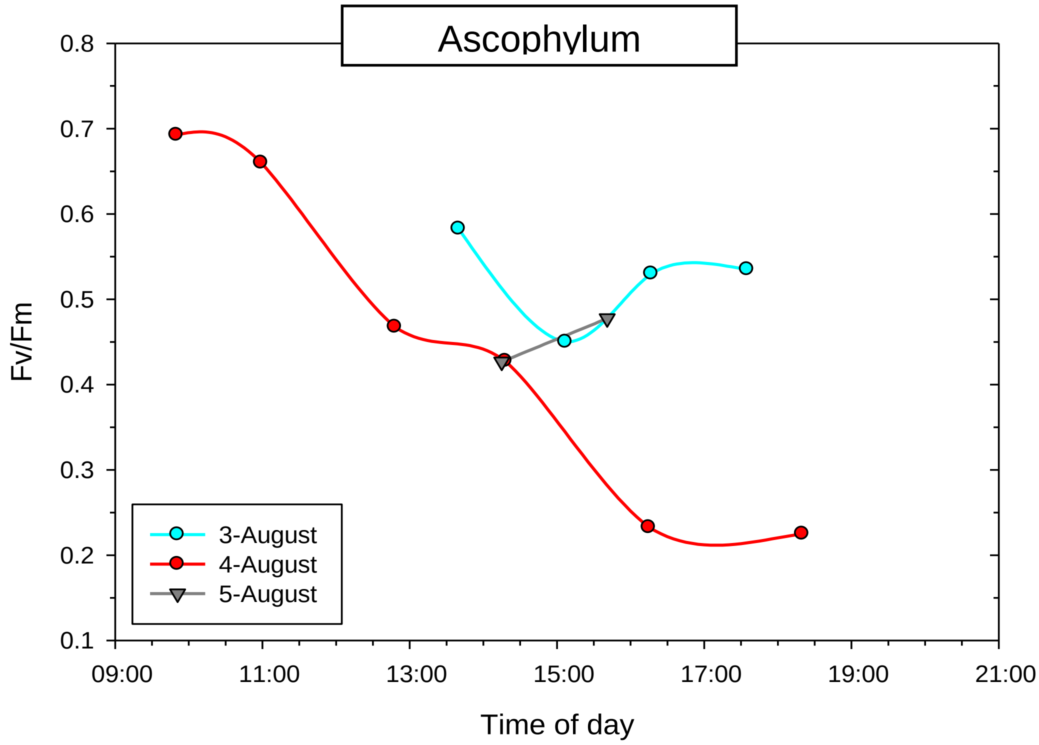
3.4.3 Knotted wrack, *Ascophylum nodosum*

Figure 11 shows the Fv/Fm data for knotted wrack. On 3 August the response was similar to that shown by *Fucus spiralis* and *Fucus vesiculosus*, with a decline at first followed by a recovery later in the afternoon when it was more humid and there was drizzle and light rain. The lowest value reached on 3 August was 0.45 at 15:07.

On 4 August the initial Fv/Fm were the highest in the data set, as the plants were covered by the larger than normal pool of water retained by the sandbags. The Fv/Fm value showed a rapid decline when the sandbags were removed and the plants became exposed. At 9:50 the Fv/Fm value was 0.69, by 16:15 it had fallen to 0.23 and stayed at this value to the end of the monitoring on 4 August. The Fv/Fm values for knotted wrack on the 4 August were lower than any others in the period of monitoring, but this was probably due to the drier and less humid conditions on 4 August. It is interesting that the decline in Fv/Fm values stopped when the weather changed from dry to occasional drizzle.

On 5 August the Fv/Fm value was lower than expected initially (0.43 at 14:15), but then rose slightly to 0.48 at 15:41. The initial low value for Fv/Fm is partly due to a single low value of 0.26 in the three replicates. The small rise in Fv/Fm was due to a single high value of 0.67 in the four replicates. However, the overall relatively low values of Fv/Fm for knotted wrack on 5 August cannot be explained by weather or desiccation, as plants were either wet (at 14:15) or still very moist (at 15:41).

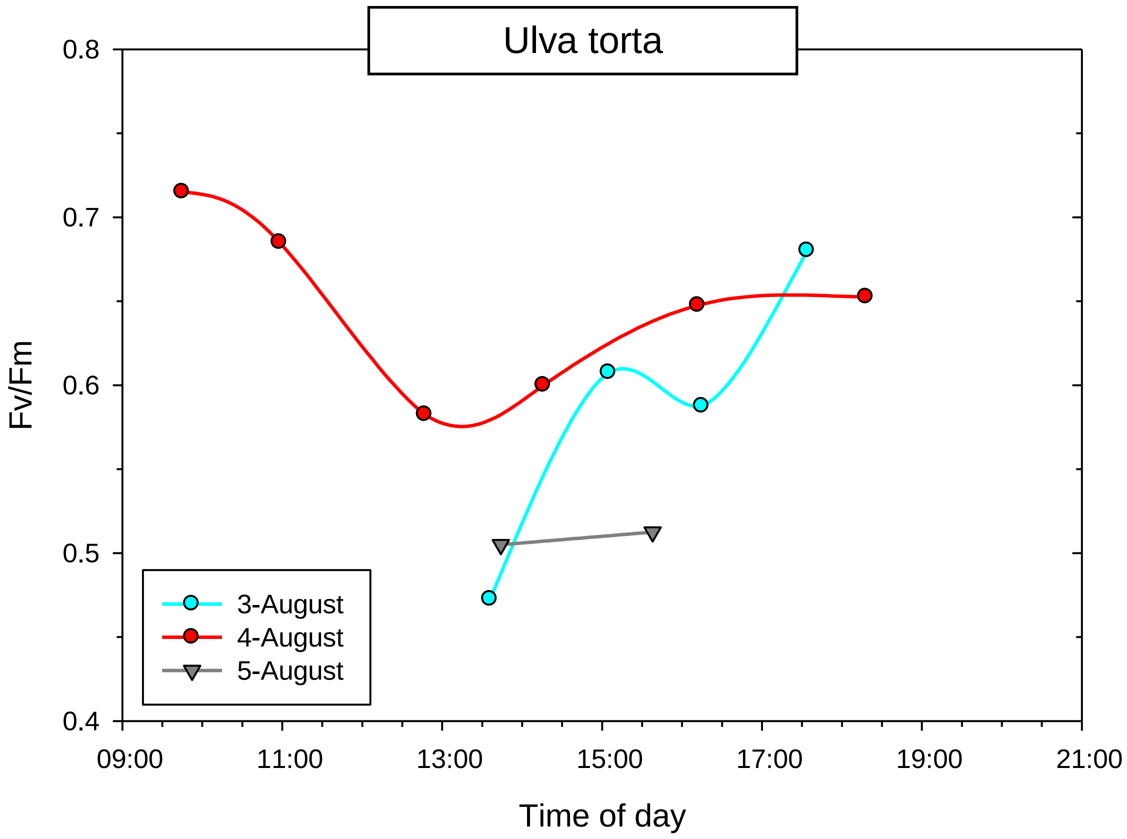
Figure 11. Fv/Fm values for Knotted wrack, *Ascophylum nodosum*.



3.4.2 *Ulva torta* – a filamentous green alga

The filamentous green seaweed *Ulva torta* was either wet or moist for the entire study period. This is mainly due to the fact it is in close contact with the sediment and water probably moves onto the outside of the plants from the sediment by capillary action. Most Fv/Fm values for *Ulva torta* were above 0.5 (Figure 12) and the plants were not adversely affected by the tidal exclusion on 4 August.

Figure 12. Fv/Fm values for *Ulva torta*.



3.5 Invertebrates

3.5.1 Ragworm, Nereis *diversicolor*

No ragworm were observed on the surface of the sediment during the 3 day study. Repeated tidal exclusions could affect the feeding and reproduction of ragworm, but it is unlikely that we could monitor any impacts on condition or reproduction without a very intensive sampling programme, as we would be looking for changes of only a few percent in condition or number of juveniles. Any data obtained would become available after several weeks of intensive study and could not be used to manage the tidal exclusion programme. Provided that the tidal exclusions are not done on hot days, or at intervals of less than 3 days we do not predict any adverse impacts on the ragworm population in Copperhouse Pool.

3.5.2 Lugworm, *Arenicola marina*

Lugworm casts were monitored on 3 – 5 August at three sites, as an index of the number of feeding lugworm in the quadrat. On each occasion, casts were counted at the predicted time of low tide on the day when numbers have peaked (based on data for 21 July survey).

Figure 13 shows that the tidal exclusion reduced feeding activity on 4 August compared to feeding activity on the previous day (3 August), at all three locations. At Sites 4 and 10 which were the more upstream sites (see Figure 2), there were 30% and 18% reductions respectively in cast counts compared to the previous day.

The most striking impact on lugworm feeding was at Site 5, which is close to the low water pool (Figure 2). Here, the number of feeding lugworm decreased by 86%. Very few casts were visible over the entire lobe of sediment close to the pool. This area is well known for lugworm and is usually covered in casts.

The striking depression in feeding activity of lugworm in the lobe of sediment around the low water pool probably resulted from prolonged period of submersion in a shallow layer of low salinity water. Site 5 (and the entire lobe of sediment containing large populations of lugworm) was underwater at the beginning of the day and was only uncovered after the removal of some of the sandbags. By 11:28 it was possible to access Site 5.

The salinity of water in the pool was 8 psu at 9:12 (Site 8) and 5.5 at 10:35 at Site 6, close to the lugworm at Site 5. The exact salinity profile is difficult to predict given the use of sandbags that raised water levels and the overnight rain that would have increased freshwater inflow and lowered salinity. However, we expect the salinity might have been less than 10 psu from about 05:30 (based on salinity results for 21 July) and possibly earlier, given the increased freshwater flow. This would mean that lugworm at Site 5 would have been covered with water of less than 10 psu for at least 6 hours.

The depression of lugworm feeding at Sites 4 and 10 may be due to prolonged low salinities in the sediment due to the lack of the high tide and overnight rain. Site 10, the most upstream site was a hummocky site with pools of water retained between mounds of sediment. The moderately saline pools retained during the ebb tide and tidal exclusion could have protected this area from the effects of rainfall. This could explain why there was less effect on feeding activity at Site 10 than at Site 4.

Detailed studies by Shumway and Davenport (1977) have shown that lugworm feed provided that the salinity of the overlying water remains above about 30% seawater (approximately 10.5 psu). Below this salinity lugworm contract into the bottom of their U-shaped burrow and their only activity is to "sample" the water above, at approximately hourly intervals. If the conditions are unsuitable they return to the bottom of the U-shaped burrow. This is a normal behaviour for lugworm. If taken out of their burrows, lugworm are osmoconformers and their body fluids follow the osmotic changes in the external environment when salinity is adjusted. In reality, they avoid these changes and the energetic requirements linked to cell volume regulation by using behavioural mechanisms to avoid exposure to low salinities.

In the day following the tidal exclusion there was evidence of an increase in the number of feeding lugworm at all sites (Figure 13). Therefore, although repeated tidal exclusions would affect lugworm feeding and growth on the day, it is unlikely that occasional tidal exclusions would have a significant effect overall.

3.5.3 *Corophium volutator* (an amphipod crustacean)

Live *Corophium volutator* were not seen crawling on the surface in either of the two quadrats on any occasion.

On 4 and 5 August we dug into the surface of the sediment at a site away from the quadrats to examine whether there were live and active Corophium present in the sediment. The Corophium appeared to be behaving normally and most were present at a depth of 1-3 cm, with a maximum depth of 6 cm. We observed a large number of *Corophium* bodies during the surveys on 21 July and 3-5 August, usually in small depressions in the sediment or floating on the surface of the low water channel. Some specimens were brought back to the laboratory. They were mainly exoskeletons, rather than dead bodies. Corophium need to shed their exoskeletons to grow, and this probably explains most of the "bodies" that we observed. However, they also have a naturally very high mortality, as densities can reach tens of thousands per square metre and they only live for several months.

A study of the salinity tolerance of Corophium volutator showed that it can tolerate down to 2 psu (McLusky, 1967), so it is highly unlikely to be adversely affected by low salinities during a tidal exclusion.

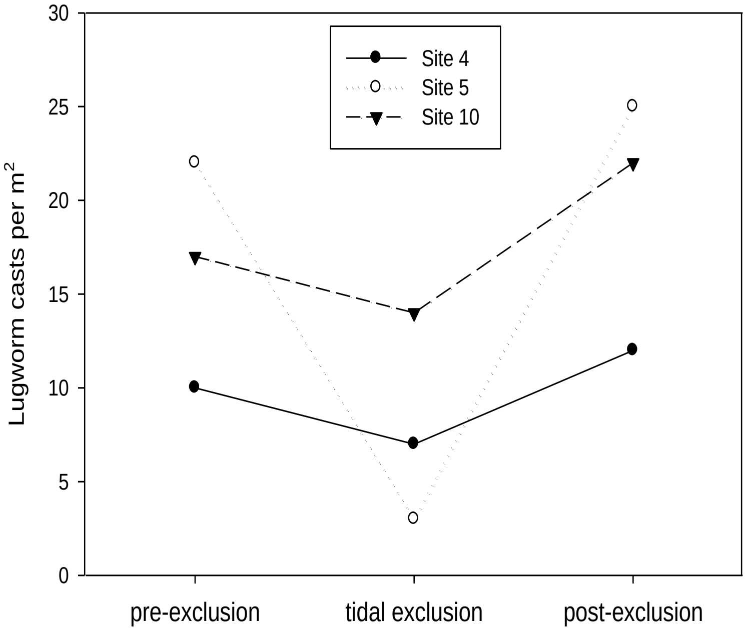
Repeated tidal exclusions would probably adversely affect feeding and reproduction in *Corophium volutator*, but occasional exclusions separated by a few days should have a minimal impact.

Impacts of tidal exclusion on feeding activity of Lugworm (*Arenicola marina*) at three locations in Copperhouse Pool. Figure 13 shows the total number of casts resulting from Lugworms feeding within the 1.0 m^2 quadrat at each location (Site 4, 5 and 10: see Figure 2), monitored at the time of the predicted low tide. Table 13 gives the results for **c**ounts of casts made in each of the four 0.25 m^2 quadrats at each location; counts for the 4 areas at each site were always made in the same order.

Table 13 Counts of lugworm casts

	Site 5	Site 4	Site 10
03-Aug	7	0	7
	4	2	4
	7	3	4
	4	5	2
totals	**22**	**10**	**17**
04-Aug	1	2	6
	2	1	3
	0	4	3
	0	0	2
totals	**3**	**7**	**14**
05-Aug	6	2	8
	7	3	6
	6	7	4
	6	0	4
totals	**25**	**12**	**22**

Figure 13 Total counts of casts on each day



3.5.4 Brown shrimp, *Crangon crangon*

Toxicity tests on brown shrimp taken from the low water channel on 21 July showed that the lethal time (LT50) for 50% of the specimens at 1 psu was 3 hours 15 minutes, but they survived well at 2 psu. Based on these results we requested that the trial exclusion should not take place after heavy rain. However, there were heavy rain showers during the early morning of 4 August, and we had previously predicted that salinity in the low water channel may fall below 2 psu after heavy rain. On the 4 August salinity fell to 1.8 psu, low enough to cause some minor mortalities. No mortalities were observed, and the brown shrimp that we examined in a white tray were alive and active. This may be because they experience slightly higher salinities when they are buried in the sediment in the channel.

The results show that continued caution is required regarding heavy rainfall, as this could cause brown shrimp mortalities. We have therefore retained the recommendation that future exclusions are not done after heavy rain, or when heavy rain is forecast on the day of the exclusion.

4. REFERENCES

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